POLITECNICO DI MILANO

SCHOOL OF ARCHITECTURE, URBAN PLANNING AND CONSTRUCTION ENGINEERING

MASTER OF SCIENCE IN BUILDING ENGINEERING

Experimental approach to fire-safety engineering
Implementation of fluid dynamics modeling in the explosion risk-analysis for an existing biogas plant

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Abstract

In a national context in which energy supply is strongly linked to imports, one of the possible solutions is the use of internal and renewable resources. Among the most developed technologies in recent years, the production of biogas from biomass could play a key role for the energetical sustainability. In this sector, characterized by the presence of plants consisting of standardized elements often arranged in a similar way to each other, the approach dedicated to fire-safety design is often purely normative and does not consider the geographical context in term of climate and surrounding. The aim of the authors is to determine if an in-depth analysis, carried out through IT tools, can allow the prediction of fire/explosion scenarios otherwise difficult to weigh, proposing a milestone for an innovative fire-safety design, based on the engineering approach. Through the formulation of an experimental methodology and using a CFD software for the fluid dynamic modeling of gaseous masses (never used before for these purposes), it is possible to consider different variables such as climatic factors and the characteristic geometries of the plant under analysis and its surroundings, evaluating their interactions. Trying an experimental approach, aided by software, particular attention is paid to the evolution of risk scenarios related to the transition from the on-site conversion of biogas in heat and electricity (cogeneration), to the valorization of biogas by upgrading in order to obtain biomethane for refueling cars and operating machines.

Abstract

In un contesto nazionale quale quello italiano, in cui l'approvvigionamento energetico è fortemente legato alle importazioni, una delle possibili soluzioni è l'utilizzo di risorse interne e rinnovabili. Tra le tecnologie più sviluppate negli ultimi anni, la produzione di biogas da biomassa potrebbe giocare un ruolo chiave per la sostenibilità energetica. In questo settore, caratterizzato dalla presenza di impianti costituiti da elementi standardizzati spesso disposti in modo simile tra loro, l'approccio dedicato alla progettazione antincendio è spesso puramente normativo e non considera il contesto geografico in termini di clima e ambiente circostante. L'obiettivo degli autori è quello di determinare se un'analisi approfondita, effettuata attraverso strumenti informatici, possa consentire la previsione di scenari di incendio/esplosione altrimenti difficili da soppesare, proponendo una pietra miliare per una progettazione innovativa della sicurezza antincendio, basata sull'approccio ingegneristico. Attraverso la formulazione di una metodologia sperimentale e l'utilizzo di un software CFD per la modellazione fluidodinamica di masse gassose (mai utilizzato prima per questi scopi), è possibile considerare diverse variabili come i fattori climatici e le geometrie caratteristiche dell'impianto in analisi e dei suoi dintorni, valutandone le interazioni. Sperimentando un approccio sperimentale, coadiuvato da software, particolare attenzione è rivolta all'evoluzione degli scenari di rischio legati al passaggio dalla conversione in loco del biogas in calore ed energia elettrica (cogenerazione), alla valorizzazione del biogas mediante upgrading al fine di ottenere biometano per il rifornimento di auto e macchine operatrici.

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Introduction

The aim of this thesis work is to approach the fire-safety engineering related to a particularly varied plant in terms of sources of risk, through an innovative technical approach. Basing on the actual legislation, a more realistic evaluation of the accidental scenarios will be proposed, according to the results observed. This evaluation will be used to integrate some useful suggestion that will help in defining the adoption of fire safety measure.

The thesis-work is divided into nine chapters in which, following a logical path, the general energy situation and the biogas/biomethane sector are first analyzed then moving on to the evaluation of a plant for the in-situ valorization of biogas through cogeneration and finally, evaluating one of the possible future scenarios, i.e. the transformation by upgrading of biogas into biomethane for the public and the supply of company vehicles.

Chapter 2 frames the energy situation at European and Italian level, introducing the biomethane and biogas sector, focusing on the Compressed Natural Gas CNG

Chapter 2 focuses on the plant taken as a case study, both in terms of production, with the decomposition into production phases and the definition of the different components of the plant, and from the climatic point of view, with the atmospherical analysis based on the characteristic data of the geographical site considered.

Chapter 3 deals with fire safety for installations of this kind. After the definition of the regulatory situation in Italy, incidental historiographical research is carried out concerning significant cases of fire and / or explosion within plants for the production of biogas. The critical points of the plant are subsequently identified from the point of view of gaseous fuel losses, considering the most relevant for the evaluation, according to ATEX regulations.

Chapter 4 deals with fluid dynamic simulations. Since this is an application never used before for this purpose, methodologies, conditions, and assumptions considered for the realization of the model being evaluated have been defined. At the end of the chapter, the results of the simulations are analyzed.

Chapter 5 deals with the integration of the existing plant (biogas production and cogeneration) with the upgrading of biogas in order to obtain biomethane for direct sale to the public and for the supply of company vehicles.

In Chapter 6 the fluid dynamics simulations of the plant in the new configuration are carried out and the results are analyzed.

In Chapter 7 a conclusive analysis of the simulations of the different configurations is made and, on the basis of this, suggestions are formulated.

In Chapter 8 a short manual for safety in biogas plants is drawn up, touching on the different risk areas and possible solutions.

1 Current energy situation

The current geopolitical scenarios, characterized by extreme uncertainty in the supply of energy resources, combined with the pressing deadline of the objectives of the Roadmap 2050 (1), relating to a low-carbon Europe, inevitably lead to the need to identify and exploit renewable energy resources as much as possible from local and sustainable origin.

The available data on electricity production in Italy in 2020 provided by Terna (the operator of the national electricity grid) suggest that 57.6% of electricity is still generated from non-renewable sources through the combustion of fossil fuel inside thermoelectric power plants, while on the natural gas side, it is evident that the system is mainly powered by gas produced in foreign countries, imported by means of international gas pipelines or transported by sea in liquefied form as LNG, with an import equal to 66.5% of national needs. (2) (3)

The timid approach to the alternative energy sources, also through the adoption of new incentives by national and local governments that give support to those who update their plants, vehicles or production processes, is undoubtedly the right one but at the same time it is essential to accelerate the energy transition and increase the production and consumption of energy from clean sources.

Along this path of renewal, the main types of alternative energy are above all solar, wind, hydroelectric and energy from biomasses.

Within the latter group, the production of biogas is of primary importance in several aspects: since it is a renewable source (such as solid and liquid biomass) with not intermittent availability, this allows the production of electricity throughout each day of the year, representing at the same time a highly decentralized resource, that is, consisting of a network of small power plants allowing to supply even centers distant from the large transport and distribution networks. The recent sector studies conducted by the *European Biogas Association* (EBA) frame the Italian situation compared to the rest of Europe which, with more than 1700 active biogas plants and a total biogas production of 23 TWh in 2020, is second only (4) to Germany considering both the number of plants and the total production of biogas. In addition to these, it is worth mentioning France, which has been experiencing strong development in this sector in recent years.

The biogas produced can be exploited on site through cogeneration (thermoelectric energy) or, after an upgrading process (a biogas refining process), transformed into bio-methane and fed into the network or distributed retail for the supply of vehicles with methane engines. Even in this juncture, Italy shows excellent prospects for the future, being the second fastest growing biomethane market in Europe, preceded only by France: from a total of 12 plants present on the Italian territory in 2019, it has passed to 23 plants operating at the end of 2020. When the European Biogas Association EBA report has been written (first half of 2021), it was expected that other 4 plants would be built in the short term while another 32 would be at different design levels.

Projections suggest, therefore, that Italy will become one of the leading bio-LNG (Liquid Natural Gas) producing countries in Europe, having set a biomethane production target of 1.1 billion cubic meters per year by 2023. (5)

The potential production of biogas and biomethane calculated for 2030, could reach up to 44 bcm, equivalent to 467 TWh. By 2050, this production can more than quadruple towards 100 billion cubic meters. This is equivalent to 25% of the current use of fossil natural gas in Europe (6). Once total gas consumption declines over the years to come, biomethane can cover 35-40% of gas demand by 2050. One of the most promising growth areas in the industry is the production of Bio-LNG and Bio-CNG (Compressed Natural Gas), which can play an important role in the decarbonization of transport. Despite current efforts by the European Union, transport is the only sector that is not decarbonizing but, on the contrary, shows an increase in greenhouse gas emissions on an annual basis since 2014. (7)

1.1 European and Italian statistics

In this chapter it was tried to provide an overview of the state of health of this sector through statistical material based on the present and the future of biogas and biomethane in Europe, subsequently focusing on the Italian peninsula. This analysis is performed on the basis of data obtained from various statistical reports including, in particular, *EBA Statistical Report 2021* and *Bioenergy Europe – Statistical Report 2021 – BIOGAS*, two of the largest organizations that make Biogas and its derivatives their object of study and support.

1.1.1 Energy production

The production capacity of a plant is closely connected to its size. In terms of annual electricity produced, despite the trend of recent years sees the tendency to build medium-small plants, it is interesting to note that in Europe the size of biogas plants allows an average production of 8 GWh per year while for biomethane plants, although lower in number, there is a production of about 36 GWh per year, or more than four times the biogas equivalent. (4)

Probably because of the costs and management difficulties, lately the average size of a plant is gradually decreasing. This has no effect on the production of biogas which, thanks to the development of sector technologies, leads to an increase in the effectiveness of these plants and the raw material with a consequent growth in energy production.

1.1.2 Number of installations

The recent surveys carried out by the *European Biogas Association* referring to the year 2021, reward Germany as the leading European nation for the number of biogas plants with the construction of 137 new plants out of 285 built throughout Europe only in 2020.

Considering the plants capable of producing biomethane, being this a product of biogas refining, these are in very small numbers when compared to those for the production of the latter, as can be seen from the following graph. Also, from the aforementioned graph it is easy to see how the construction of biogas plants has seen a strong increase between 2009 and 2014 followed by a stabilization in the following years. This is due to the issuance of various incentives at European and local level that have then ceased to exist.

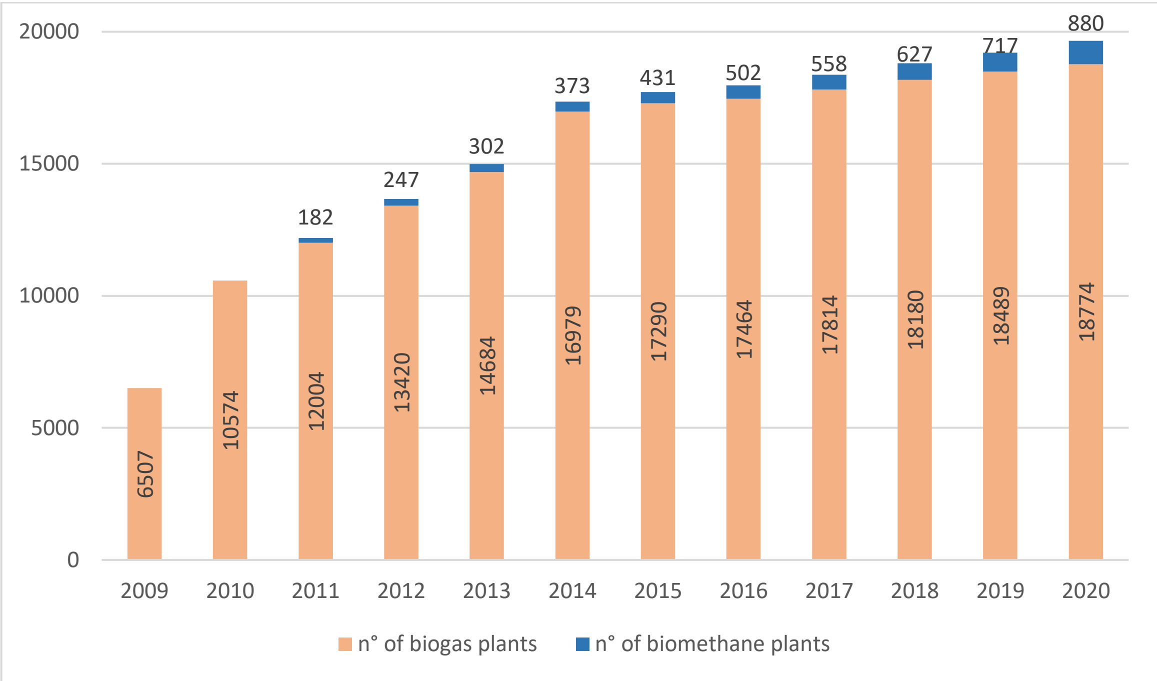

Figure 1: Number of biogas plant in Europe   Source: EBA _ Statistical report 2021

Although to a small extent, it can be noted that the construction of biomethane producing plants is growing especially between the years 2019 and 2020, despite the pandemic has had heavy and negative results on the study process, procurement of materials and on the construction of new structures. In addition, according to the EBA, 2021 will represent a further year of growth for biomethane plants thanks to the construction of 115 plants by August 2021. France represents, within the European community, the country that is most willing to invest in this sector in the near future, with as many as 950 projects at different stages of detail and development (4).

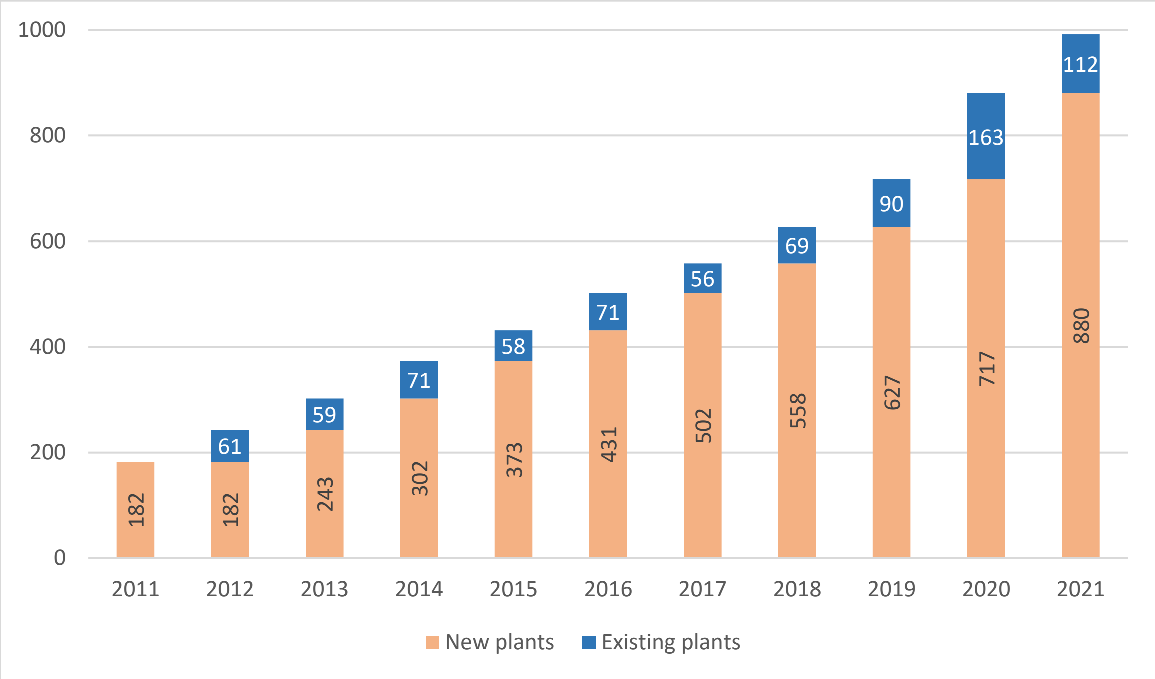

Figure 2: Developement of biomethane plants in Europe   Source: EBA _ Statistical report 2021

For a more in-depth study of the development in numerical terms of biomethane plants in Europe, the EBA has classified and counted all the plants known to it, noting that the medium-small plants are the most present in the territory. This phenomenon can be explained considering the incidence of total costs and the difficulty of operating a large plant.

This survey has considered both completely new biomethane plants and biogas plant then implemented with upgrading unit. In the second case, the owner of the plant has to define the amount of biogas that he desires to dedicate to the upgrading and the volume of biogas useful for the cogeneration. The importance of this investment in biogas is based consideration regarding availability of biogas to send to the cogenerator and to the upgrading unit. Further logistic, economical and energetic reasoning must be done on the typology of upgrading for the biomethane. In a period of uncertainty like this, the presence of many desperate biomethane plants can only help other producers to adhere to this type of energy evolution leading to a further increase in number of new biomethane plants.

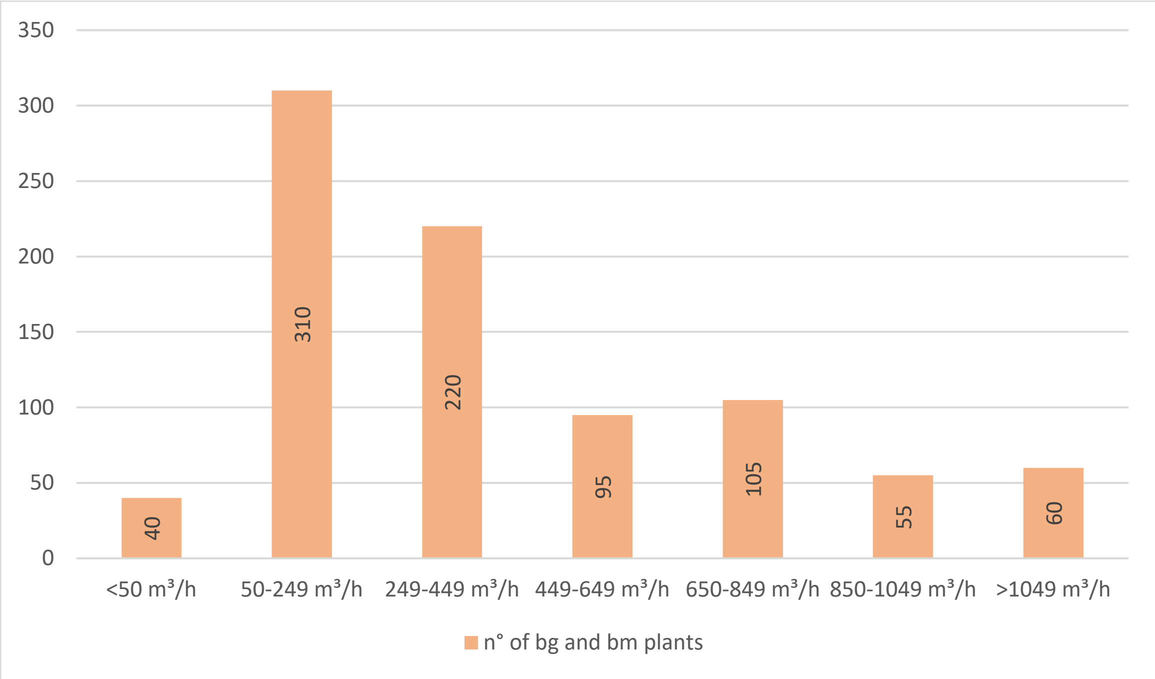

Figure 3: Active biomethane plants in Europe per plant size   Source: EBA-Statistical report 2021

To date, there are many studies for the prediction of future developments in the biogas and biomethane production sector. These treatments differ in predictive methodologies and input data and do not always lead to agreed results depending on the different sources. Despite this, most of these surveys come to the conclusion that by 2030, the current European production capacity can even be doubled reaching production volumes between 35 and 42 billion cubic meters corresponding to 370 and 467 TWh (conversion based on the caloric value of biomethane equal to 10.61 kWh / Nm^3) and (according to Eurogas quintupled by 2050 leading to the production of 95 billion cubic meters or 1020 TWh with a total energy production equivalent to 126GW) (4). Considering that about 95bcm of biogas and biomethane cover about 24% of European natural gas demand in 2020 and estimating that the actual consumption of gas in the coming years will be reduced, it will be possible to count on a coverage of 30-40% of the total demand for natural gas by 2050. A less remote statistic than those of 2050 is provided by the IEA (International Energy Agency) which predicts a European production of 125 bcm of biomethane and a production of 166GW, all this by 2040. (8)

In 2019, biomethane produced by biomass processing covered a marginal percentage of the total consumption of the European Union, leading to the production of about 10% of the total amount of energy produced from renewable sources. It should be noted that these numbers are a consequence of the fact that the production of energy from biogas is a practice developed only in recent years and mainly at local level, which involves a still fairly limited catchment area, with the future developments of biomethane especially in the automotive sector. These numbers will see an important growth, thanks also to the various incentives made available to the Union and individual nations (it is expected that thanks to economic incentives both at national and local level, Italy in the future will aim to become the largest supplier of biomethane for transport among the EU27). (4)At the topof the main consumer countries of this type of gas, there are Germany (with a consumption in2019, equal to 7550 ktoe) and Italy (with a consumption in 2019 equal to 2013 ktoe) (9).

The following graph shows the forecasts of production of both biogas and methane in accordance with the various studies. The timesteps analyzed consist of the years 2020, 2030, 2040 and 2050. It is clear that these are forecasts developed considering a stable geopolitical situation: the recent changes in the Eurasia area have definitely influenced the search for independent gas supplies, which could lead to a massive increase in investments in this sector, with a rather positive consequence both in terms of production capacity and in terms of technological advancement.

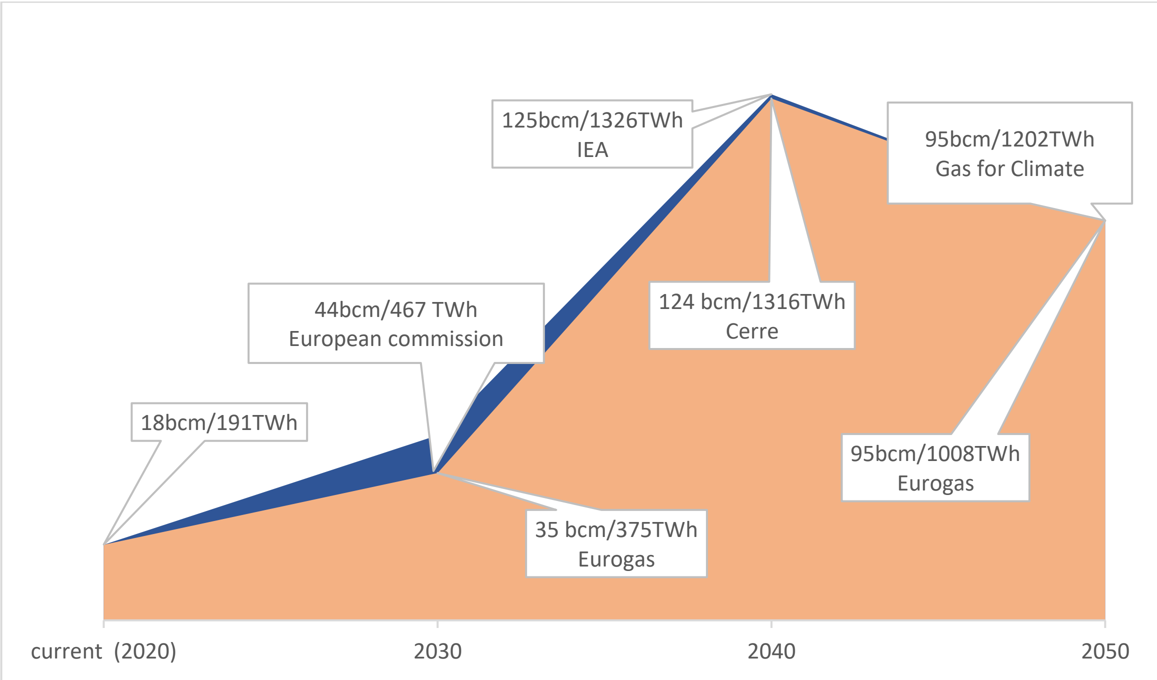

Figure 4: Potential European biogas and biomethane production for 2030,2040 and 2050 Source: European Biogas Association

One of the most promising sectors for this type of biofuel is that related to the production of *Liquid Natural Gas* LNG and *Compressed Natural Gas* CNG. On the market, the supply of these automotive fuels is still quite limited but the measures taken by the individual states and the European community will lead to important developments regarding biomethane distributors along the main European road and motorway sections, with a subsequent reduction in the consumption of fossil fuels and a decrease in the release into the atmosphere of *the Green House Gases* GHG, which to date in 2022 is still too high. (10)

1.1.3 Methane transport and distribution network

The methane infrastructure network requires determined gas quality standards and high input pressures due to the long distances that need to be covered. For this reason, the introduction into the transport network concerns only biomethane and not biogas. Due to the costs, the connection to the main network (transport pipelines) is convenient mainly for medium and large biomethane plants able to guarantee a supply of large volumes of gas and also constant. Interesting developments could concern plants with smaller production capacities, if the introduction into local methane distribution network is also promoted.

Depending on the location of the plant, the supply of gas to the network can be carried out through the transmission network (higher volumes and greater distances) or through the distribution network (smaller volumes and smaller ranges of action). In any case, the gas must be subjected to compression treatments that make it suitable for feeding into the network, for transport or for the supply of fuel distributors directly on the roads.

The situation in 2021 in Europe finds about 47% of biomethane plants connected to the distribution network, while 20% to the transport network, the remaining percentage includes plants used for the wholesale sale of biomethane, for refilling cylinders or plants whose end use of the gas produced is not known. As can be seen in the following graph, according to the *EBA statistical report 2021* among the European countries that have installed biomethane plants on their territory, Italy is the leading country for input into the transport network, unlike Denmark and Austria which produce and distribute in a more localized way. This can show how much Italy is oriented in this direction at national level, spreading biomethane even in areas otherwise equipped only with methane extracted from underground deposits. (4)

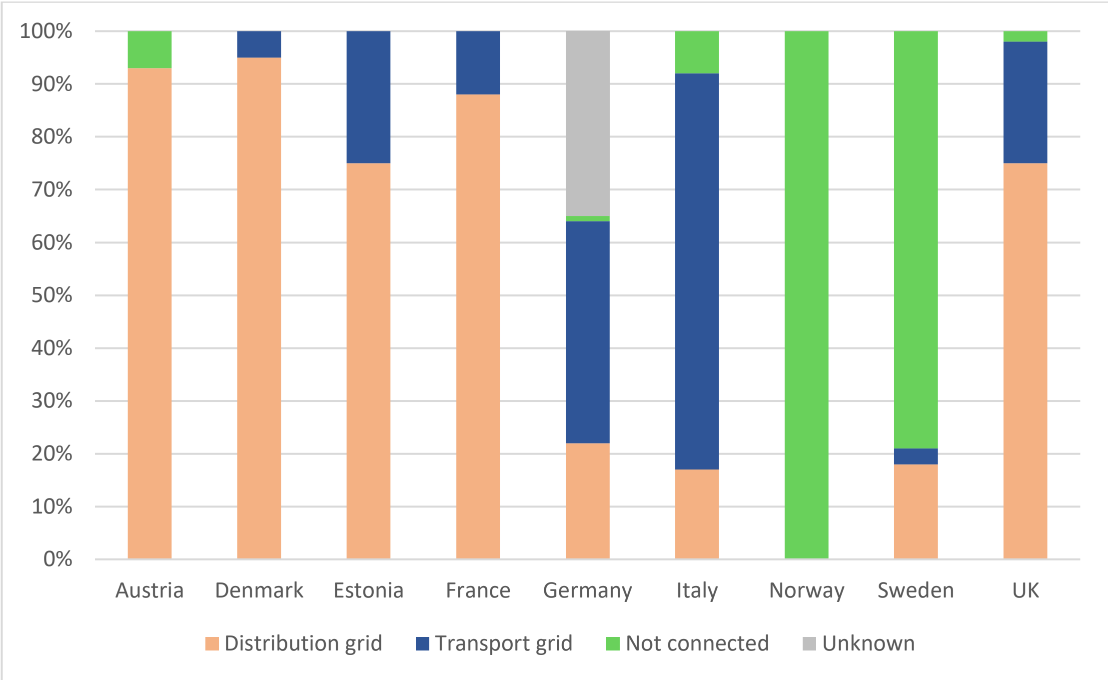

Figure 5: Percentage of biomethane plants connected to the distribution and transport grids in Europe (2020) Source: EBA-Statistical report 2021

1.1.4 Biomethane for automotive

One of the next objectives related to the reduction of CO_2 emissions into the atmosphere concerns the diffusion throughout the European territory of methane distributors along the main road and motorway routes. The use of biomethane for this purpose does not seem to present any disadvantage compared to the extracted methane given that the chemical composition of this biofuel is identical to that of conventionally consumed methane and given that no technological adaptation of the existing infrastructures is required. The refueling of internal combustion engines or internal tanks with bio-methane can take place after compression or liquefaction of the gas, transforming it into Bio-CNG and Bio-LNG respectively. The difference between these two fuels lies in the storage mode and yield: compared to Bio-CNG, Bio-LNG has a higher energy density, which makes it suitable for refueling both road and marine means of transport (11) (long distances with important loads).

The production of CNG is much higher than LNG due to the high costs related to the cooling of the gas that leads to its liquefaction.

A practical example of this disparity is as follows: there are currently a small number of distributors in service along the European motorway networks, both liquid natural gas (LNG) and compressed natural gas (CNG), respectively 441 and 4056. (12)

In mid-2021, 16 liquefied biomethane plants were active throughout Europe, this number is expected to grow; in fact, by the end of 2021 another 7 plants were being activated, in 2022 23 additional plants will be completed and in 2023 another 29 plants.

The forecast for 2024 is that it will be able to produce about 10.6TWh from Bio-LNG capable of powering 25,000 trucks. Of these 10.6TWh, 0.9TWh can be produced by currently active plants, the remaining 9.7TWh are associated with plants at various stages of development and construction.

Italy is currently home to 4 large liquefied biomethane plants and another 32 are in various stages of development. On average, the production capacity of Italian plants is around 82GWh/year. (4)

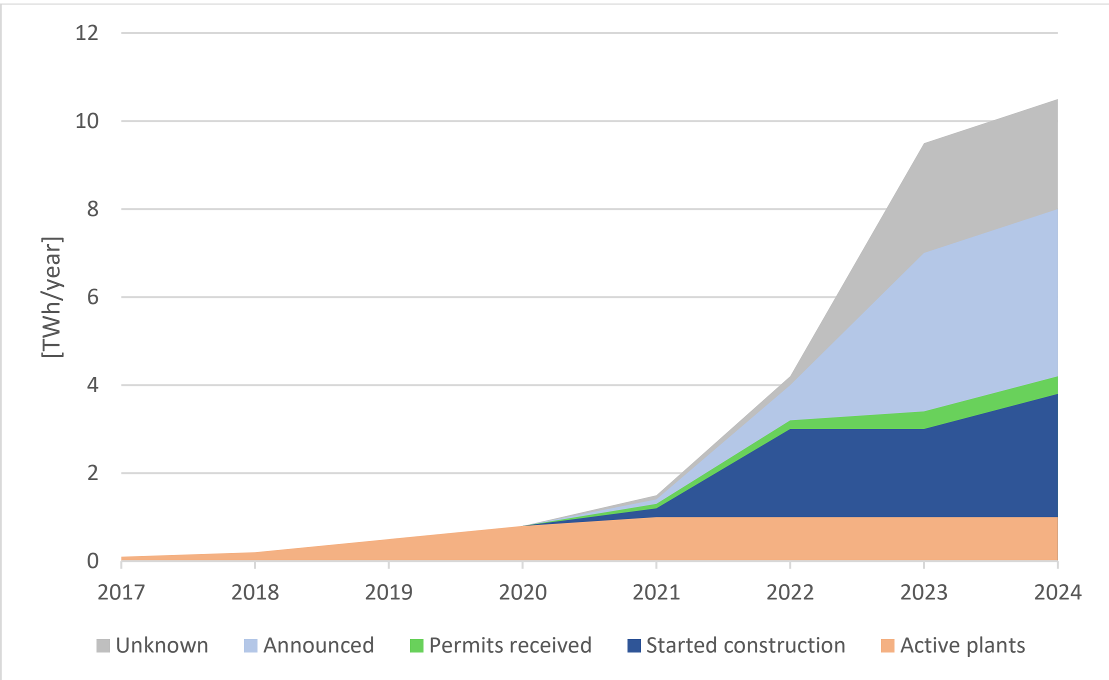

Figure 6: Current and future development of Bio-LNG production capacity in Europe Source EBA-Statistical report 2021

The increase in the volumes of bio-methane produced will also affect the number of methane vehicles registered in the coming years, just think that according to the NGVA (Natural & biogas Vehicle Association) the number of trucks on the roads that will be powered by methane will reach 280 thousand units. (4)

1.1.4.1 Compressed Natural Gas – CNG

Compressed biomethane CNG is currently the best alternative to fossil fuels conventionally adopted for transport. This is due to a final balance of CO_2 emissions into the atmosphere, equal to zero. Bio-CNG is produced simply by compressing the bio-methane leading to a reduction in the volume occupied and an increase in the energy density of the gas.

Also conventionally adopted for the supply of motor vehicles, it is spread through fuel stations equipped with the equipment useful for refueling vehicles already with compressed methane. Unlike Liquid Natural Gas, this type of fuel can be compressed at the manufacturer plant or transported via the distribution network and then compressed at the dealer. This also allows greater freedom with regard to the geographical location of the distributor.

Among the countries with the highest production of Bio-CNG there are Sweden, Finland and Norway that have favored this variant of methane in order to use it on site due to a little extensive transport network on the territory (see figure above), only in the southern areas of Sweden, where large gas distribution routes are passing through that connect other neighboring states such as Denmark, the amount of gas in the transport network increases. In Norway, out of 16 plants, 14 are active for the production of Bio-CNG, in Finland 21 out of 22 plants produce compressed biomethane (4).

1.1.4.2 Biogas, biomethane and automotive in Italy

As already highlighted in the previous paragraphs, Italy represents one of the largest and most virtuous European states in the field of Biogas and Bio-Methane, all this thanks to a technological development in this sector started during the 90s and supported by a series of state incentives issued over the years. One of the main stimuli to the spread of biogas is to be attributed to the "all-inclusive tariff" published in 2008 and which led to an important diffusion of the plants during the four-year period 2008-2012. Despite a reduction in investments in this sector that have slowed down the speed of propagation of these plants, the construction of new infrastructures has remained almost constant until 2020, leading Italy to occupy the second step of the podium among European countries for energy production, with a total amount of 23 TWh thanks to its 1710 active plants, mainly located in the northern area of the peninsula. In this last year, the Italian Ministry of Energy Transition is expected to breathe new life into this sector through the issuance of additional subsidies and guidelines.

As in all other countries, even in Italy the aim is to exploit only energy sources deriving from agricultural and industrial waste, but it should be emphasized that still a considerable part, albeit minor, of the energy produced is the result of the processing of the so-called *Energy Crops* that certainly have a greater impact on the environment. Energy *crops* consist of materials of vegetable origin specially cultivated for the sole supply of biogas plants.

The first biomethane production plant in Italy was built in 2012. Only in 2018, thanks to the Italian Ministerial Decree of 02/03/2018, which proved to be very effective, other plants for the upgrading of biogas were started. In mid-2021, 23 active plants were located in Italy and 4 under construction, making it the second with the strongest growth in this sector only after France among the EU countries. Through the aforementioned Decree, the Italian government strongly demonstrates what the final aim of this process wants to be, i.e. the supply of motor vehicles. The plants that will be able to benefit from subsidies deriving from the Decree, will necessarily have to produce biomethane only for the supply of motor vehicles. This imposed regulation has meant that 100% of the biomethane produced is used only for the power supply of bio-CNG and bio-LNG vehicles and within two years it is expected that the plants will reach the total production of 1.1 billion cubic meters of biomethane each year. In doing so, Italy could become the first state able to completely replace the conventional methane, for this use, with that produced inside the digesters and subsequently refined, this result takes on even more importance if it is considered that the Italian roads are traveled by the largest fleet of methane vehicles in Europe. Along the Italian road network there are about 1400 filling stations for compressed natural gas and 85 for liquefied gas, in 2021 only 4 bio-LNG production plants were active but with 32 new plants at different stages of construction, this growth could bring to our country the primacy of the main producer of bio-LNG, with a production forecast for 2023 of about 2800 GWh deriving from bio-LNG.

It is expected that some of the next incentive will be focused more on the consumption of bio-methane in the industrial sector and in the direct injection of bio-methane gas into the public distribution and transport network.

Of the 23 plants currently operative, 4 are connected and supply the distribution network while 17 are connected to the transport network and 2 plants are not connected to any type of infrastructure. It has been estimated that in 2020 the 23 plants were able to produce about 2100 GWh of energy, most of which came from the processing of municipal solid waste (FORSU). According to the European Biogas Association EBA sources, by the end of 2021, there will be at least 27 active plants, framing the Italian market as the second fastest growing market in Europe, after France. (4)

1.1.5 Environmental and energetic considerations

The combustion of biogas has all the typical advantages of methane gas compared to other fossil fuels, releasing very low levels of volatile hydrocarbons and nitrogen oxide and, at the same time, leading to a zeroing of substances dangerous to human health such as lead, sulfur and fine dust.

A plant for the generation of electricity through the enhancement of 1 Megawatt biogas produces about 8 million kWh of electricity per year and, taking into account that each citizen in our economic and social context consumes just over 2,800 kWh per year, is therefore sufficient to meet the needs of 2800 inhabitants.

The official formulas consider that one Ton of Oil Equivalent (TOE) produces 10,000 kWh: from this it follows that the planned plant leads to a saving of 800 TOE per year (13).

In order to properly assess the contribution that this kind of plant brings to the environmental balance, it is necessary to start from the awareness that the production of electricity through biogas, emits CO_2 of agricultural and non-fossil origin into the atmosphere. The production of energy is therefore zero emission of fossil CO_2 and therefore zero climate impact (greenhouse effect), or with the use of biogas for the production of electricity: nothing is removed and is not added to the CO_2 present in the atmosphere. For this reason, it is possible therefore to speak of neutrality, intended as invariance of the environmental balance. The actual and concrete positive contribution to the environmental balance therefore derives from the so-called "avoided cost", that is to say from the fact that cogeneration with the planned plant makes it possible to avoid that this energy must be produced with a traditional, fossil fuel plant.

The reasons just explained are the basis of the strategic direction that sees the use of plant biomass as one of the most efficient systems to reduce greenhouse gas emissions, in implementation of the 1998 Kyoto agreements. It is important to underline that in the perspective of the fight against climate change, one of the most important issues on the world agenda after the entry into force of the Paris Agreement, biogas is indicated by international institutions as one of the main resources that can guarantee energy autonomy and the gradual reduction of the current state of air pollution and the greenhouse effect. It is possible to predict that the biogas industry will therefore increasingly play a decisive role in the energy transition, in the process towards decarbonization and in the green and circular economy. (14) (15)

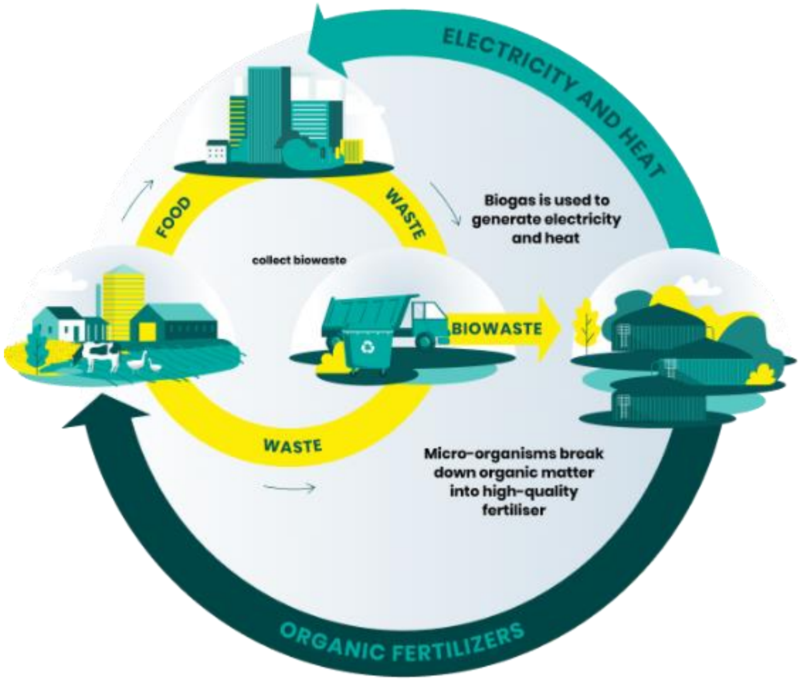

Figure 7: Circular economy of biogas   Source: greengenius.com

1.2 Biogas

Biogas is a natural fuel composed mainly of methane (CH_4) and carbon dioxide (CO_2) and is obtained through anaerobic digestion, i.e. the process of bacterial fermentation of organic substances of plant or animal origin that takes place in the absence of oxygen. A wide range of organic materials, such as household and commercial food waste, municipal and industrial sewage, agricultural material and livestock manure, can be treated in such plants to produce energy both on a small scale (e.g. households and farms) and on a large scale (for small towns). In the agricultural field, this organic substance consists of plant residues, processing waste of products intended for consumption, livestock waste, crop residues and, in recent years, corn silage (shredded) specially grown for feeding the digester. It should be noted, however, that already today, and even more so in the future, the gaze is increasingly turned towards an economy of the plant that allows to reduce its impact on the environment, while avoiding the distraction of agricultural areas intended for the cultivation of species intended for the feeding of these plants. To this end, more and more use is being made of the exploitation of livestock waste, waste deriving from food production both domestically and industrially and from agricultural processing and, albeit in still small quantities, to urban liquid waste.

Advantages:

- one of the advantages linked to the eco-sustainable production of this natural fuel is the absence of a precise recipe to follow: this allows to exploit the locally available resources, allowing the supply as much as possible at "zero km" and increasingly reducing the carbon footprint;
- moving towards a circular economy model characterized by the sustainable use of energy and careful protection of the environment, a responsible "green economy" is promoted;
- the exploitation of livestock waste allows a reduction in the emission into the atmosphere of methane gas naturally produced during storage: this gas is one of the main causes of the greenhouse effect;
- the exploitation of biomass allows to operate an energy diversification, that is, it allows to reduce the dependence on traditional energy sources and is therefore counted among the sources of clean and sustainable energy;
- the supply of energy supplied by this kind of plants takes place continuously, allowing to modulate the production and guaranteeing, therefore, the possibility of slowing down or even turning off the system according to the need that in most cases are related to scheduled maintenance tasks;
- the simplicity of construction, also linked to the relatively modest technological level typical of this type of system, allows to find the components easily on the market and at the same time containing costs, making the investment manageable by a wider catchment area.

Disadvantages:

- the economy of production makes sense as long as the distance between the plant and the areas of production of raw materials remains limited. Otherwise, the transport of raw materials and wastewater resulting from digestion would be an unsustainable cost both in terms of economy and sustainability (CO_2 emissions);

- the quality and composition of the raw material must meet certain characteristics: a high concentration of fiber, for example, can limit digestion by anaerobic bacteria, which leads to problems related to mixing and the formation of surface crusts, increasing self-consumption and leading to a reduction in the effectiveness of the plant in terms of energy;
- the wastewater from the plant gives off a strong smell and it is therefore necessary that the production installations are located sufficiently far from the inhabited centers so as not to disturb the citizens;
- if energy crop is used, approximately 300 hectares are needed to be able to power a 1MW power plant, which will then be subtracted from the production of products for human or animal nutrition. (16)

The process of digestion of organic matter by microorganisms takes place within a highly controlled environment (*digesters*) with variable times and temperatures, depending on the mode of digestion. This process is called *anaerobic digestion* precisely because it takes place in the absence of oxygen. The initial purity and the amount of gas produced are dependent, of course, on the composition of the matter introduced into the digester. The choice of raw material is, therefore, dependent on different factors such as the type of *supply* typical of the area, the conditions of digestion and above all the desired amount of gas.

Below are the characteristics of the biomass used to feed the digester and the relative energy potential (17) (18) (19) divided by sector of origin:

Table 1: ST and potential methane production of biomasses:

Agricolture		
Type	ST (Solid matter over total) %	m^3 CH_4/t
Maize silage	28-35	95-1253
Triticale silage	28-35	95-1254
Wheat straw	89-93	205-215
Hay	86-93	300
Arundo donax	25-40	45-75
Breeding		
Type	ST (Solid matter over total) %	m^3 CH_4/t
Cow manure	17-25	25-40
Cow slurry	6-8	10-15
Avicultural manure	32-32.5	240
Avicultural slurry	15-70	30-150
Swine manure	2-6	5-10
Agro Industry		
Type	ST (Solid matter over total) %	m^3 CH_4/t
Production waste – vegetables processing	8-15	25-50
Production waste – potatoes processing	10-25	30-80
Olive pomace	15-50	30-1003
Citrus paste	15-20	45-70

The influence of the external climate also leads to small but important variations on the productivity of the plant, this factor must also be considered during the daily adjustments of the plant. The mixture resulting from digestion, called biogas, consists of about 45-70% methane (CH_4) and the remaining part of carbon dioxide (CO_2) and other minor components (carbon monoxide, nitrogen, hydrogen, hydrogen sulfide) and, once treated appropriately, is able to power the endothermic engine of the cogeneration plant, in order to produce totally renewable electricity and thermal energy.

The remaining organic matter deriving from the digestion process, called digestate, is initially separated into the liquid and solid components and subsequently and again exploited for agricultural purposes; in fact, thanks to its fertilizing properties it can be directly introduced into the soil enriching it with nitrogen, phosphates, potassium and water.

The energy from the combustion of biogas can be used for different purposes:

- direct combustion in the home or used in gas lamps, for lighting, after a minor treatment;
- combustion inside boilers for heat generation;
- power supply for internal or external combustion engines for the production of electricity;
- power supply of cogeneration plants (CHP) for the production of both heat and electricity;
- power supply trigeneration systems to provide cooling through absorption chillers in addition to heat and electricity, these are less widespread than the previous technology;
- if further purified into biomethane, it can be used as fuel for methane-powered vehicles, can and can be used instead of natural gas in industrial, commercial and domestic uses, or fed into methane distribution networks to replace natural gas supplied to households and businesses.

The refining of biogas allows the conversion into bio-methane, passing from a gaseous mixture containing between 40-60% of methane (CH_4) reaching a concentration of about 96%. This treatment, called (20)*upgrading*, leads to the production of a gas with the same characteristics in terms of chemical composition and purity of normal methane of fossil origin. Bio-methane, if subjected to compression (CNG) or liquefaction (LNG) processes, represents the most valid alternative to all gases of natural origin used both in the industrial sector and for transport. Precisely on this alternative, many states are focusing on starting the energy conversion now necessary.

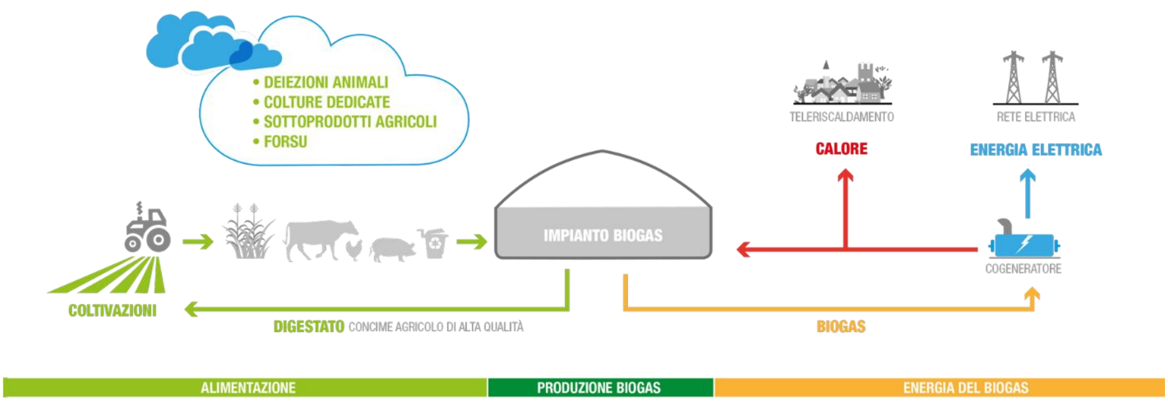

Figure 8: Biogas production chain Source: IES-Biogas

1.2.1 Anaerobic digestion

The organic matter, properly filtered and cleaned of foreign material that could have direct and indirect effects on the productivity of digestion, is placed inside the first digester where the total absence of oxygen characterizes what is defined as "anaerobic digestion". This decomposition process, depending on the time required to obtain the gas, is characterized by different conditions, shown below for completeness:

- Mesophilic digestion: this process takes place within a temperature range between 35°C and 40°C, resulting very stable in these conditions. The duration of the cycle is between 15 and 40 days (long times). This type, to date, does not appear to have commercial use (17);
- Thermophilic digestion: this process, very common in the agro-zootechnical field, has a biomass temperature range between 55 °C and 60 °C. This type of digestion represents a good compromise between biogas production rate and retention times, allowing reduced extraction times and ensuring effective bio-gas extraction. On the other hand, it requires more controls throughout the digestion period that lasts about 20 days. The demand for energy useful for heating the tanks has a greater impact on the final balance of the processing (21);
- Psychrophilic digestion: digestion takes place between 10 °C and 25 °C, involving a treatment period of more than 30 days and reaching, in some cases, even 90 days. This kind of process is widespread in plants for the valorization of FORSU and waste in general. The peculiar feature of this technology is the greater reduction of the pathogenic charge within the biomass in digestion (17).

In order to promote the survival of all microbiological groups that allow a complete biological matter processing, the environment inside the digester must remain in a pH range between 7 and 7.5.

In addition to the fermentation temperature of the mass, what substantially characterizes anaerobic digestion is the amount of dry matter mixed with the wet one. Depending on the proportions, the same process can lead to different results obtained even at different times. The choice of the type of digestion is also influenced by the type of raw material available to be fed into the digester. (22)

With a dry mass in a concentration of less than 10%, is possible to speak *of wet digestion*. This kind of solution is typical of plants that exploit more livestock wastewater. To allow an exhaustive homogenization of the mass, in some cases it is resorted to the dilution of the dry part with water, often obtained from the recirculation of the liquid fraction of the plant or coming from the rainwater collection network, so as to minimize the exploitation of water resources.

Operating with a percentage of dry part equal to 20%, is a characteristic of *dry digestion*. The greater presence of the dry component allows to reduce energy consumption related to heating inside the digester and to increase the production efficiency of biomass, allowing a greater production of biogas with the same mass if compared to the wet process. Conversely, the higher density of organic matter requires more energy for internal movement. This methodology is recommended when the treatment concerns solid municipal waste.

A practice used very rarely is *semi-dry digestion*: in this case the concentration of dry is between 12 and 18% of the total mass.

Independently to the type of digestion, the chemical phases that allow the breakdown of organic matter, leading to the consequent production of biogas and digestate, are common to the different processes. The following are shown in chronological order:

- *hydrolysis*: complex organic compounds such as carbohydrates, fats and proteins are broken down into glucose molecules, fatty acids and amino acids;
- *acidogenesis:* the bacterial flora in action in the fermenter, breaks down the molecules produced during hydrolysis into volatile fatty acids and alcohols (with production of hydrogen sulfide, carbon dioxide and ammonia);
- *acetogenesis:* from the further breakdown of the products listed above, hydrogen H_2, carbon dioxide CO_2 and ammonia NH_3 are obtained;
- *methanogenesis:* microorganisms of the ARCHEA kingdom (group of organisms other than eukaryotes and bacteria) convert hydrogen and acetic acid into methane and carbon dioxide.

The diagram below illustrates in a very clear way the digestion phases, indicating the results of each step and the main bacterial strains that act. (23)

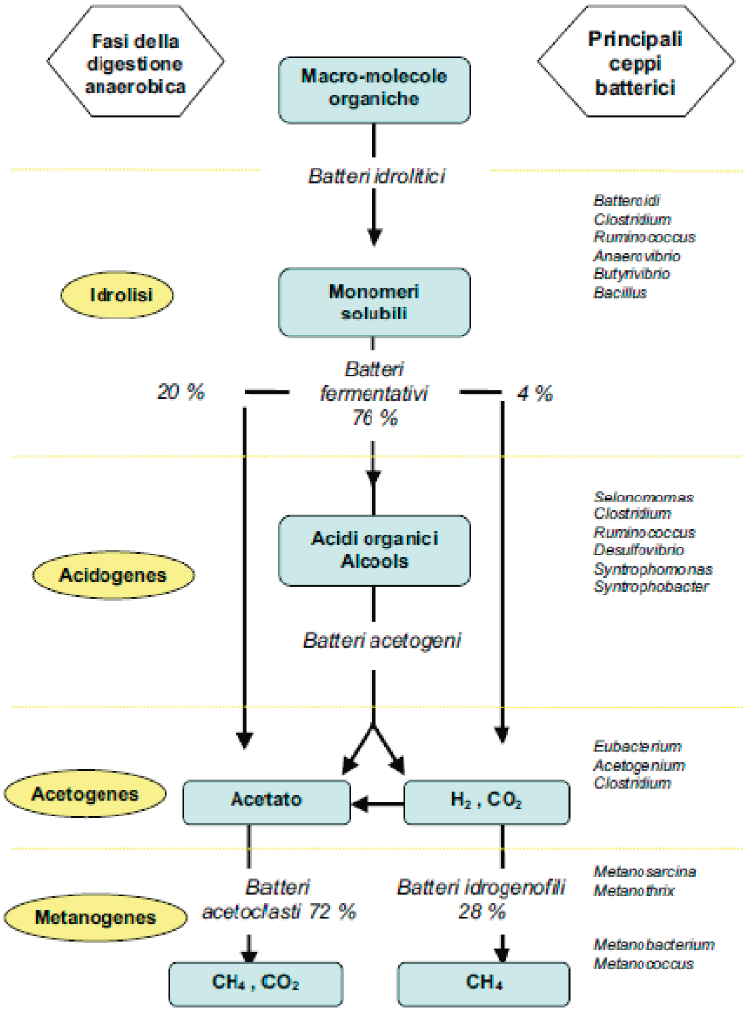

Figure 9: Scheme of the phases of anaerobic digestion   Source: Cecchi F.,2005

1.2.2 Desulfurization

The biogas produced by the anaerobic digestion of organic solids, as already mentioned above, is a mixture of different gases, some of which are incombustible and others with oxidizing properties. One of the most important obstacles to the spread of the use of biogas as a fuel is related to the high quality required for the supply of endothermic engines of cogeneration plants and automotive engines. One of the most critical elements is hydrogen sulfide H_2S, contained in considerable quantities within the raw biogas and with a high corrosive power for the energy production plant. For this reason, hydrogen sulfide must be removed from the gas, both for reasons of protection of the mechanical parts (therefore economic), and environmental protection.
Once the digestion process is concluded, the gas is started, inside a purification plant where the gaseous compound is separated from the sulfur component through a chemical process called *desulfurization*.

Several techniques are available on the market:

- *desulfurization on site – precipitation of sulfide*: this technique is applied before the digestion process is started altogether. Inside the mixer or during the introduction of the raw material into the digester, a certain amount of liquid mixtures composed of different metal salts is added that cause sulfur to precipitate to the bottom of the tank. This precipitate, precisely it is iron sulfide, is soluble only in a very small part in the digestate. The sulfur residue will eventually be removed along with the digestate;
- *biological desulfuration – biologic scrubbing:* the action of separation of biogas from hydrogen sulfide is exerted by a certain family of microorganisms (chemoautotropic of the species Thiobacillus or Sulfolobus) which produces an oxidation action onH_2S. The oxidation process is clearly possible only in the presence of a certain amount of oxygen that is introduced in a controlled manner into the digester. This amount is very low at the tip so as not to affect the anaerobic process. In some plants these microorganisms live on nets placed inside the gas bag, and the oxidation process leads to the creation of

stalactites that once reached a certain weight detach from the network and settle at the bottom of the digester;

- *adsorption on metal oxides or activated carbon*: Metal oxides such as iron or zinc oxides or activated carbons can absorb hydrogen sulfide. Absorption due to oxides leads to the release of water vapor. This process requires that once the material used for desulfuration becomes saturated it is replaced. The use of activated carbon requires, unlike metal oxides, a small amount of oxygen so as to make the bond with hydrogen sulfide stronger. (24)

2 Case study biogas plant

The object of the study will be a really existing plant, currently configured for the valorization of biomasses for the production of biogas and, through the combustion of this within a CHP (Combined Heat and Power gas engine) co-generator, the simultaneous production of electricity for input into the national grid and heat for various uses.

2.1 Geographic location

The plant is located in Azzano Decimo (PD), in the EDR (Ente di Decentramento Regionale) of Pordenone – Friuli-Venezia Giulia, located in the Po Valley-Veneto and more precisely in the lower Friulian plain, south of the Carnic Prealps. The town, located at 14 m above sea level, is a few kilometers from the left bank of the Meduna and about 10 km from the city of Pordenone. The entire production complex stands on site that also houses a wine cellar with retail resale, administrative offices, single-family residences, stables, and buildings for the storage of agricultural and breeding material.

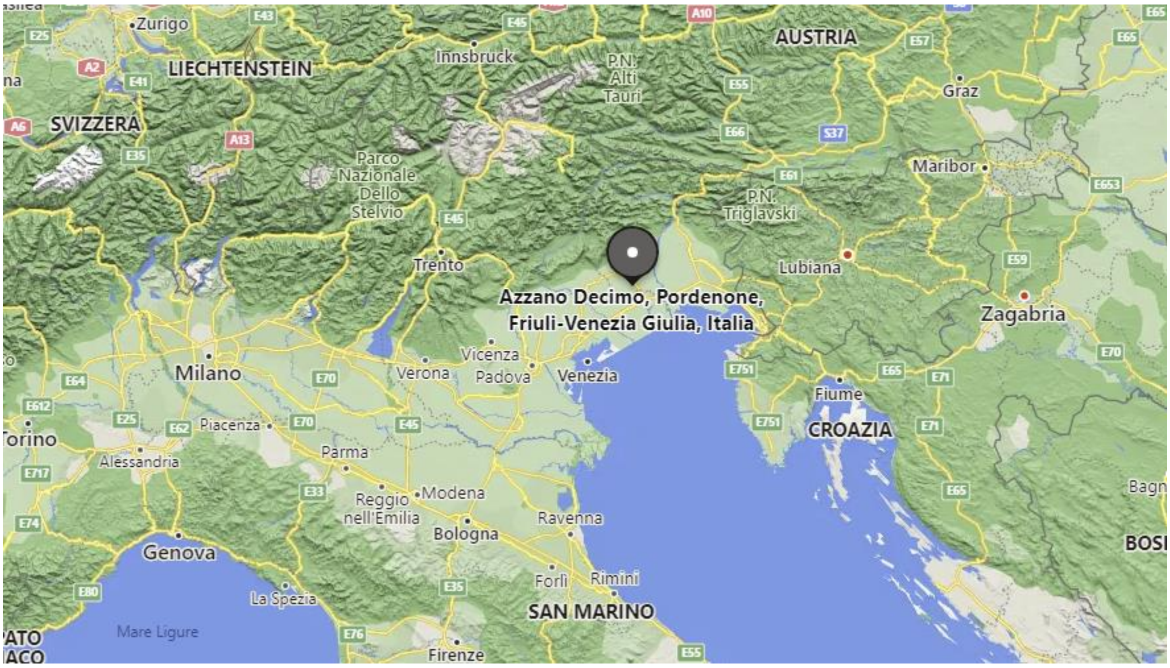

Figure 10: Geographic location of Azzano Decimo (PN) Source: Google Maps

2.1.1 Climate analysis of Azzano Decimo (PN)

The climatic conditions, typical of the plant site, must be determined with precision in order to be able to carry out fluid dynamic simulations adhering to reality. Below is a detailed investigation of the climatic conditions that characterize Azzano Decimo (PN) throughout the year.

The source of the starting data is represented by the file in ".epw" format, obtained through the energyplus.net website owned by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), which makes available for free a (25) large archive of files useful for the climatic analysis of multiple sites scattered around the world. The reference files are provided by different institutions, typically one for each country: as far as Italy is concerned, the data collection comes from *the Italian Climatic data collection "Gianni De Giorgio"* (IGDG) and elaborated by Professor Livio Mazzarella of the Politecnico di Milano (26). The points of execution of the survey are represented by meteorological stations located in areas such as airports, smaller islands or more simply locations in positions that allow to complete a small network of points extended enough to cover a large part of the Italian territory. For Azzano Decimo, the site closest to the analyzed area is represented by the US Air Force base located in Aviano (PD), about 20km away and north of Azzano Decimo. It must be considered that the greater proximity to the sea of the Azzano Decimo site compared to the Aviano Air Base would require more specific data which are not available except through specific surveys carried out on site.

This type of file is composed of hourly data distributed throughout the year (in total there will be 8760 rows of information) and concern information such as wet bulb temperature (T_{wb}) and dry bulb (T_{db}), atmospheric pressure, wind speed and direction, direct and diffuse solar radiation (some stations do not allow the measurement of this value) and relative humidity. The data collected within the database do not represent the results of measurements made during a single year but are representations of what could be considered as a "typical" year, that is, obtained through statistical series of climate data collected, possibly, on a twenty-year basis. (27)

From this point on, as far as the climatic conditions analyzed are concerned, the data will be referred to as if they had been detected by a station located exactly in Azzano Decimo (PN).

Considering the nature of the work that is addressed in this paper, only some data of interest will be considered and analyzed, which will be commented and illustrated graphically. The following values are considered:

- dry bulb temperature T_{db} [°C];
- wind speed [m/s];
- wind direction [expressed in degrees measured clockwise relative to the North].

These data are then used for the choice of the conditions to be adopted for the characterization of the climatic context adopted during the various simulations.

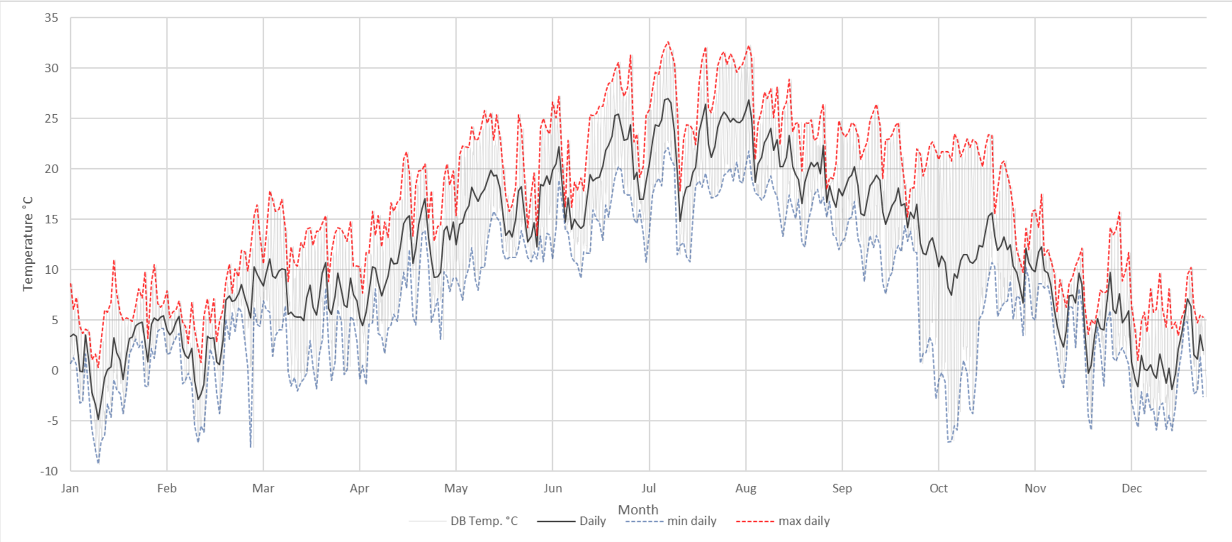

Figure 11: Distribution of T_{db} for Azzano Decimo (PN)   Source: EPW

The graph obtained from the processing of the hourly data of the dry bulb temperature T_{db} (thin and gray line) shown above, shows the average daily temperature (black line) and the maximum and minimum daily values (respectively red and blue dashed lines). From the analysis of the graph, it is clear that Azzano Decimo is characterized by a summer with mild temperatures and with some maximum peaks over 30°C in the two-month period June-July, always in this period the highest temperature is recorded, that is 32.6°C on 12 / July at 14:00. Again, in the summer, moreover, during some nights the minimum temperatures reach values that approach 10°C, thus leading to a strong variation in temperatures within a few days. Even in October it is possible to observe how the temperature range is particularly wide, also considering the daily situation: on the same day, temperatures go from a maximum between 20 and 25°C to a minimum below 0°C. Generally, winters are cold, although not particularly harsh: the minimum temperature reached throughout the year is -9.3°C, measured on January 10 at 07:00.

The data on an annual basis of interest for the simulations are summarized below:

- the maximum temperature is 32.6°C;
- the minimum temperature is -9.3°C;
- the average temperature calculated arithmetically is 11.80°C;
- the average temperature between the minimum daily values is 7.03°C;
- the average temperature between the maximum daily values is 16.77°C;

- the average daily variation ΔT_{avg} between maximum and minimum is 9.74°C.

Below is the spider's web chart representing the distribution of data recorded on wind direction on a monthly and annual basis (dotted blue line):

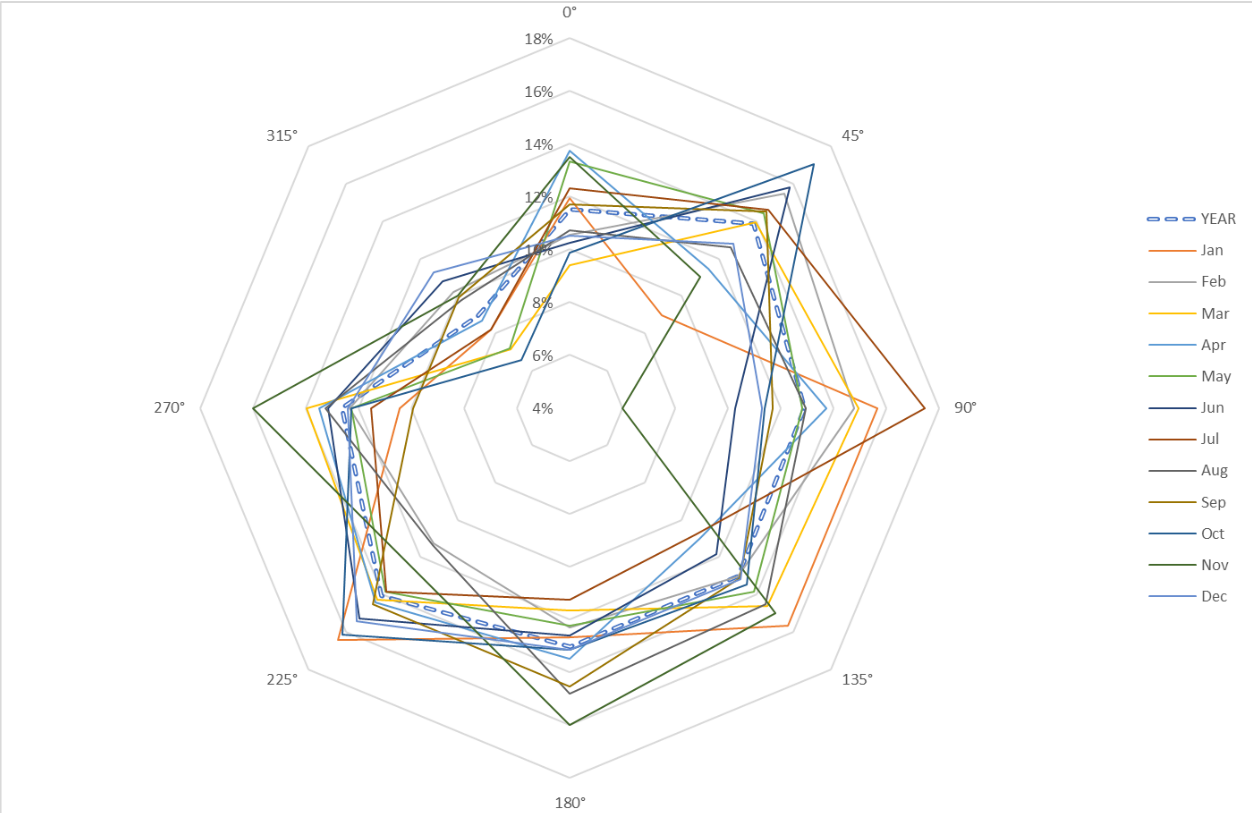

Figure 12: Wind direction distribution

From the graph it is possible to observe how the data provided by the .epw file are divided into 360 different directions but, for greater simplification in reading the graph, all the distributions have been collected and divided into 8 major directions, corresponding to North (corresponding to 0°), North-East, East, South-East, South, South-West, West, North-West. These orientations are then used for the attribution of boundary conditions during simulations, with arbitrary considerations also on the choice of unfavorable winds and their directions to be adopted.

From the annual distribution of the wind is easily noticeable that the wind blows, on average, in a very similar way from all directions (distribution between 13% and 15%), with the exception of the North-West direction.

The most pronounced monthly peaks concern:

- in November, the directions West (270°) and South (180°) with monthly distribution close in both cases to 16%;
- in October, the North-East direction (45°) with monthly distribution close to 18%;
- in July, the east direction (90°) with monthly distribution close to the 18%.

Below, the graph of the cumulative and absolute frequency of wind speed on annual basis:

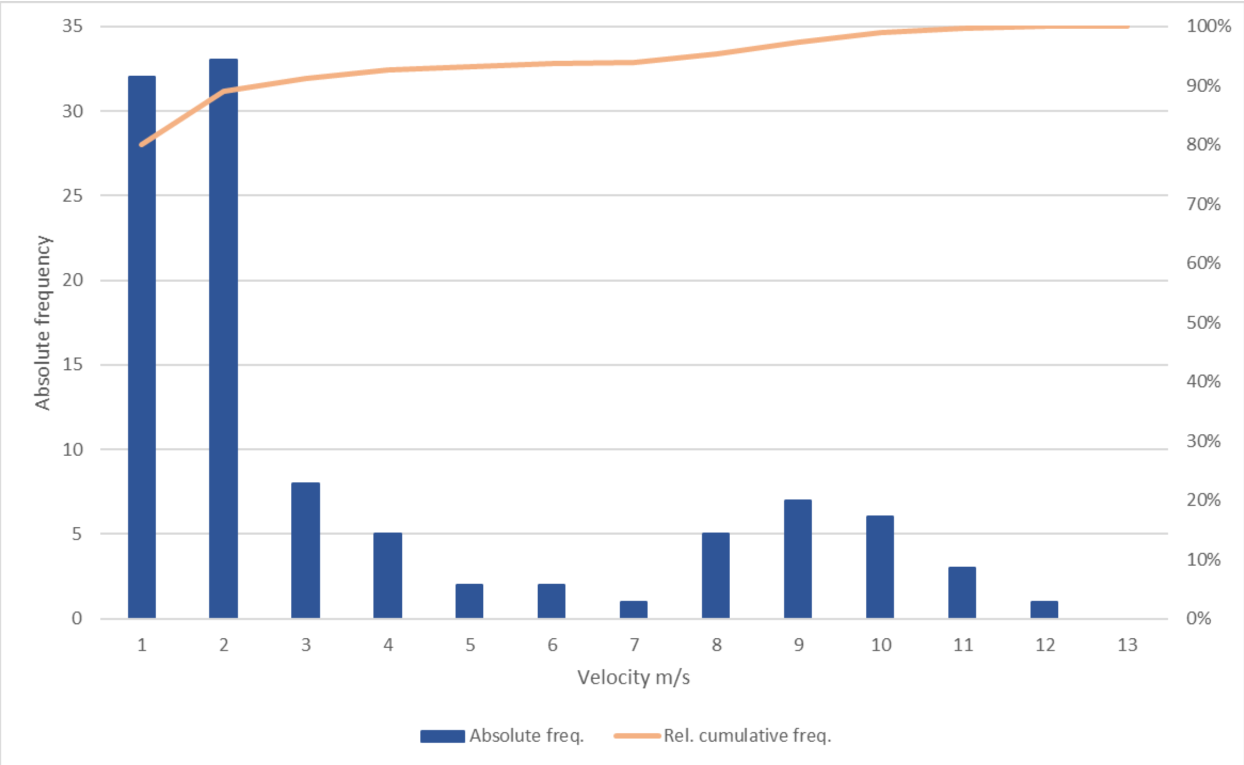

Figure 13: Cumulative wind velocity frequency

Analyzing the previous graph, it is possible to define the recurring speeds in Azzano Decimo throughout the year. Its construction is based on daily data obtained with the arithmetic mean of velocities. Looking at the cumulative relative frequency, it is possible to notice how the respective trend starts from 0.5 m / s: this trick was taken in view of the fact that about 70% of the surveys are characterized by practically zero wind (260 recordings out of 365) and therefore the positioning in the graph of this series of data would have made it difficult to read the subsequent data.

The area of Azzano Decimo (PN) is characterized by winds with low speeds: already considering speeds equal to 2 m / s, the relative cumulative frequency reaches about 90% of the registrations throughout the year. Considering the daily averages, 100% of the frequency is reached at 12 m/s speed.

Below are the annual data regarding wind speed:

- the maximum speed (on an hourly basis) is 17°C recorded on August 9 at 01:00;
- the minimum speed is 0 m/s present during several moments along the year;
- the average speed calculated arithmetically without considering the null wind is 2.67 m/s;
- the average speed, calculated arithmetically considering the null wind is 1.12 m/s.

The three types of data summarized, constitute the starting point for the setting of the boundary conditions for the different simulations.

It should be emphasized that, with regard to the directions of the wind, directions are selected, even arbitrarily, that allow wind and gas in dispersion in the environment, to meet along their path buildings or machinery considered critical due to the presence of possible sources of ignition, so as to simulate the worst possible scenario.

2.2 The “Principi di Porcia e di Brugnera” farm

The farm that owns the plant under analysis, articulates the production on an area of 850 hectares divided between the municipalities of Azzano Decimo, Porcìa and Pramaggiore, all in the province of Pordenone. The company's core business ranges from the production of wine grapes (140 hectares), cereals, tree cultures and oil seeds, as well as the breeding of dairy cattle. In addition to these activities considered "traditional", the property maintains a careful look at the so called “agroenergie”, moving towards an integrated, innovative and sustainable agriculture.

The owners of the farm are the Principi di Porcia e Brugnera, a family of noble Friulian origins who, always attentive to the theme of sustainability, carry out the activity following the principle of "dynamic tradition", or the maintenance of traditions but with an innovative spirit and attentive look at the outside world. Moving in this direction, various renewable energy sources have been integrated into the company surface: in addition to the plants for the exploiting of biogas, capable of generating a total of 10,800,000 kWh / year, in fact, there are two parks of photovoltaic panels of 123kW and 100kW respectively and a small plant for the production of hydroelectric energy. In particular, the photovoltaic panels present, for an area of 2500 square meters, were installed as part of the reconversion of the roofing structures of part of the farms, the cellar and the tool shed, allowing the balance of electricity production-consumption budget. The turbine of the Porcia power plant exploits the presence of the Rio Buion stream, characterized by almost constant water flow for the majority of the year, allows the obtaining of about 300,000 kWh / year (28) (29).

2.3 The biogas plant of Azzano Decimo (PN)

Focusing the attention on the plant for the production and enhancement of biogas located in Azzano Decimo (Pn): it is an innovative and efficient biogas plant, built by IES Biogas - Pordenone, characterized by an excellent integration into the production cycle of the company, able to enter the national electricity grid up to 999 kW per hour (limited by law), which therefore allows the introduction into the network of 8,400,000 kWh / year and therefore meet the estimated needs of 3000 families, avoiding waste and the production of odors, to the benefit of the environment and the community. The project has effectively completed the cycle of self-sufficiency of the farm and wine: exploiting and enhancing everything that the plant discards, including the residues of the processing of grapes (after special treatment) for the production of wine, biogas is produced and subsequently energy through cogeneration, or returns to the fields as organic fertilizer.

A cogeneration plant is essentially composed of an internal-combustion endothermic engine based on Otto-cycle, powered in this case by biogas, which produces mechanical energy that is conveyed to an alternator to generate low-voltage electricity, which in turn is transformed, in its part not used for self-consumption, into medium voltage and fed into the network. The energy component linked to heat recovery is recovered on two fronts:

- directly from the cooling water of the engine, through a plate exchanger that allows to obtain water at high temperature;
- from exhaust fumes, which, being close to 400°C, can be used to produce hot water, superheated water, steam or diathermic oil through a boiler, or be used pure in the process.

In particular, in the Azzano Decimo plant, the part of heat that is not used to maintain the optimum temperature inside the digesters, is conveyed through a water system of underground pipes in order to heat the soil for the early production (compared to normal seasonality) of asparagus.

The portion of the company dedicated to the production and enhancement of biogas is located in a decentralized area located at the south of the farm core and bordering the land intended for cultivation.

The following (Figure 14). is an aerial view of the company site.

Figure 14: Aerial view of the production site   Source: Google Earth

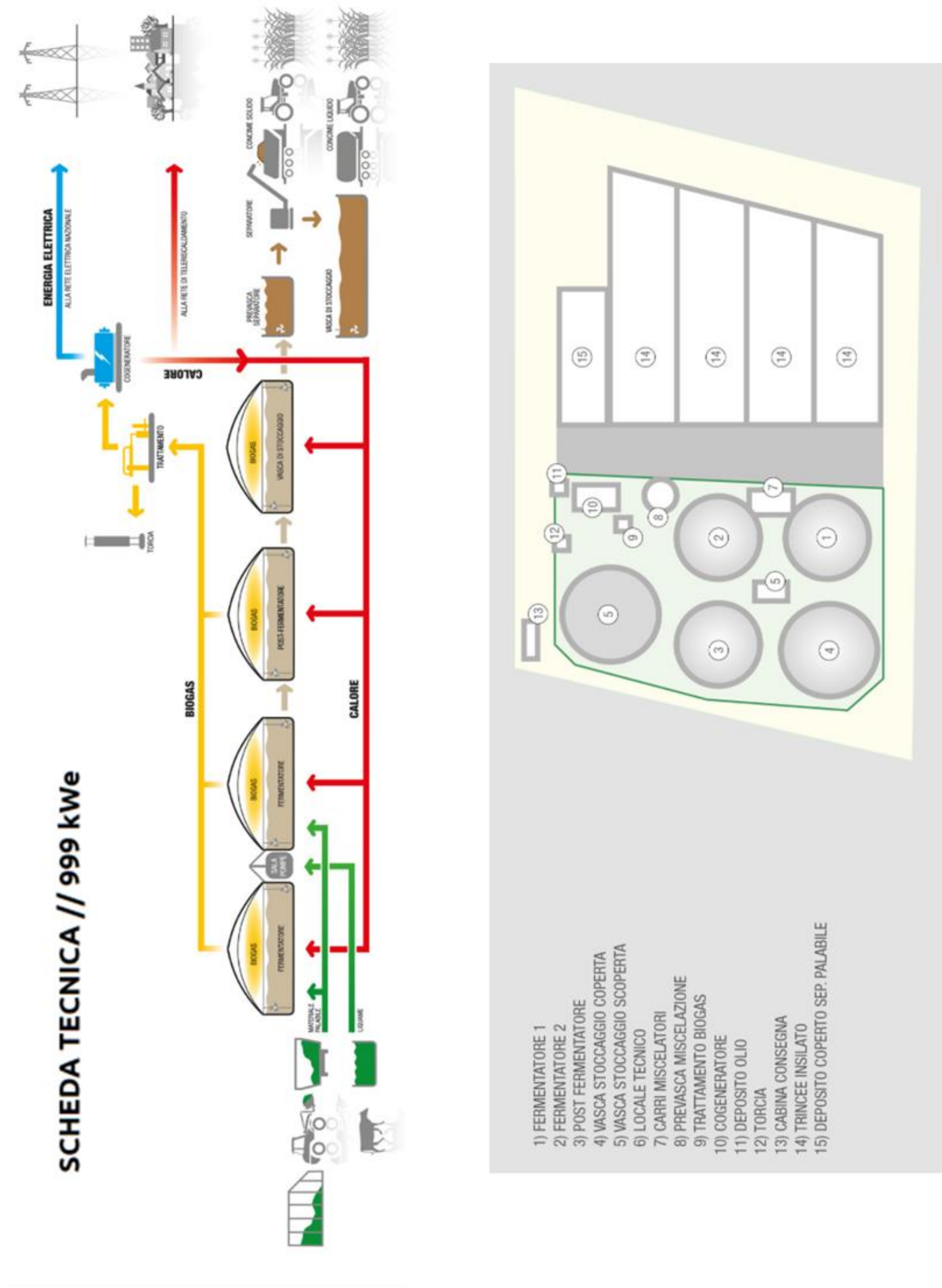

Figure 15: Functional scheme and plant of the production site   Source: IES-biogas

In Table 2 are reported the characteristic data of the plant, supplied directly by the Principi di Porcia and Brugnera farm.

Table 2: Technical data of the plant

INSTALLED ELECTRICAL POWER			**999kW**
DOUBLE STAGE MESOPHILIC PROCESS			
Digestor	n.2	ϕ 25m	h=6m
Post-digestor	n.1	ϕ 25m	h=6m
Covered storage tank	n.1	ϕ 28m	h=6m
Uncovered storage tank	n.1	ϕ 28m	h=6m
Biomass feeder	n.2	Feed mixer	40mc
DAILY FEEDING PLAN			
Cow manure			5 tons
Cow manure			6 tons
Maize silage			40 tons
Triticale silage			10 tons
ENERGY EFFICIENCY			
Annual electric power production			8.400.000 kWh
Annual Biogas production			4.200.000 mc
Methane concentration in Biogas			52-54%
COGENERATION SYSTEM			
Factory			AB Energy
Model			Ecomax 10 Bio
ENGINE			
Factory			Jenbacher
Model			J 320 GS-C25

2.4 Organization of a biogas-cogeneration (current state)

In order to better understand the possible sources of risk deriving from a possible malfunction of the prevention devices, it is useful to define and know the processes in which it is possible to divide the normal operation of a plant of this kind. The production cycle can be segmented into five different phases, listed below:

- step 1: production and storage of biomass;
- step 2: anaerobic digestion process;

- step 3: biogas treatment;
- step 4: production of thermo-electric energy;
- step 5: use of digested biomass.

These phases resume the flow pattern in which the organic substance produced in agriculture is first collected, silaged and stored in special trenches and tanks near the mixers (Step 1).

The next step involves a biochemical process and consists in the production of Biogas through the *anaerobic* digestion of organic substances in a controlled and watertight environment (digesters; Step 2) using a complex biological process at a high temperature of about 38-55 °C, in which more than half of the gas resulting from this process consists of methane (CH_4), while the rest is carbon dioxide (CO_2) with a small component represented by other more sparse gases. The raw biogas produced is treated (Step 3) in order to ensure a perfect functioning (and yield) of the cogeneration engines (Step 4). The outgoing *digestate* product is stored and used as a fertilizer and soil improver in agriculture (Phase 5) (30).

It should be emphasized that, if biogas represents the main product of the digestion process, an important role to close the cycle is played by the organic matter exploited during all the passages inside the digesters, also called *digestate*. The latter consists of a liquid and a solid component that, depending on the needs, can be separated or used jointly. This *by-product* can be entirely used for agricultural purposes and, thanks to its composition rich in phosphates, nitrogen and water, can be used as a natural fertilizer for the soil, returning part of the organic substance subtracted with the harvest.

Analyzing in more detail the different phases closely related to production, it is possible to identify the main processes that take place within a plant for the enhancement of biogas from biomass of plant origin (31):

1. *loading of the liquid fraction by pumps:* the liquid phase of the biomass entering the digesters is taken from special storage tanks equipped with an adequate mixing and filtering system, in order to homogenize the mass and pump for conveying. In order to obtain the greatest possible production of biogas, in relation to the feeding of the digester it is advisable that the same is fed with new sewage and that the quality of the biomass is integrated into its energy

structure (understood as the content of feed substances for methane bacteria). It will therefore be necessary to adopt all the most appropriate measures to evacuate the sewage as quickly as possible from the livestock shelters in which it was produced, conveying them into special pre-collection and equalization tanks;

Figure 16: Lobe pump for slurry   Source: Vogelsang

2. *loading of the solid fraction:* for the management of materials that can be moved by shovels, a hopper equipped with load cells and equipped with special dosing augers is used which, through the interface with a specific program for feeding, provides for the introduction into the digester of the necessary quantity of materials to ensure a good functioning of the digestion process. A special mixer device, consisting of an endless screw equipped with blades and positioned inside the hopper, guarantees an adequate mixing of the different dry substances before placing them in the digester. Depending on the type of raw material, it must be subject to a first-treatment process in order to ensure that the contents of the digester have the desired characteristics and components. This phase consists of a screening of organic matter and cleaning from any foreign objects that could affect the income of

the digestate and the durability of the machinery. This process varies according to the state and type of material introduced into the plant. The presence of foreign objects (such as plastic or metal objects) could cause damage to machinery or create sediment on the bottom of the digester causing an ineffective mixing of the matter in digestion with a consequent production of gases below expectations;

Figure 17: Loading of raw material   Source: Principi di Porcia e Brugnera

3. *mixing through slow motion mixers:* the guideline used for the sizing of anaerobic digesters is based on the need to ensure a residence time of the matrices (SRT – Sludge Retention Time) within a fully mixed compartment, high enough to guarantee a substantial degree of extraction of the volatile part. Once the biomass has been introduced into the digesters, the mixing system positioned inside them allows to obtain the optimal homogeneity of the two phases (liquid + solid). This operation is essential in order to ensure maximum contact between the biomass and microorganisms and also avoid problems related to the presence of floating substances in the form of crusts or foams, or sedimented on the bottom of the digester. Slow-motion mixers generally consist of a horizontal axis on which four blades are mounted that

mix the mass inside the digester preventing the formation of surface crusts and deposits on the bottom, thus ensuring a high degree of mixing; (32)

Figure 18: Mixer inside the digester   Source: Principi di Porcia e Brugnera

4. *biogas extraction:* the biogas produced tends to accumulate in the upper part of the digester, enclosed by a gasometric dome, which in this case performs the function of gasometer (pressostatic accumulator for biogas), or that of absorbing any volume variations related to the intrinsic variability of production. Inside the domes and connecting pipes between the digesters forming a ring, an overpressure of 0.004 bar is maintained. The sampling pipe is in conditions of slight depression of the biogas (0.004 bar) thanks to a blower placed in the terminal section of the circuit, near the dehumidification batteries, which then supplies the cogenerator;

Figure 19: Connection piping   Source: Principi di Porcia e Brugnera

5. *biological desulphurization:* one of the most important obstacles to the spread of the use of biogas as a fuel is linked to its high quality required by cogeneration plants and automotive engines. In anaerobic fermentation plants, the biogas produced contains significant amounts of hydrogen sulfide (H_2S) that is highly hazardous to health and corrosive to the power generation plant. This H_2S must be removed from the gas, both for reasons of environmental protection and for corrosion hazards. Biological desulphurization is the optimal solution in this area: this happens thanks to the activity of aerobic bacteria that oxidize H_2S causing it to precipitate into sulfur crystals. This treatment is normally integrated into the headspace of the digesters in which a limited amount of air is introduced, about 5% of the gas produced, in order to create the appropriate conditions for bacterial activity. Supports such as a wooden roof or special nets must be present inside the digester, which act as ideal surfaces for the engraftment of desulphurizing bacteria. The oxidation process leads to the creation of stalactites mainly composed of sulfur, which once reached a certain weight lose contact with the network and settle at the bottom of the digester;

(

Figure 20: Tower desulphurization Source: Airdep.eu

6. *biogas treatment with moisture removal:* further treatment of biogas, carried out with the aim of eliminating moisture content and at the same time reducing the hydrogen sulfide content, is carried out before entry to the engines. A first phase of dehumidification consists in the cooling of the biogas through its passage in special underground pipes, laid with an adequate slope. Thanks to the thermal capacity of the soil it is in fact possible to condense the water present in the biogas mixture, then conveying it into special manholes. In addition to this, additional techniques for dehumidification can be used. The treatment of gas with special refrigerant filters and activated carbon offers the advantages deriving from a significantly increased level of biogas purity, allowing to increase the intervals between engine oil changes and ensuring lower maintenance costs of the cogenerators.

   The system, consisting of the equipment and instrumentation necessary for the operation, can be installed as equipment of the suction system or assembled separately on a specially designed frame.

   The main components of the system are: (33)

   - the biogas-water heat exchanger;
   - the chiller and storage equipment;

- condensate drainage.

Cooling in a heat exchanger, sometimes supplemented with gas compression before its inlet, can be replaced by adsorption on activated carbon, silica gel or molecular sieves. The biogas passes through a column filled with selective adsorbent material against water vapor. For its continuous use, two columns are required, one in operation and one in regeneration.

Alternatively, absorption into glycol or hygroscopic salts can be considered, conducted in a column filled with reagent granules (non-regenerative process);

Figure 21: Dehumidification unit Source:Bricchi Alessandro e Ambrogio s.s.

7. *cogeneration*: it is possible to define a cogeneration plant is a type of plant that allows the simultaneous production of electricity and heat starting from a single energy source within a single integrated system, or a "combined production" system. By using the same fuel, biogas in the case considered, to generate two energy carriers (electricity and heat), it is possible to increase the efficiency of use of the starting fuel by up to 85%, resulting in a reduction in costs and CO_2 emissions compared to the separate production of electricity and heat. The use of the heat generated during the process, which would otherwise be dispersed, allows cogeneration to obtain the highest energy

efficiency performance, with the advantage of being able to manage energy production in a continuous, reliable and safe way. (34)
The electricity thus generated is partly transferred to the electricity distribution network and partly used to power the anaerobic digestion plant. The thermal energy produced by the engine can be used to heat the digester by regulating the biogas production process, heat any greenhouses, or be fed into a district heating network. (35)
The level of efficiency of the cogenerator, added to that of the gas production plant, must be elevate in order to obtain the greatest overall efficiency and the consequent best economic result. For cogeneration, endothermic (internal combustion) engines or microturbines are used.
Internal combustion cogenerators consist of the following components:

- alternative endothermic engine that, in addition to producing mechanical energy, is also the component where thermal energy is produced.
- alternator, usually asynchronous, for the production of three-phase alternating electric current.
- centralized heat recovery, consisting of a heat exchanger that recovers the heat produced by the system (both from the exhaust gases and from the engine cooling circuit).
- transformation and supply section, which allows the use of the electricity produced and the interfacing with the national power line.

Figure 22: Biogas co-generator   Source: Energas

8. *digestate transfer and discharge pumps*: the transfer of the digestate from the primary digester to the secondary and from these to subsequent treatments and storage is guaranteed by single-screw pumps, equipped with good reliability thanks to the intrinsic simplicity, which allow through special level probes, to automatically control the various phases of the process. In this phase, further treatments are carried out on the digested effluent to facilitate its management in the case of nitrogen surpluses compared to the surface available for spreading (in addition to these, nitrogen abatement systems can be adopted to fall within the parameters required by law).

   In particular, these are separation, nitro-denitro and stripping plants depending on the level of reduction required; (36)

Figure 23: Rotary pumps Source: Vogelsang

9. *combustion in safety flare:* biogas cannot be released into the atmosphere as methane is recognized to be a much more harmful greenhouse gas than carbon dioxide. In the event of the impossibility of partial or total exploitation of the biogas, it is then sent to combustion in emergency torch. Under the normal operating conditions of the plant, it comes into operation only if the high-pressure alarm is activated, while at normal operating pressures of the plant the biogas flow rate is conveyed in full to the cogeneration unit. Its drive makes it possible to dispose of the gas surplus and restore the pre-established value of the overpressure in the anaerobic digester.
   In addition to these, it is expected that the safety torch will come into operation in the following cases:

   - in the start-up phase: at the time of starting the digesters these would not produce enough biogas to power the cogenerator. For this reason, the biogas is sent directly to the safety torch until the plant reaches a range usually equal to 45% of full operation.

- In case of fire: if a fire is detected within the production area, the digester supply line is dissected and all biogas production (non-stoppable) is started at the safety torch.

There are different types of safety torches, which differ essentially in the combustion temperature (800-1200°C), the presence of internal insulation, the condition of the flame (exposed or not) and for the air supply (forced or with natural ventilation).

Figure 24: Safety torch   Source: Bricchi Alessandro e Ambrogio s.s.

3 Fire safety (current state)

The growing number of this kind of production facilities in our territory has attracted strong attention with respect to the safety aspects intrinsically linked to the normal operation of these plants (risk of fire and explosion). As already mentioned above with reference to the state of the plant, all biogas production is used for "in situ" valorization, i.e. for the production of thermal and electrical energy through cogeneration in the same place of extraction. During the normal operation of the plant, however, biogas emissions caused by elements that are not fully watertight cannot be excluded. Any leaks, such as through the gasometric membrane, can occur and are tolerated if limited; these losses depend above all on the techniques and materials used to ensure the watertightness of the system. The maximum methane penetrability of hermetic sealing elements usually stands at values equal to 1000 $cm^3/(m^2$ bar). In addition to this, methane can leak due to non-watertight components in substrate loading systems, at connection points between pipes or in safety valves against overpressure. In view of these aspects, it was assumed that 1% of the methane produced is released into the atmosphere due to perfectly - airtight elements. Because of these intrinsic (37) and inevitable characteristics, it is necessary to classify this kind of plants as subjects at risk of explosion.

3.1 Italian fire-safety regulations

From a regulatory point of view, there is no single directive for the construction of a biogas plant, but different and depending on the type of plant itself, the different phases of the process and consequently the related fire risk. The type of plant is determined, therefore, by the technology adopted and the production capacity but it can be considered, however, a transversal reference configuration to the different types of plants that has the following sections:

- feeding and pre-treatment of incoming biomass;
- anaerobic digestion and biogas production and digestate storage;
- conveyance, biogas storage and energy conversion.

It is therefore possible to distinguish different combustible substances in relation to the sections of the plant and in particular it is possible to identify: solid substances (biomass with low moisture content), gaseous substances (biogas), substances and liquids (lubricating oils).

It should be noted that in addition to the fire risk, in such plants there is a risk of explosion linked in particular to any unwanted emissions of biogas that may be caused, for example, by holes in the polymer domes of the storage tanks (gasometers) or by failures of the sealing systems placed on the transport network or on the digesters themselves (the different possible sources of biogas leakage will be analyzed in more detail later, identifying possible critical points). In addition to the scenarios previously considered, it should be remembered that in the plants, equipped with after-treatment systems of the digestate, there is also the possible presence of combustible dust deriving from the processing of the latter. During the design phase, it is therefore important to proceed with a preliminary classification of the areas at risk of explosion due to the presence of flammable gases, or combustible dust. The classification of the zones is essential for a correct choice and installation of the equipment. Equipment falling within the identified areas must comply with the ATEX directive. (38)

Among the different regulations that have followed one another over time within the complex regulatory framework, the most recently issued is the Ministerial Decree of 3 February 2016 of the Italian Ministry of the Interior in agreement with the Italian Ministry for Economic Development, containing "Approval of the technical regulation of fire prevention for the design, construction and operation of natural gas deposits with a density not exceeding 0.8 and biogas deposits, even if of density greater than 0.8".

The objectives of the abovementioned Italian Ministerial Decree are expressed in Article 2:

In order to achieve the primary safety objectives related to the protection of people and the protection of property against the risks of fire of the natural gas and biogas plants and deposits indicated above, these are designed and managed in such a way as to:

a) minimize the causes of fire;
b) ensure the stability of the load-bearing structures in order to ensure the rescue of the occupants;

c) limit the production and spread of a fire within the premises;
d) limit the spread of a fire to adjacent buildings or premises;
e) ensure that the occupants may leave the room unharmed or otherwise be rescued;
f) ensure that rescue-teams can operate safely.

The regulatory text contained in the annex is divided into six different sections, each containing the technical provisions deemed necessary to allow the achievement of the objectives previously illustrated.

- Section I deals with the general provisions, i.e. the regulatory scope: the treated rules apply to surface deposits in which gas is stored in fixed tanks or in cylinders and other mobile containers. In this context, it is emphasized that, if the deposit falls within activities at risk of a major accident, the legislation in force in this matter also applies.
- section II deals with fixed tanks;
- section III deals with deposits in mobile containers;
- section IV deals with the direct supply of networks from vehicles used for the transport of natural gas;
- section V deals with loading and unloading operations;
- section VI deals with common provisions.

The legislation requires, among other things, that the personnel involved in loading / unloading operations must be of proven ability and in possession of the necessary knowledge for a correct and safe execution of all related operations. In this regard, the profitable attendance at a specific training course is required.

From the date of commencement of the Ministerial Decree of 3 February 2016, the second part of the annex to the decree of the Minister of the Interior of 24 November 1984, entitled "Deposits for the accumulation of natural gas", is therefore repealed. (39)

The previous legislation for this sector is UNI-10458, issued in 2011: it is basically a law made for the production and use of biogas. It deals with various issues, including the classification of plants and essential requirements, providing useful information for the preparation of the final offer, ordering, construction and testing. It applies to all plants based on the process of anaerobic digestion of organic matter contained in biomass, of various origins with simultaneous production of biogas. It is important to underline that the aforementioned rule does not apply to biogas collection plants from landfills and plants fed with civil wastewater and, moreover, does not address issues such as health and safety in the workplace.

The Italian Ministerial Decree of 03/02/2016 states that the relative provisions apply to newly built deposits and to those existing on the date of entry into force of the decree in the case of restructuring interventions, even partial (or extension subsequent to the date of publication of the Decree) limited to the parties affected by the intervention. It can be seen, therefore, that the technical regulation referred to the ministerial decree 03/02/2016 does not apply to warehouses for which construction, expansion or renovation works have been planned, or are in progress, on the basis of a project approved by the Competent Provincial Command of the Fire Brigade (Vigili del Fuoco).

As part of the plant, the activities subject to fire prevention control by the Fire Brigade Command are identified pursuant to Article 3 of Presidential Decree 151/2011, issued on 01 August 2011 and are as follows:

- 1.1.C Production plants where flammable and/or oxidising gases are produced and/or used with total quantities in cycle exceeding 25 Nm^3/h;
- 12.2.B Deposit and/or resales of liquids with a flash point above 65°C, with a capacity exceeding 9 and up to 50 m^3; deposits and/or resales of flammable liquids with a capacity from 1 to 50 cubic meters;
- 49.3.C Groups for the production of subsidiary electricity with endothermic engines and cogeneration plants with a total power > 700 Kw.

The provisions for lightning protection for this type of installation are treated in the standards of the CEI-EN 62305 series.

With regard to the risk of explosion, it is necessary that all equipment and protective systems intended for exposure to hazardous atmospheres have certain safety features, which are also certified. Currently, at European level, safety in workplaces with danger of explosion is regulated by two directives commonly called ATEX (ATmosphères EXplosibles). These deal with the explosive phenomenon considering first of all the causes that can lead to the generation of an "explosive mixture" and the conditions that can cause its ignition and its consequences. The UNI EN 1127-1 standard defines the "explosive phenomenon" as "*the sudden increase in pressure and* *temperature, due to oxidation or other exothermic reaction*" and is a direct consequence of the encounter between an explosive atmosphere and an ignition. The explosive atmosphere is defined by the Italian Legislative Decree 81/08 as "*a mixture in atmospheric conditions composed of two fundamental elements: a fuel (gas, flammable steam or even a cloud of combustible dust) and an oxidizer (generally the oxygen contained in the air in a percentage equal to about 21%), in concentration such as to be able to give rise, in the presence of a trigger source that provides the necessary activation energy, to a strongly exothermic reaction that can manifest itself with an explosion*".

The risk condition is represented with the so-called *fire triangle*, in which it is evident that the three components must be present at the same time for the explosion to occur.

Figure 25: Explosion triangle   Source: GM-international.com

In the field of fire-safety design for explosive atmospheres, it is necessary to examine the causal and chemical-physical factors that characterize the problem, considering legislative aspects, European ATEX directives, good technical standards and the interventions necessary to prevent explosions and to protect against the consequences to people, buildings and the surrounding environment.

The laws that currently regulate the world of work in the field of health and safety against the risk from explosive atmospheres are: (40)

- Legislative Decree 81/2008, also known as the Consolidated Law on health and safety in the workplace, amended by Legislative Decree no. 3 August 2009, n. 106;

- Product Directive 2014/34/EU (which replaced Directive 94/9/EC) containing provisions on equipment and protective systems intended for use in potentially explosive atmospheres (also known as ATEX Directive 95);
- Social Directive 99/92/EC which defines the minimum requirements for the health and safety of workplaces with the presence of potentially explosive atmospheres (also known as ATEX Directive 137).

The rules of good technique and for the classification of areas or places at risk, the application of which constitutes presumption of conformity with the legislative dictate, are:

- CEI EN 60079-10-1:2016 Explosive atmospheres: Classification of places – Explosive atmospheres for the presence of gases (CEI 31-87 standard with the relative guide 31-35);
- CEI EN 60079-10-2:2016 Classification of places - Explosive atmospheres due to the presence of combustible dust (CEI 31-88 standard with the relative guide 31-56).

For hazard analysis, risk assessment and prevention and protection measures, reference should be made to the standard:

- EN UNI 1127-1 "Explosive atmospheres - Explosion prevention and explosion protection - Part 1: Fundamental concepts and methodology", within which fifteen possible sources of ignition are identified, differentiating them. This general protection legislation takes into account the various possible sources of ignition, including lightning which, given the frequent installation of this type of installation in the open countryside, constitute a serious source of danger:
    - warm surfaces;
    - welding sparks, flames and hot gases of other origin;
    - hot surfaces of mechanical origin;
    - sparks of mechanical origin;
    - electrical equipment;
    - stray currents;
    - electrostatic;
    - radio frequency (RF) electromagnetic waves from 104 Hz to 3×1012 Hz;

- electromagnetic waves from 3×1011 Hz to 3×1015 Hz;
- ionizing radiation;
- ultrasonic;
- adiabatic compression and shock waves;
- temperature increases due to chemical reactions or unstable materials;
- combustion of a layer of dust or other combustible material;
- lightning.

This possibility is also an important source of danger for the population, infrastructure and other establishments located in their vicinity, given the considerable quantities of dangerous substances present. In addition to the effects directly caused by the explosion, the leakage and dispersion into the atmosphere of quantities of biogas capable not only of generating damage on the site, but also of reaching neighboring areas, extending the area at risk of explosion to even considerable distances from the initial source, are also to be considered.

In this regard, environments with explosive atmospheres must be divided into risk zones, following the dictates of the normative EN 60079-10-1 with regard to gases and normative EN 60079-10-2 with regard to dust. Depending on the results of the risk assessment, the definition of hazardous areas is to be described in a document for protection against the danger of explosion. All electrical equipment located in classified areas must meet the safety requirements and be of the degree of protection suitable for the type of classified area, in accordance with the provisions of the ATEX Directive 94/9/EC, in order to reduce the risk of ignition. (41)

In the following chapters, a classification of the various explosion risk zones is drawn up according to regulation 60079-10, in order to be able to make a comparison between the risk scenarios provided for by current legislation and those that could occur in faulty conditions and with an atmosphere subject to the typical climatic conditions of the place.

3.2 Significant cases of accidents in similar plants

As part of the prediction of possible accident scenarios within a plant, it is of particular importance to research and analyze the detection events that occurred in similar realities, in order to establish a starting point for the determination of critical issues.

Below are the articles concerning the different accidents that have occurred in recent years in Italy and, since they are particularly significant, two that have occurred in Germany.

- Incident 1

Figure 26: Biogas plant of Castel Goffredo   Source: Gazzetta di Mantova.it

Castel Goffredo (Casalpoglio) (MN)), 13/05/2012 – Gazzetta di Mantova

"In the plant of Castel Goffredo (MN) the explosion of the gasometric dome occurred. The damage would have been a problem of overpressure of the plant that two months ago was acquired by the Trelaghi company of Como. Inside the two structures there are the substances in the process of fermentation, the so-called digestate that produces the gas that will then become energy. According to what was leaked, to burst one cover tarpaulin and damage the other would have been a

problem with the engines of the plant that would have stopped, while the digestate continued to ferment. The safety valves would not have started and this would have prevented us from noticing the malfunction of the system. The tarpaulins, subjected to a pressure greater than their range, then gave way by leaking oxygen, water vapor and methane: no risk of pollution. The only discomfort for the inhabitants of the Casalpoglio area is an annoying smell that is fading with the passing of the hours."

https://www.sanfocadelfriuli.it/digestore-biogas-squarciato-incidente-alla-biopower-di-lendinara-ro/670/

- Incident 2

Figure 27: Biogas plant of Lendinara Source: Santafocadelfriuli.it

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Lendinara (RO) 02/05/2013 – Santafocadelfriuli.it

From online sources it was only possible to find a notice but no further documentation regarding the incident could be found. The importance of this accident is due to the massive dimension of the structure that has been subjected to explosion.

- Incident 3

Figure 28: Biogas plant of Coccaglio (BS)   Source: Ilgiorno.it

Coccaglio (BS), 11/08/2019 – Il Giorno

"Fire in a plant where biogas is produced, *in the heart of the Franciacorta wine area, in Coccaglio, around dawn yesterday. The affected company is the Società Agricola Caruna, located in the countryside, which has long decided to invest in clean energy. The reasons for the fire are currently unknown. The causes are being examined by the technicians of the fire brigade command of via Scuole, in Brescia, and by the carabinieri of the Compagnia di Chiari. The damage would be particularly considerable*. *The alarm went off around six in the morning, when the village of Coccaglio was invaded by smoke and when some people noticed the flames rising from the property of the farm. To be lost, according to the first information collected, were some cover caps. The call to 112 was immediate. Shortly after, the Brescia fire brigade and the volunteers of the Palazzolo sull'Oglio and Chiari detachments arrived on the spot. In total, about 15 male and female operators were employed. It took about three hours to get the fire right. The ceased alarm was declared around ten in the morning, then firefighters worked for a long time to secure the area. Despite the discomfort experienced due to the acrid smoke that has invaded the*

streets of the village, Coccaglio has not experienced any danger. The material used to produce biogas, i.e. animal wastewater, in fact, does not produce fumes harmful to health. The biogas plant of the Società Agricola Caruna, active since 2011, has never had problems and is considered one of those with high efficiency. The investment made at the time of construction was seven million euros. Potentially the Caruna biogas plant was capable of producing eight million kilowatt-hours per year. The company also has a photovoltaic system and also deals with the breeding of pigs"

- Incident 4

Figure 29: Biogas plant of Pavia di Udine   Source: Il gazzettino.it

Pavia di Udine 24/11/2017 – Il Gazzettino

"Fire in the biogas plant: very high flames, burned worker *ends up in the hospital. The fire broke out in the industrial area of Lauzacco,* in *Pavia di Udine, in the Eneri Giove* plant, *around 9.30 am today, Friday 24 November, for reasons under investigation by the fire brigade of the Udine Command. From what has been understood so far, a worker employed by an external company who was carrying*

out maintenance work in a part of the biogas plant was reached in the hands and arms by violent flames and strong heat. At that moment the man was operating near an external storage tank, consisting of a concrete structure. The fire completely destroyed the roof of this tank, which was made of flexible plastic material, and the flames rose very high. The firefighters managed to tame them but now, without coverage, the tank must be monitored: from the digester, in fact, more biogas comes out and it is necessary to guard the whole area. The worker, meanwhile, was rescued first by colleagues and then by the medical staff of 118 arrived on the spot with an ambulance from Palmanova. He suffered second-degree burns to his hands and arms: the injuries are serious, but the worker is not in danger of life; he was transported to the Palmanova hospital with the green code by ambulance. The State Police and the Carabinieri also intervened on the spot."

https://www.ilgazzettino.it/nordest/udine/infortunio_lavoro_operaio_ustionato_pavia_udine_centrale_biogas-3387155.html

- Incident 5

Figure 30: Biogas plant of S.Egidio (PG)   Source: Corrieredellumbria.it

Sant'Egidio (PG) 11/06/2019

"Moments of fear for a fire that developed around 3 pm, on a conveyor belt of a local Biogas plant. The flames destroyed the equipment without causing damage to people."

https://corrieredellumbria.corr.it/news/cronaca/959986/incendio-in-una-centrale-a-biogas.html

- Incident 6

Figure 31: Biogas plant of Flaibano (UD)   Source: Messaggeroveneto.it

Flaibano (UD) 07/11/2014

"An explosion followed by a fire occurred this morning in a biogas plant of an agricultural company in Flaibano. At the time of the outbreak there were no people around. According to a first reconstruction carried out by the Fire Brigade, the origin of the explosion could have been a loss of biogas produced by the plant through the use of chopped corn, triggered by an electrical contact. The Udine Fire

Brigade, intervened with two teams, contained the fire and made the plant safe, thus stopping the fermentation process. No problem for residents, as the plant is located in a remote agricultural area of the town."

https://messaggeroveneto.gelocal.it/udine/cronaca/2014/11/07/news/esplosione-nella-notte-in-fiamme-l-impianto-biogas-1.10264346

- Incident 7

Figure 32: Biogas plant of Roverbella (MN) Source: Sgonfiailbiogas.it

Roverbella (MN) 11/02/2015

"Inspection of Arpa and local police to the company that in Sei Vie manages the biogas electricity production plant. The inspection visit took place after numerous citizens complained of bad smells and submitted reports and petitions. In fact, the audit showed that of the four digesters with which the company is equipped, one had a breakdown. It would be a break of the first membrane, the inner one of the two present in the "balls". Already in December, the company turned off the digester affected by the failure, ordering the spare tarp. A custom-made piece that will arrive, most likely, only in mid-March. Meanwhile, citizens living nearby complained of a

strong smell of gas. Citizens have reported olfactory harassment several times in recent weeks. Benedetta Lorenzi, an opposition municipal councilor, also intervenes in the case. "We have reported several times to the administration and also to the previous one the problems deriving from this biogas – explains Lorenzi -. The current mayor is so quiet that on the matter he has decided to protect himself through legal assistance that citizens will pay»."

http://sgonfiailbiogas.blogspot.com/2015/02/roverbella-mn-digestore-perde-biogas.html

- Incident 8

Figure 33: Biogas plant   Source: Google.it

- Cà Turcata - Eraclea (Ve) 26/07/2019

"Fire in a biogas plant tonight, Friday 26 July, in the hamlet of Ca' Turcata, in Eraclea. The fire brigade teams were alerted just before 9 pm and left Jesolo, San Donà and Venice towards the locality, in via Pradivisi, where the farm that uses biomass to produce energy is located. The flames would have started from a tape that carries manure and scraps. Firefighters are at work to contain the fire and restore safety conditions. Perhaps the overheating of a part of the plant is the cause

of the incident, according to the first checks. The intervention of the fire brigade prevented the spread of the fire.”

https://www.veneziatoday.it/cronaca/incendio-impianto-biogas-eraclea-via-pradivisi-stasera-26-luglio.html

- Incident 9

Figure 34: Biogas plant of Acqualagna   Source: Ilrestodelcarlino.it

- Acqualagna (PU) 23/12/2017

“Two teams of firefighters, from Cagli and Fano, have been working since 5 pm today to extinguish a fire that has developed inside a biogas plant located in Bellaria di Acqualagna. The fire broke out for reasons still under investigation and affected a dryer of the company Agroenergie Ar. L. located in Bellaria di Acqualagna (Pesaro Urbino). Remarkable the cloud of gray smoke that was released from the sheds. The company produces renewable energy. According to the first findings of the fire brigade, the flames started from the plant where the sewage is treated with acids and ammonia. The fire would have been immediately contained, although the teams are still on site. There was no damage to people or harmful fumes. On the spot,

however, the residents, very worried about the quality of the air, protest for a persistent stench present for about two years in the area, simultaneously with the construction of the plant."

https://www.ilrestodelcarlino.it/pesaro/cronaca/incendio-energie-rinnovabili-1.3626213

- Incident 10

Figure 35: Biogas plant of Chiari (BS)

- Chiari (BS) 04/05/2020

"The residents of the hamlet of Santellone in Chiari, in the western part of the province of Brescia, say they are worried after what happened a week ago, Monday 4 May, but of which there was news – as reported by Bresciaoggi – only yesterday, Sunday 10. In fact, at the Chiari 1 plant in via Pontoglio that produces biogas, a dome exploded. It probably did not withstand the force of the gas that thus escaped and ended up in the atmosphere. The residents, who had felt that outbreak, had asked for the intervention of the fire brigade and the carabinieri. And so it was in

the following days to check what had happened and the possible dangers on the population and on some farms in the vicinity. The incident was reported to the Province of Brescia which could order the revocation or suspension of the activity within that plant. A machine often criticized by the inhabitants for the presence of noises and smells."

https://www.quibrescia.it/provincia/bassa-bresciana-2/2020/05/11/chiari-esplode-una-cupola-allimpianto-di-produzione-biogas/561286/

- Incident 11

Figure 36: Biogas plant of Kempten (DEU) Source: All-in.de

- Kempten – Germania 17/03/2015

"On Tuesday there was an estimated damage of 300,000 euros in a fire in the biogas community of Heiligkreuz near Kempten. The fire broke out shortly after 4 pm in the workshop room of the plant for reasons not yet clarified. The room, completely burned, stands about ten meters from the two large ones. To prevent the flames from spreading to these giant covered vats, firefighters cooled the system for hours with extinguishing water. Thus, according to the commander of the Kempten Fire

Brigade Andreas Hofer, the risk of biogas deflagration was avoided. In the fire, one of the plant's operators was slightly injured by the flue gases. As a precaution he was taken to the hospital. In total, 80 firefighters, ten police officers and ten paramedics were deployed. The access roads around the fire were cordoned off by police for several hours. Traffic has been largely diverted."

https://www.all-in.de/kempten/c-lokales/vollbrand-bei-einer-biogasanlage-in-kempten-brand-ist-geloescht-ein-verletzter_a1913705

- Incident 12

Figure 37: Biogas plant of Daugendorf   Source: Google.com

- Daugendorf – Germania 16/12/2007

"In 2007, a plant exploded in a fireball in Daugendorf, Baden-Württemberg. The debris spread within a radius of more than a hundred meters, after which a smelling rain of slurry settled over the country. The most serious accident to date occurred in 2005 in Rhadereistedt, Lower Saxony. A toxic cloud of hydrogen sulfide killed four people after a tanker truck was dumping animal waste.

Such cases of serious damage are the exception: often hand-crafted systems filter, drip or sparkle somewhere. "The problems with biogas plants are considerable," says Roland Fendler, head of plant safety for slurry farmers at the Federal Environment Agency in Dessau (UBA).."

https://www.epd.gov.hk/eia/register/report/eiareport/eia_2182013/Appendix%204.1.pdf

https://www.andtreff.de/explosion-in-biogasanlage-t19216.html

3.3 Identification of critical points of the plant

In order to be able to carry out a fluid dynamic simulation in a scrupulous manner, a pivotal step is the identification of the possible critical points of the system. The criticalities of these elements are of various kinds and reside for some in the very nature of the interface between the inside of the digester and the outside (eg. hydraulic guards), for others in the discontinuity between different materials (inspection porthole and outer ring between wall and membrane) or even in the presence of moving parts (eg. mixer height variators, rope sensor seats, air blowers etc).

It should be remembered that the biogas/air mixture is explosive if the biogas is present in a 5-12% ratio compared to the air. (42)

The critical element of the plant considered are reported in the followings.

- Hydraulic guards

  This safety valve, conceptually simple and automatically operated, is aimed at controlling the overpressure inside the gasometric dome and comes into operation if the pressure of the biogas exceeds a certain value, given by the hydrostatic leaf of the fluid present in the closed volume that constitutes the valve body itself. The hydraulic guard is designed to act redundantly and subsequently with respect to the pressure sensors provided inside the dome itself. Usually, biogas plants require the presence of two hydraulic guards: one for overpressure (calibrated to intervene at a pressure equal to 24 mbar) and one with a vacuum breaker function (calibrated to intervene at a pressure equal to -10mbar). In order to avoid malfunctions during normal operation in this type of safety system, it is necessary to provide for the use of glycol as a liquid for filling the valve body, in order to avoid the freezing of water and the consequent momentary functional ineffectiveness of the valve itself or even the impairment of the structural integrity of the safety torch. In addition to this, it could be a useful integration a replenishment line of any water decreased due to evaporation phenomena.

Figure 38: Hydraulic guards   Source: Principi di Porcia e Brugnera

Conceptual scheme of hydraulic guards:

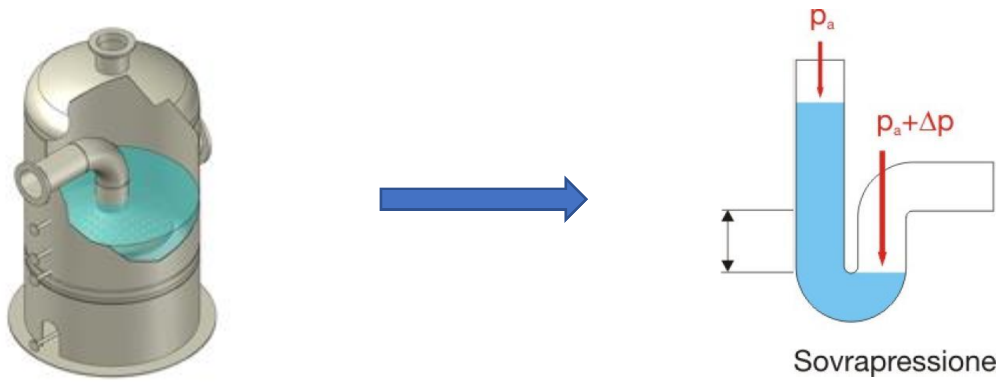


Figure 39: Functional scheme of the hydraulic guards   Source: Google.com

- Inspection portholes

  Necessary for the visual control of the interior of the digester, those elements are generally made up of circular windows and equipped if necessary, with special lighting to protect ATEX, manual or automatic wipers-glass and nozzle for washing the internal glass itself. The compartments for the portholes are obtained in the upper part of the vertical walls of the digesters by coring or, more rarely, in the dome of the digester. The seal at the interface between glass and steel flanges is guaranteed by special compression gaskets, resistant to the mechanical actions and the chemical effect of the products present in the digester and maintained in compression by a series of pressure bolts.

Figure 40: Inspection porthole   Source: Principi di Porcia e Brugnera

- Mixer height variator controls and string level sensor seat

  The rotary agitators arranged along the inner walls of the digester have a system for orientation and height variation that can be managed manually from the outside. The handling tie rod passes through the interface between the inside and outside of the digester and can therefore represent a critical point from which a gas leak could occur.

Figure 41: Winch for mixer height variation   Source: Principi di Porcia e Brugnera

- Air blowers and vent clapet

Thanks to the aid of a fan, the volume between the two membranes is maintained in conditions of slight overpressure (about 1.5 millibars), sufficient to ensure that the outermost membrane with the function of protection from the weather, to maintain the conical shape and at the same time applying pressure on the inner membrane, favoring the passage of gas from one tank to another. Any leakage of biogas from the innermost membrane, having the function of sealing the gaseous biofuel, could be caused by intrinsic production defects of the cloth or by overpressures. The leaked biogas would be mixed with the insufflated air and together with this, expelled from the venting clapet under mixed conditions.

Figure 42: Gasometer blowers   Source: Principi di Porcia e Brugnera

Figure 43: Relief clapet   Source: Principi di Porcia e Brugnera

- Supply matrix inlet pipes

Once the solid raw materials have been mixed in special mixers, they are conveyed by electric augers (elevators consisting of an endless screw placed inside a pipeline and driven by an electric motor) inside the digester. In the event that the level of the mass being digested inside the digester falls below a certain level, the biogas could find vent to the outside by going backwards along the input pipes of the raw material. The passage of gas through this element is unlikely as it is always loaded with solid biological mass (the moments immediately following any maintenance interventions are beyond this consideration)

Figure 44: Loading augers   Source: Principi di Porcia e Brugnera

- Gasometer membrane – concrete wall joint

The hermetic seal between the membrane and the upper part of the masonry is provided by special compression gaskets. If this sealing system were to fail, the biogas could leak more or less conspicuously depending on the extent of the defect.

Figure 45: Gasometer-wall junction   Source: Principi di Porcia e Brugnera

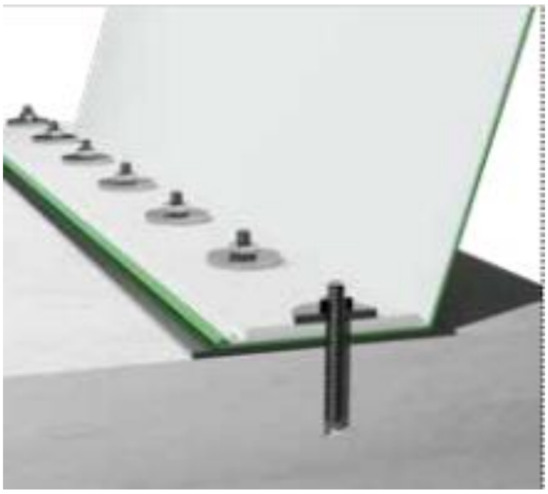


Figure 46: Detail of the gasometer-wall junction   Source: Ecomembrane

- Digester biogas pipes

The digesters and the post digesters are connected to each other by means of partially aerial and partially underground pipes, having the function of allowing the free passage of biogas from one structure to another in order to avoid pressure differences between the four tanks, until the capture of this at the end of the compensation ring. Any breakage of the pipes can be related to impacts caused by machinery during maneuvering movements or other, by failure due to material production defects or by the failure of the joining system near the flanges. In this failure scenario, the biogas could leak until the capacity contained in the gasometric domes is exhausted.

Figure 47: Biogas intake pipes   Source: Principi di Porcia e Brugnera

Figure 48: Overhead piping   Source: Principi di Porcia e Brugnera

- Cogenerator and associated components (chiller, blower, etc)
  The pressure of the biogas taken from the digesters and processed inside a dehumidification battery is raised by means of a blower (mono or two-stage) to about 110 mbar necessary for the supply of the cogenerator. Any breakage of pipes, flanges or the blower itself, could cause biogas leaks into the atmosphere.

Figure 49: Biogas blower   Source: Principi di Porcia e Brugnera

- Safety flare area pipes

  The safety torch is connected to the main supply line via stainless steel pipes. Any breakage of the pipes, solenoid valves or malfunctions of the gas ignition system, would lead to the leakage of biogas and the consequent dispersion into the atmosphere. Another eventuality could concern the emission of the gas not burned directly through the torch due to a malfunction of the flame ignition.

Figure 50: Safety torch solenoid valves   Source: Principi di Porcia e Brugnera

3.4 ATEX evaluation

Once the critical points of the plant have been identified, i.e. any hazardous areas where risks associated with the presence of flammable substances may occur, it is possible to proceed with the determination of the different danger zones (ZONE 0, ZONE 1, ZONE 2) and with the calculation of the relative extension. For completeness, any security measures to be adopted will be proposed, in accordance with current regulations or good technique for the protection of installations and for the protection of people.

For the Authors of this work it is important to specify that the following ATEX evaluation has the sole purpose of graphically presenting the situation from a regulatory point of view, with the intention of comparing it with the results of fluid dynamic modeling. It does not therefore constitute an assessment with legal value.

3.4.1 Purpose of the evaluation and methodology

In order to determine the hazardous areas, the criterion of risk assessment was adopted, hypothesizing different scenarios inherent with the type of plant, both the normal management and the emergency situations due to operating anomalies or failures of the critical components of the system.

The various calculations and evaluations were carried out based on data and parameters resulting from research in the bibliographies indicated and partly provided directly by the technical office of the Azienda Agricola Principi di Porcia, with particular reference to:

- type of substances used;
- quantities of the same present in work cycles or deposits;
- working methods used in the company;
- existing parameters of artificial ventilation;
- historical analysis of anomalies found on implants of the same kind.

On the basis of the analysis of the critical points carried out in the previous paragraph, the sources that have been considered as representative of all possible emission sources are listed below:

1. interface between the cloth and the membrane of the digester: hypothesis of cutting, hole or failure of the fixing system);
2. safety valve with hydraulic guard of the digesters: hypothesis of entry into operation following an overpressure / depression inside the digester);
3. flanges of the biogas pipe leaning against the digesters: hypothesis of loss of tightness as a result of rupture of the flanged joints (representative of the other possible leaks from the walls of the digesters);
4. flanges and valves downstream of the blower and in the cogenerator zone: hypothesis of loss of tightness as a result of the rupture of the flanged joints;
5. safety flare: hypothesis of loss of tightness as a result of breakage of the flanged connections or malfunction of the burner.

3.4.2 Reference standard

For the purposes of the project, reference was made to the provisions laid down or recalled by the following Italian Laws and Decrees of a general nature and subsequent updates where and to the extent that they are applicable:

- D.M.09-04-2008 n. 81 "Implementation of Article 1 of Law 3 August 2007, n. 123, on the protection of health and safety in the workplace.";
- D.M.01-03-68 n.186 "Provisions concerning the production of materials, equipment, machinery, installations and electrical and electronic systems";
- D.M22-01-08 n.37 "Regulation on the reorganization of the provisions on the installation of systems inside buildings";
- CEI standards and recommendations and in particular:
  - CEI 31-87 "Electrical constructions for explosive atmospheres due to the presence of gases. Part 10: classification of hazardous places" (CEI EN 60079-10-1);
  - CEI 31-33 "Electrical constructions for explosive atmospheres due to the presence of gases. Part 14: Electrical installations in places with danger of explosion due to the presence of gas" (CEI EN 60079-14);
  - CEI 31-34 "Electrical constructions for explosive atmospheres due to the presence of gases. Part 17: Verification and maintenance of electrical systems in places with danger of explosion due to the presence of gas" (CEI EN 60079-17);
  - CEI 31-35 (although repealed) "Electrical constructions for explosive atmospheres due to the presence of gases. Guide to the classification of dangerous places".

3.4.3 Risk assesment procedure

For the classification of places, the risk assessment criterion provided for by the CEI EN 60079-10 standard has been adopted, namely:

- identification of all continuous or discontinuous emission sources for long periods (zero-degree source);
- identification of the sources of periodic or occasional emission and due to normal working procedures (source of first degree);
- identification of emission sources not foreseen in normal operation and only for short periods, or due to anomalies, failures, breakages (grade second source).

On the basis of the evaluations carried out, the following emission sources have been identified for the environments considered:

- *zero-grade emissions:*
  Not present inside the plant.

- *first degree emissions:*
  Present in the ordinary operation (linked to the principle of operation of the valve itself but represents an extraordinary event) of the hydraulic guard.

- *second degree emissions:*
  Present due to a leak from a pipe (linked for example to the rupture of a flange), from the supply line in the blower area on the cogenerator supply ramp or in the safety torch area.

3.4.4 Dangerous areas (presence flammable gases)

In order to carry out the assessment of hazardous areas, steps must be followed relating to the data provided, the risk assessment and the processing system.

Below are the definitions of the nomenclature used by the Italian standard CEI 31-87.

3.4.4.1 Definitions

- Explosive atmosphere due to the presence of gases: mixture in air of a flammable substance in the form of gas or steam, under normal atmospheric conditions, in which, after ignition, combustion propagates to the unburned mixture.
  A mixture having a concentration greater than the Upper Explosive Limit (UEL), is not an explosive atmosphere, but can easily become such; therefore, in certain cases, for the purposes of classification, it is advisable to consider it an explosive atmosphere.

- Hazardous place: the place where an explosive atmosphere is or may be present due to the presence of gases, in such quantities as to require special measures for the construction, installation and use of the buildings (apparatus).

- Non-hazardous place: the place where the presence of an explosive atmosphere is not expected due to the presence of gases, in such quantities as to require special measures for the construction, installation and use of buildings (apparatus).

- Zones: in relation to the frequency of formation and permanence of an explosive atmosphere due to the presence of gases, dangerous places are classified in the following areas:
  - zone 0: Place where an explosive atmosphere is present continuously or for long periods due to the presence of gases;
  - zone 1: place where an explosive atmosphere due to the presence of gases may be present during normal operation;
  - zone 2: where it is not possible for an explosive atmosphere to be present due to the presence of gases during normal operation or, if this occurs, it is possible to be present only infrequently and for a short time.

- Emission source: a point or part from which a flammable gas, vapour or liquid can be emitted into the atmosphere in such a way as to give rise to an explosive atmosphere.

  An emission source may give rise to one of these three emission grades or a combination thereof:

  - continuous grade emission: continuous emission or that can occur for long periods;
  - first degree emission: emission that may occur periodically or occasionally during normal operation;
  - second degree emission: emission that is not expected during normal operation and that if it occurs is possible only infrequently and for short periods.
- Emission degrees: three basic degrees of emission are established, listed below in descending order of probability of the presence of explosive atmosphere due to the presence of gases:
  - continuous degree;
  - first degree;
  - second degree.

- Emission flow rate: amount of flammable gas or vapor emitted in the unit of time from the emission source.

- Normal operation: situation in which the plant operates within the characteristic design quantities.

- In these circumstances, the following may arise:
  - small emissions of flammable substances can be included in normal operation. For example, small emissions are considered to be leaks from seals;
  - failures such as breakage of seals of gaskets or flanges are not considered to be part of normal operation;

- Ventilation: air movement and exchange with fresh air caused by the effect of wind, temperature gradients, or artificial means (e.g. fans or extractors).

- Explosive limits:
  - lower explosive limit (LEL): concentration of flammable gas or vapor in air, below which the atmosphere is not explosive;
  - upper explosive limit (UEL): Concentration in air of flammable gas or vapour, above which the atmosphere is not explosive.

  For the purposes of the Standard, the terms "explosive" and "flammable" are considered synonymous.

- Relative density of a gas or vapor: density of a gas or vapor relative to that of air at the same pressure and temperature (the relative density of air is equal to 1,0).

- Flammable substance: a substance which is flammable in itself or capable of producing a flammable gas, vapor or mist.

- Flammable liquid: liquid capable of producing flammable vapor in any foreseeable operating condition.

- Flammable gas or vapor: gas or vapor which, when mixed with air in certain proportions, gives rise to an explosive atmosphere due to the presence of gases.

- Flammable mist: droplets of flammable liquid dispersed in air so as to form an explosive atmosphere.

- Flammability temperature: the lowest temperature of a liquid at which, under specific normalized conditions, it emits vapors in sufficient quantity to form a flammable mixture with the air.

- Boiling temperature: temperature at which a liquid boil at ambient pressure of 101.3 kPa (1 013 mbar).

- Vapor pressure (vapor pressure): resistance exerted when a solid or liquid is in equilibrium with its own vapors. The vapor pressure varies depending on the temperature and the type of substance.

- Ignition temperature of an explosive atmosphere due to the presence of gases: Minimum temperature of a heated surface at which, under specified conditions, the ignition of a flammable substance to the state of gas or steam in mixture with air takes place.

3.4.4.2 Calculation of the explosion limits

The explosive limits of a gas or vapors of a liquid correspond to the extremes of the concentration range within which the flammable air-gas mixture ignites when exposed to appropriate ignition. In this case, two cases can occur: the mixture can detonate or deflagrate (deflagration occurs at subsonic speeds and propagates by conduction, detonation occurs at supersonic speeds and propagates through pressure waves), depending on numerous factors, including the concentration of fuel itself and the conditions of confinement of the mixture. The critical concentration range is between the two limits that make up the lower extreme (LEL = lower explosive limit) and higher extreme (UEL = upper explosive limit) (43).

NB: For the type of application and for how the system is configured, only the LEL is considered, moving in favor of safety. An atmosphere under conditions above the UEL does not in itself constitute an explosive atmosphere but can easily become so.

For the conversion of the *minimum* explosive level expressed in ${m^3}/{m^3} \cdot 100$ in *LEL* expressed in ${kg}/{m^3}$, the guidelines provided by the Guide to the application of the CEI EN 60079-10-1 standard provide several formulas, including the following:

$$LEL_m(\frac{kg}{m^3}) = \frac{LEL_V}{100} \cdot \rho_{0gas} \qquad [f.5.5.11\text{-}2]$$

Where:

- LEL_m corresponds to the minimum explosive limit expressed in ${m^3}/{m^3} \cdot 100$
- LEL_V corresponds to the minimum explosive limit expressed in ${kg}/{m^3}$
- P_{0gas} corresponds to the density of the gas and is derived from the formula:

$$\rho_{0gas} = \frac{p_a \cdot M}{R \cdot T_0} \text{ espressa in } {kg}/{m^3} \qquad [f.5.5.4\text{-}2]$$

Where:

- Pa corresponds to the atmospheric pressure of the environment under consideration. Equal to 99797 Pa;
- M corresponds to the molar mass of the flammable substance, in the case of biogas equal to *27.2 kg/kmol*;
- R corresponds to the universal constant of gases, corresponding to 8314 *J/(kmol· K)* ;
- T_0 corresponds to the absolute temperature immediately after exiting the container or containment system. As far as biogas is concerned, the temperature is equal to 313.15°*K.*

Considering that the formula takes into account the value of the temperature, it is necessary to calculate two different LEL_V:

- LEL_V (-9.3°C) = 61.87 g/m^3;
- LEL_V (32.6°C) = 53.4 g/m^3.

A lower temperature causes a higher density.

According to the guidelines, the maximum explosive value is not considered for studies in open environments [5.5.11].

3.4.4.3 Determination of emission sources

The term "Emission Source" (SE) means a point or part of the containment system from which flammable gas can be emitted into the atmosphere in such a way as to give rise to an explosive atmosphere. These sources can emit gases, both during normal operation of the plant, during abnormal operation (extraordinary occurrence, for example a fault), and in case of maintenance.

Within the Standard there are three degrees of emission from the SE: continuous, first and second, in descending order of probability of emission of flammable gas into the environment:

- continuous formation of a gas cloud: places where a gas cloud may be present continuously or for long periods, or for short periods at frequent intervals;
- first-degree emission: source that is expected to release flammable gases occasionally during ordinary operation;
- second degree emission: source that is expected not to release flammable gases occasionally during ordinary operation but if it occurs it is possible only infrequently and for short periods.

Continuous and first-degree emissions are expected during normal operation, so they can generally be defined, both in terms of emission characteristics, in terms of duration, and as emission frequency.

An emission that occurs even if infrequently and for short periods, but during normal (ordinary) operation cannot be considered second-degree; it must normally be regarded as first instance.

Second-degree emissions are not expected during normal operation, they are usually attributable only to unwanted events, such as: failures and foreseeable defective states, reasonably foreseeable incorrect use; therefore, to define their duration and frequency, it is necessary to refer to the methods of surveillance (operation) and maintenance of the containment systems of flammable substances and their components.

It should be emphasized that parts that could emit gases into the atmosphere only in the event of catastrophic events, such as welded vessels and pipes (without joints), including closed manholes, flanged joints with special precautions to avoid gas leakage, are not to be considered emission sources.

In this case, the emission sources considered possible are:

- Zero-grade emissions:
  Not present.
- First degree emissions:
  Not present.
- Second degree emissions:
  Present due to a leak from a valve, from a pipe flange close to the digester or in the blower and cogenerator area.

3.4.4.4 Presence of explosivity-detectors

On the walls of the digesters, installed outside, gas detectors are placed, about 1 m from the shutters of the gas supply pipes to the underground collector. As a precautionary measure, the presence of any installed detectors is not taken into account in this report.

3.4.4.5 Structural emissions

Structural emissions, treated in the Italian CEI guide 31-35, are emissions of continuous or first degree, generated by the wear of time in appliances, pipes or structural parts of plants, which contain flammable liquids or gases. Structural emissions generally do not give rise to hazardous areas. In the event that, however, there is an evident wear of the components, a high pressure of use, a high danger of the gas or flammable liquid, it is advisable to perform the calculations of the danger zones.

In the present case, the pipes and equipment do not present an evident wear and a high pressure inside the containment system. Therefore, structural emissions were not considered.

3.4.5 Assessment of dangerous zones

The elements considered worthy of consideration among the critical areas identified in the chapter 3.3 are evaluated within the ATEX requirements, considering some specific parameters given by legislation, such as the degree of emission, and the presence of any ventilation.

Below are the elements considered, the characteristics useful for the evaluation and the results.

3.4.5.1 Connection flange

The valves, flanges, connections, joints present on the pipes are considered as emission sources. The flange will be considered as representative of all second-degree emission sources.

In order to assess the type and size of the danger zone, it is necessary to consider:

- degree of magnitude of the emission;
- availability of ventilation;
- degree of extent of ventilation.

The degree of magnitude of the emission is of type *two*, as the emission is due to a failure of the component.

The availability of ventilation is *good*, since natural ventilation is present continuously.

The degree of ventilation, derived from table B.1 of the CEI guide 31-35, is *average*, since the ratio between the amount of ventilation air affecting the *SE* [Emitting Source] and the amount of flammable gases or vapors emitted into the atmosphere is such as to contain the extension of the danger zone within defined limits and such as to limit the time of persistence of the explosive atmosphere at the cessation of emission. However, it cannot be considered negligible. In fact, the calculated maximum Dz dangerous distance is not negligible.

The danger zone is therefore a ZONE 2.

3.4.5.2 Gasometer membrane – concrete wall joint

The interface between the gasometric dome and the top of the digester masonry represents a possible source of emission.

In order to be able to assess the type and size of the danger zone, it is necessary to consider:

- degree of magnitude of the emission;
- availability of ventilation;
- degree of extent of ventilation.

The degree of magnitude of the emission is of type *two*, as the emission is due to a failure of the component.

The availability for ventilation is *good*, as natural ventilation is present continuously.

The degree of ventilation, derived from table B.1 of guide CEI 31-35, is *average*, since the ratio between the amount of ventilation air affecting the SE and the amount of flammable gases or vapors emitted into the atmosphere is such as to contain the extension of the danger zone within defined limits and such as to limit the time of persistence of the explosive atmosphere at the cessation of emission. However, it cannot be considered negligible since, the calculated maximum Dz dangerous distance is not minimal.

In particular, the hole considered as a possible emission point is 1000 mm^2, given by the product of the thickness of 1 mm for the distance between two anchor points, approximated approximately to the value of 1 m.

The danger zone is therefore a ZONE 2.

Table 3 and *Table 4* summarize what is defined above.

Table 3: Summary table

DEGREE OF EMISSION	VENTILATION DEGREE						
	HIGH		MEDIUM			POOR	
	VENTILATION AVAILABILITY		VENTILATION AVAILABILITY			VENTILATION AVAILABILITY	
	GOOD	ADEQUATE	POOR	**GOOD**	ADEQUATE	POOR	GOOD, ADEQUATE OR POOR
CONTINUOUS	ZONE 0NE NOT DANGEROUS PLACE	ZONE 0NE + ZONE 2	ZONE ONE + ZONE 1	ZONE 0	ZONE 0 + ZONE 2	ZONE 0 + ZONE 1	ZONE 0
FIRST	ZONE 1NE NOT DANGEROUS PLACE	ZONE 1NE + ZONE 2	ZONE 1NE + ZONE 2	ZONE 1	ZONE 1 + ZONE 2	ZONE 1 + ZONE 2	ZONE 1 O ZONE 0
SECOND	ZONE 2NE NOT DANGEROUS PLACE	ZONE 2NE NOT DANGEROUS PLACE	ZONE 2NE + ZONE 2	ZONE 2	ZONE 2 + ZONE 2	ZONE 2 + ZONE 2	ZONE 1 O ALSO ZONE 0

Table 4: Zone table

ZONE	PROBABILITY OF EXPLOSIVE ATMOSPHERE IN 365 DAYS (1 YEAR)	TOTAL DURATION OF EXPLOSIVE ATMOSPHERE IN 365 DAYS (1 YEAR)
ZONE	$P>10^{-1}$	more than 1000 h
ZONE 1	**$10^{-1} \geq P > 10^{-3}$**	**more then 10 h less then a 1000 h**
ZONE 2	$10^{-3} \geq P > 10^{-5}$	more than 0,1 h less then a 10 h

3.4.5.3 Hydraulic Guard

This source will be considered as representative of all first-degree emission sources

Since the hydraulic guard can intervene exceptionally even during normal operation (first degree emission), the relative flow rate of biogas output is considered as a function of the relative pressure that causes it to intervene.

In particular, the gasometer is sized to guarantee an output flow rate of 500 Nm^3/h of biogas, divided into 4 different digesters (2 digesters proper + 1 post digester + 1 covered storage tank), for a total of 125 Nm^3/h per element.

In order to be able to assess the type and size of the danger zone, it is necessary to consider:

- degree of emission;
- availability of ventilation;
- degree of ventilation.

The degree of emission is of type *one*, as the emission is of a continuous type only in case of intervention of the hydraulic guard itself.

The availability for ventilation is *good*, as the emission is outdoors

The degree of ventilation, derived from table B.1 of guide CEI 31-35, is *average*, since the ratio between the amount of ventilation air affecting the SE and the amount of flammable gases or vapors emitted into the atmosphere is such as to contain the extension of the danger zone within defined limits and such as to limit the time of persistence of the explosive atmosphere at the cessation of emission. However, it cannot be considered negligible.

In fact, the calculated maximum *Dz* dangerous distance is not negligible.

The danger zone is therefore a **ZONE 1.**

Table 5 and *Table 6* summarize what is defined above

Table 5: Summary table

DEGREE OF EMISSION	VENTILATION DEGREE						
	HIGH		MEDIUM			POOR	
	VENTILATION AVAILABILITY		VENTILATION AVAILABILITY			VENTILATION AVAILABILITY	
	GOOD	ADEQUATE	POOR	GOOD	ADEQUATE	POOR	GOOD, ADEQUATE OR POOR
CONTINUOUS	ZONE 0NE NOT DANGEROUS PLACE	ZONE 0NE + ZONE 2	ZONE ONE + ZONE 1	ZONE 0	ZONE 0 + ZONE 2	ZONE 0 + ZONE 1	ZONE 0
FIRST	ZONE 1NE NOT DANGEROUS PLACE	ZONE 1NE + ZONE 2	ZONE 1NE + ZONE 2	ZONE 1	ZONE 1 + ZONE 2	ZONE 1 + ZONE 2	ZONE 1 O ZONE 0
SECOND	ZONE 2NE NOT DANGEROUS PLACE	ZONE 2NE NOT DANGEROUS PLACE	ZONE 2NE + ZONE 2	ZONE 2	ZONE 2 + ZONE 2	ZONE 2 + ZONE 2	ZONE 1 O ALSO ZONE 0

Table 6: Zone table

ZONE	PROBABILITY OF EXPLOSIVE ATMOSPHERE IN 365 DAYS (1 YEAR)	TOTAL DURATION OF EXPLOSIVE ATMOSPHERE IN 365 DAYS (1 YEAR)
ZONE	$P>10^{-1}$	more than 1000 h
ZONE 1	$10^{-1}\geq P>10^{-3}$	**more then 10 h less then a 1000 h**
ZONE 2	$10^{-3}\geq P>10^{-5}$	more than 0,1 h less then a 10 h

3.4.6 Determination of the extension of the dangerous areas

The project parameters considered are as follows:

- parameter K (continuous and first degree): 0.25;
- parameter K (degree second): 0.5;
- parameter Kdz (continuous degree and prime): 0.25;
- Kdz parameter (degree second): 0.5;
- parameter K0: 2;
- safety factor Ka: 1,2.

Environment: Code A001 - Description: Gas Digesters and Pipelines

- environment Type: Open;
- atmospheric pressure (Pa): 100127;
- ambient temperature (°C): 11.8;
- ventilation efficacy factor f: 2;
- the emission sources are located at a height from the ground both below and above 3 m;
- minimum wind speed within 3 m above the ground, w (m/s): 0,25;
- minimum wind speed over 3 m above the ground, w (m/s): 0.5;
- ventilation availability: Good.

Flammable substance: Biogas

- number: -1;
- LEL % volume: 7,3;
- LEL (kg/m^3): 7.71E-02;
- UEL % volume: 28;
- relative air density: 0.9;
- molar mass (kg/kmol): 26;
- gamma coefficient (specific heat ratio): 1.3;
- liquid density (kg/m^3): 674;
- specific heat at room temperature csl (J/(kg/K)): 2073;
- gas diffusion coefficient cd (m^2/h): 0,074;
- latent heat of vaporization clv (J/kg): 5.10E5;

- boiling point Tb (°C): -161,4;
- ignition temperature (°C): 700;
- flammability temperature (°C): -10;
- electrical Construction Group: IIA;
- temperature class: T1.

Emission source Code: SE001 Description: Digester membrane-concrete wall interface

- hazardous substance: Biogas;
- ventilation efficacy factor for the emission source: 2;
- the emission source is located over 3 m above the ground;
- emission degree: second
- emission mode: gas/steam;
- pressure inside the containment system:
  - Relative (bar): 0.002
  - Absolute (Pa): 100327
- pressure outside the containment system (Pa): 100127;
- emission hole area (mm^2): 1000;
- efflux coefficient: 0.8;
- substance temperature (°C): 20;
- emission flow Qg (kg/s): 0,01653353.

Control of the environment

- staff surveillance;
- place: unsupervised.

Hazardous areas (generated by SE: SE001 - Membrane Digesters) Second-grade emission

- number of air changes Co (1/s): 0.05374391;
- minimum air flow Qa,min (m^3/s): 0.4292287;
- persistence time t(s): 97.4;
- Vex Volume (m^3): 7.986555;
- volume Vz (m^3): 15.97311 (not negligible);
- ventilation grade: Medium;

- direction of issue: note;
- zone Type: Zone 2;
- dangerous distance dz (m): 3.87641;
- toroidal diameter: 1.64 m;
- shape of the danger zone: Toroidal.

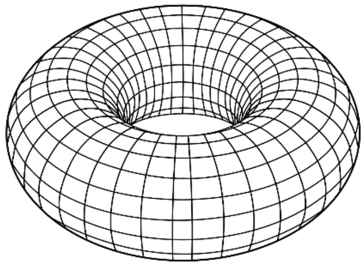


Figure 51: Toroidal shape   Source: Mathworld.com

Emission source Code: SE002 Description: Hydraulic Guard

- hazardous substance: Biogas;
- ventilation efficacy factor for the emission source: 2;
- the emission source is located over 3 m above the ground;
- degree of emission: first;
- emission mode: gas/steam
- pressure inside the containment system:
- relative (bar): 0.002;
- absolute (Pa): 100327;
- pressure outside the containment system (Pa): 100127;
- efflux coefficient: 0.8;
- substance temperature (°C): 20;
- emission flow Qg (kg/s): 0.03472042 = 125 Nm^3/h.

Control of the environment:

- staff surveillance;
- place: unsupervised.

Hazardous areas (generated by the SE: SE002 - Hydraulic Guard)

- first grade emission;

- number of air changes Co (1/s): 0.01854339;
- minimum air flow Qa,min (m^3/s): 1.80276;
- persistence time t(s): 357.05;
- Vex Volume (m^3): 48.60925;
- volume Vz (m^3): 194,437 (not negligible);
- ventilation grade: Medium;
- direction of issue: note;
- zone type: Zone 1;
- dangerous distance dz (m): 11.23491;
- altitude a (m): 4,02;
- altitude b (m): 1,61;
- altitude c (m): 0,4;
- hazard Zone Volume (m^3): 10.9;
- shape of the danger zone: see the figure below.

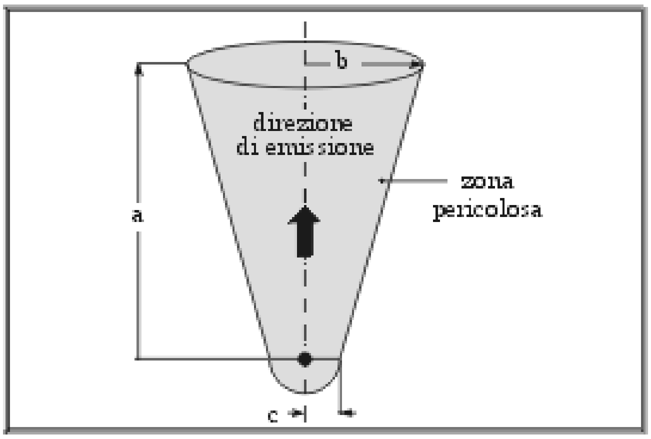


Figure 52: Emission cone

Emission source Code: SE003 Description: Shutters upstream of the Blower

- hazardous substance: Biogas;
- ventilation efficacy factor for the emission source: 2;
- the emission source is within 3 m of ground clearance;
- emission degree: second;
- emission mode: gas/steam;

- pressure inside the containment system:
  - Relative (bar): 0.002;
  - Absolute (Pa): 100327;
- pressure outside the containment system (Pa): 100127;
- emission hole area (mm^2): 2.5;
- efflux coefficient: 0.8;
- substance temperature (°C): 20;
- emission capacity Qg (kg/s): 0,0000413338.

Controllo dell'ambiente

- staff surveillance;
- place: unsupervised.

Hazardous areas (generated by the SE: SE003 - Shutters upstream of the blower)

- grade second emission;
- number of air changes Co (1/s): 0.5374495;
- minimum Qamin air flow rate (m^3/s): 0.001073071;
- persistence time t(s): 9.74;
- Vex Volume (m^3): 0.001996598;
- volume Vz (m^3): 0.003993197 (not negligible);
- ventilation grade: Medium;
- direction of issue: note;
- zone Type: Zone 2;
- dangerous distance dz (m): 0.19382;
- altitude a (m): 0,25;
- altitude b (m): 0,1;
- share c (m): 0,025;
- danger Zone Volume (m^3): 0.003468842;
- shape of the danger zone: see the figure below.

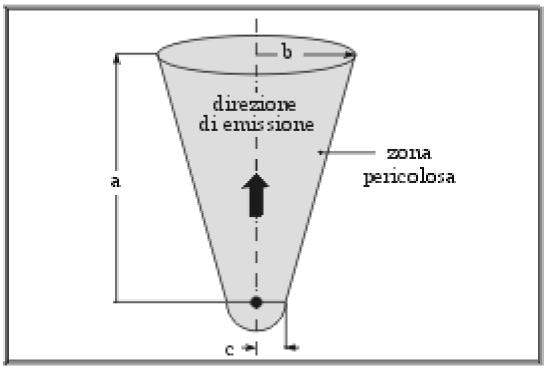


Figure 53: Emission cone

Emission source Code: SE004 Description: Shutters downstream of the Soffiante

- hazardous substance: Biogas;
- ventilation efficacy factor for the emission source: 2;
- the emission source is within 3 m of ground clearance;
- emission degree: second;
- emission mode: gas/steam;
- pressure inside the containment system:
  - Relative (bar): 0,5;
  - Absolute (Pa): 150127;
- pressure outside the containment system (Pa): 100127;
- emission hole area (mm^2): 2.5;
- efflux coefficient: 0.8;
- substance temperature (°C): 20;
- emission flow Qg (kg/s): 0,0006315499.

Control of the environment

- staff surveillance;
- place: unsupervised.

Hazardous areas (generated by the SE: SE004 - Shutters downstream of the blower)

- grade second emission;
- number of air changes Co (1/s): 0.4393519;
- minimum Qamin air flow rate (m^3/s): 0.01639573;
- persistence time t(s): 11.91;

- Vex Volume (m^3): 0.03731799;
- volume Vz (m^3): 0.07463599 (not negligible);
- ventilation grade: Medium;
- direction of issue: note;
- zone Type: Zone 2;
- dangerous distance dz (m): 0.23709;
- altitude a (m): 0,3;
- share b (m): 0,12;
- share c (m): 0,03;
- danger Zone Volume (m^3): 0.005994159;
- shape of the danger zone: see the figure below;

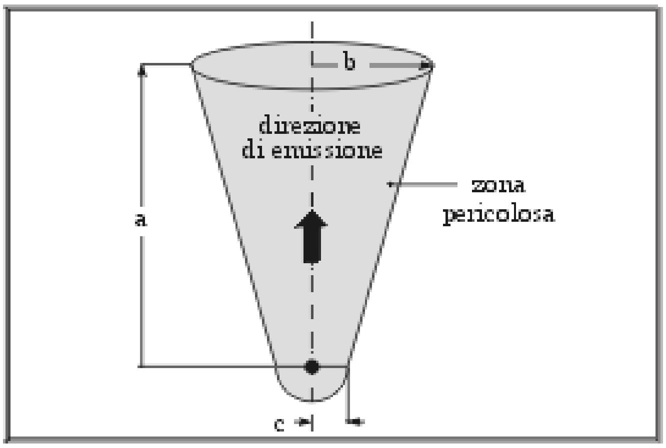


Figure 54: Emission cone

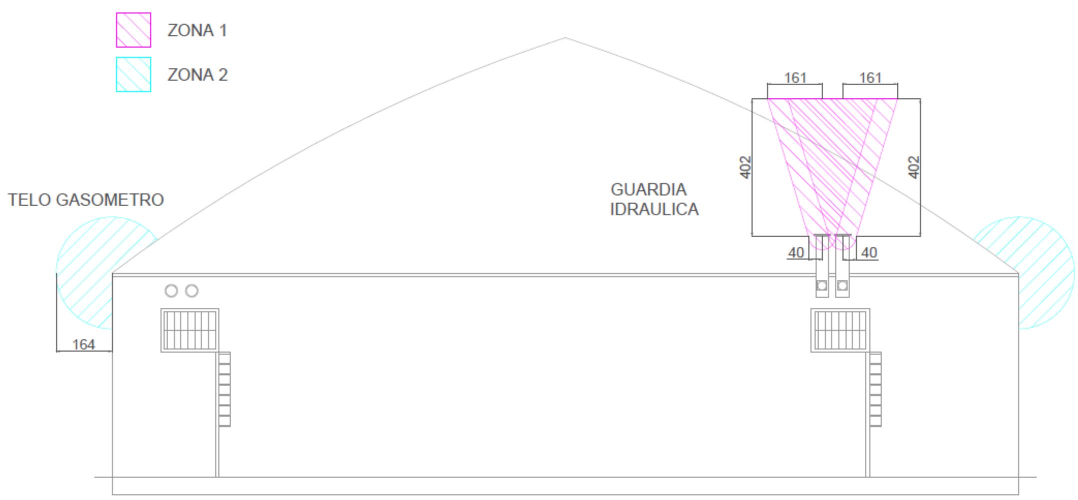
Note – In the event that practical experience shows that, for a given zone, identified in this classification as zone 1 or zone 2, the total duration of explosive atmosphere actually present during the year is longer than that provided for in guide CEI 31-35 for the type of zone identified, it is appropriate to modify the type of that zone accordingly (in zone 0 or zone 1).

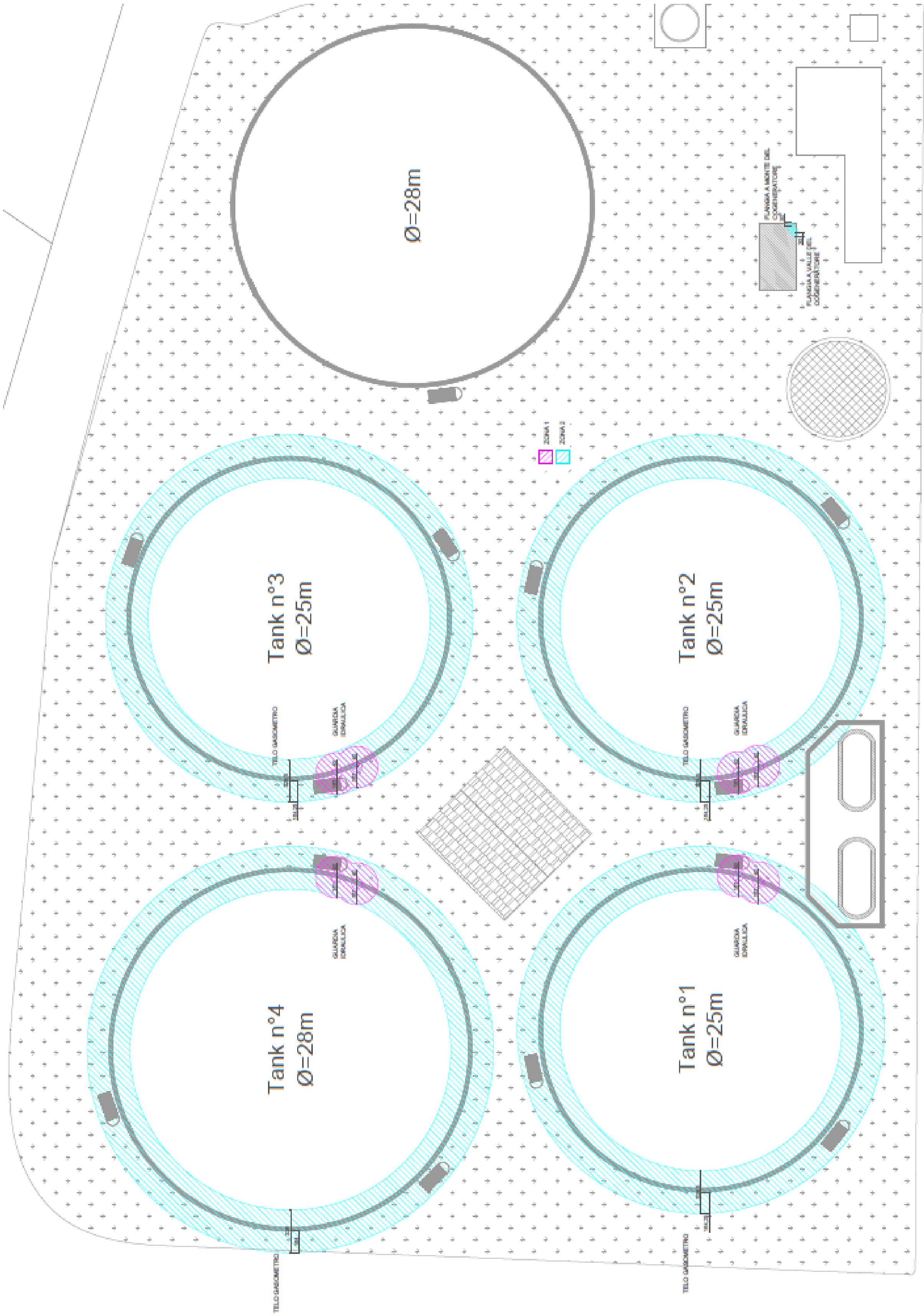
3.4.7 Conclusions

From the above calculations carried out according to legislation, it emerges that:

- for emissions generated by blowers, shutters and flanges, less than a small volume around the emission sources, the whole environment can be considered ordinary pursuant to CEI 31-87.
- for emissions generated by the membrane interface (Zone 2) and the hydraulic guard (Zone 1), the classified zones are quite extensive, but far from possible ignition sources, except for some electrical appliances installed in zone 2, but still suitable for this type of zone.

It is necessary to underline that the interior of the digester, in particular the area of the gasometric dome, where the biogas is contained, is not considered Zone 0 but Zone 2 since it is in saturation conditions (100% biogas). This entails the fact that, under normal operation conditions, the mixture cannot ignite due to lack of oxidizer.




Ø=28m
Tank n°3
Ø=25m
Tank n°2
Ø=25m
Tank n°4
Ø=28m
Tank n°1
Ø=25m

4 Fluid dynamic analysis (current state)

With the aim to evaluate the explosion risk scenarios related to significant losses in the plant, after the determination of the standard climatic conditions found at the production site in Azzano Decimo (PN), several simulations were carried out through fluid dynamic computation (CFD) and, analysing the results, the distances and volumes reached by the "cloud" of biogas leaking from the leakage sources were evaluated.

The critical points identified, as seen in the previous chapter, are many and of various kinds. In order to limit the number of fluid dynamic simulations, whose execution would take several hours, only the leaks from the most significant sources in terms of flow rate and criticality are considered within the modelling. If the magnitude of these scenarios proves to be particularly important, the critical issues considered minor will also be evaluated.

Below is a map of the production site in which the components and critical points are uniquely identified. These are then reported in the following legend, also indicating the color of the relative biogas cloud, in order to make it easy to identify the source. (Figure 55)

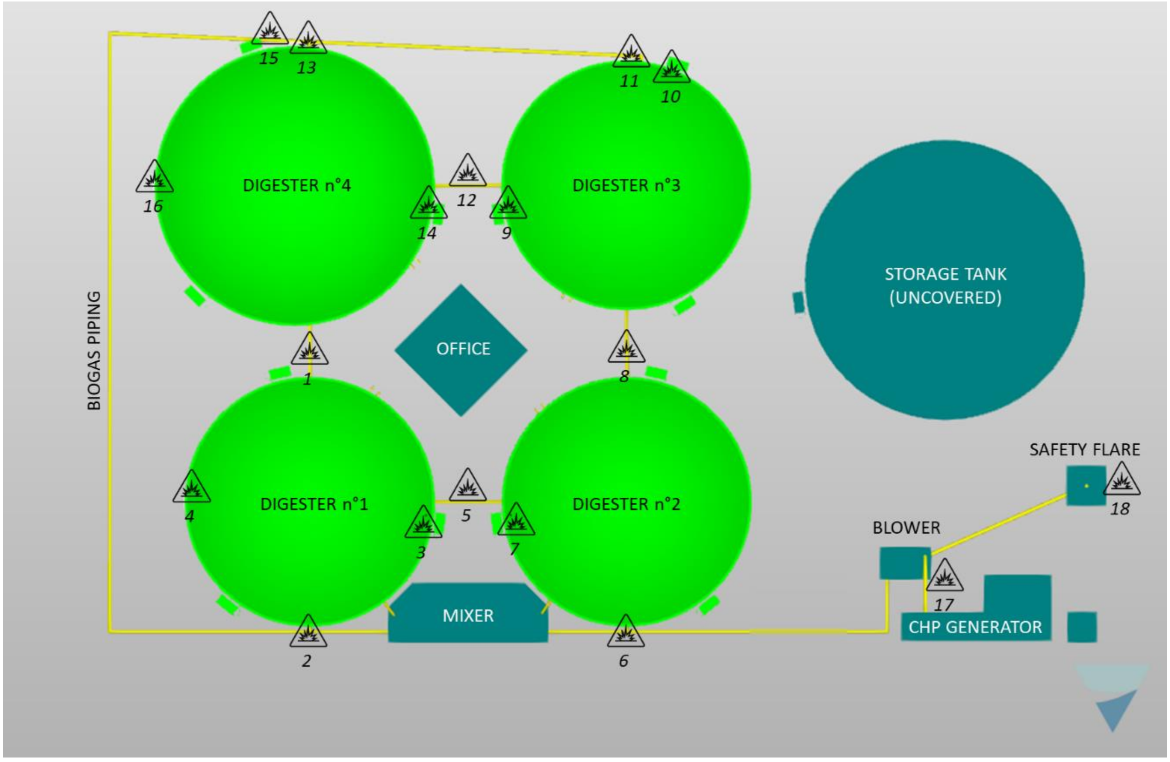


Figure 55: Legenda Plant emission sources

Element	Critical point	ID	Biogas Cloud
Digester 1	Air lift	1	
	Extraction Piping	2	
	Hydraulic seal	3	
	Tarp	4	
Digester 2	Air lift	5	
	Extraction Piping	6	
	Hydraulic seal	7	
Digester 3	Air lift	8	
	Hydraulic seal	9	
	Tarp to silo	10	
	Extraction Piping	11	
Digester 4	Air lift	12	
	Extraction Piping	13	
	Hydraulic seal	14	
	Tarp to silo	15	
	Tarp	16	
Cogenerator	Cogenerator	17	
Flare	Flare	18	

Figure 56: Legend of the emission sources

The model is characterized by the presence of six different biogases, different only in nomenclature but having the same in characteristics and molar mass (Figure 56). The choice to use different biogas comes from the need to reduce as much as possible the variables considered during the simulation. Some of these variables are represented, in fact, by the gases emitted. For an easier reading of the results, it would have been necessary to assign its biogas to each dispersing surface, so as to be able to *"turn it off and on"* and avoid problems related to biogas *clouds* from different surfaces which, however, often tend to overlap. As mentioned above, in order to achieve a small margin of approximation error within a simulation, a high number of iterations involving several hours of processing are required. For this reason, the biogas configuration represented above has been adopted: a configuration such as to reduce processing times as much as possible, also avoiding problems due to the overlapping of clouds. Acting in this way, as can be seen from the results below, each mass of air and biogas around the relative critical points within the calculated explosive limits is clearly distinguishable. It should be emphasized that, if the biogas concentration limit shown falls below values below LEL_V, there would be a risk that the different clouds will no longer be distinguishable from each other because they are too large.

4.1 Introduction to Vento-CFD

The simulations of the different loss scenarios were carried out using Computational Fluid Dynamics (CFD) simulations using the "Vento" software, developed by the software-house Vento Cfd srl of Cagliari (CA) and distributed by CSPFea of Este (PD).

A CFD program allows the analysis of systems involving fluid movement, heat exchange and related phenomena through the resolution of the Navier-Stokes equations and others related to them. This is necessary because, while the analytical resolution of these equations is feasible only in simple cases with laminar flows and simple geometries (spheres, flat plates), the resolutions of real cases, in which turbulent flows frequently appear, necessarily require a numerical approach. (44).

In order to carry out simulations as plausible as possible, the software-house VENTO-CFD has made available to the authors a version of the software currently still under development, characterized by the constant implementation of new improvements.

4.2 Analysis of fluid dynamic simulations

In this chapter it is explained, step by step, the procedure followed, and the reasoning applied for the realization of the model and the setting of the fluid dynamic simulations under study in this thesis paper.

The main tool adopted is the *VentoAEC* software, a program designed to provide a useful tool in the analysis in the field of computational fluid dynamics (CFD). The developers have made a specific software for CFD but Vento, unlike other available software, is able to provide additional working tools. Within the virtual workspace it is possible, even within certain limits, to make changes to surfaces and volumes previously created with 3D modeling software and imported into Vento. It is also possible to directly create volumes and surfaces with simple conformation. For the more detailed realization of the elements to be included in the context of analysis it is, therefore, necessary to rely on third-party software for two- and three-dimensional modeling. *VentoAEC* is designed so that it can accommodate within its *canvas* drawing files made with *.obj*, *stl* and *. plv*.

4.2.1 Realization of the 3D model and import

For the modeling phase of the Azzano Decimo plant and the surrounding buildings, the commercial application software for the 3D modeling of Rhinoceros surfaces (Rhino 7) was used, which allows to create volumes, objects and even more simply surfaces. Because of the needs of surface processing and simulation development timing, the different buildings surrounding the plant were represented only by simplified volumes, and as regards the plant and its critical points the level of detail was raised while still aiming at a simplified representation of the complex. It is crucial pointing out that all the dimensions of all the objects shown in the model are adherent to reality as they have been reconstructed as a result of surveys carried out directly in the field or through an analysis of the existing documentation provided directly by the operators of the Azzano Decimo plant itself.

The model made containing the various surfaces was then exported in *.obj* format. This type of file is characteristic of three-dimensional models to which three coordinates are attributed for each vertex present and is composed of basic elements such as points, lines and planes. The file is realized using several numbers of elements (polygonal meshes), depending on the definition it is demanded to adopt during the export phase. This affects the graphical representation of lines: this definition is more marked with curved lines or surfaces that are reduced to polygons with more or less sides. The discretization of the elements leads to the creation of a model that par excellence is less precise than the real and that, although it could represent a disadvantage from the graphic point of view, as regards the computational aspect makes it more manageable both for VentoAEC and for other programs.

The phase of realization of the surfaces assumes fundamental importance, in fact anticipating what will be discussed in the next paragraphs, it is appropriate to warn that due to the simplification of the model at the time of the creation of *the .obj* it could be possible that an inaccurate drawing would lead to the production of surfaces intended as in perfect contact but that in reality for small inaccuracies are such. The presence of these *defects* can lead to the realization of a grid of cells that is not really precise and heavier than necessary because it is also extended to areas where there are no fluids useful for analysis. For this type of work, a precaution of this type was taken during one of the first stages of plant modeling because the grid extended to the inside of the digesters causing an important overload if it is considered that the cells are arranged by filling the entire volume of the digester. It is therefore important for the effectiveness of simulations to ensure that all contiguous surfaces are such when modelling.

When the program starts, this immediately makes visible in its three-dimensional workspace what it defines as *a bounding box.* This *box* represents the domain (parallelepiped shaped) within which the fictitious atmosphere is located and where all the simulations take place. The program allows to change the size of this element. It is crucial to consider this possibility as a *bounding box* with dimensions limited to those of the analyzed lot could be the cause of untruthful results due to the influence of the proximity of the analyzed surfaces and the faces of the domain, which would lead to the materialization *of edge* effects with consequent negative influences on the real behavior of the model. To avoid problems during the resolution of the simulation, in this case the domain is sized well beyond the initial measures set by the software with sides in the horizontal plane of 5km and a height of 500m (Figure 57).

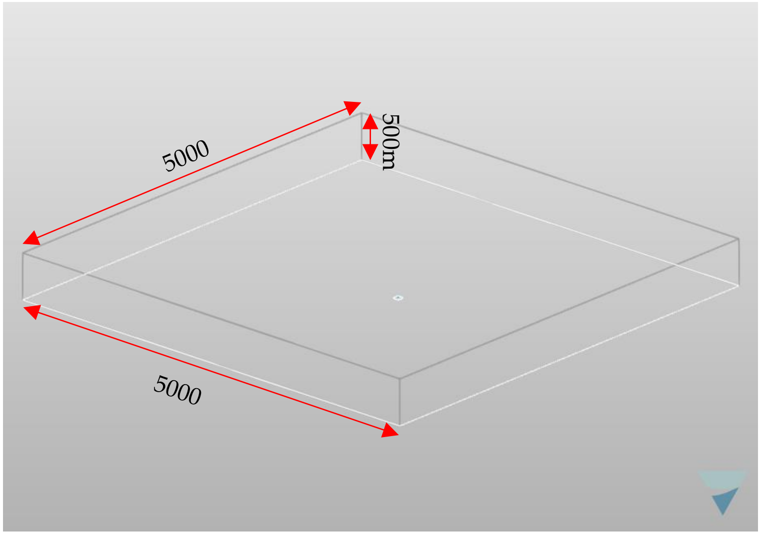


Figure 57: Bounding-box

Below is the graphic representation of the flow field (plan view) of a wind of 17 m/s in a 315 ° direction at an altitude of 0.1 m where it is made evident that along the edges crossed by the incoming wind, the speed is not immediately constant but much lower (about 7 m/s). While approaching the plant (in the center of the box) the speed reaches the maximum value achievable if the aerodynamic effects are considered, including the aerodynamic roughness of the ground, which limit the wind speed as the ground is approached (Figure 58).

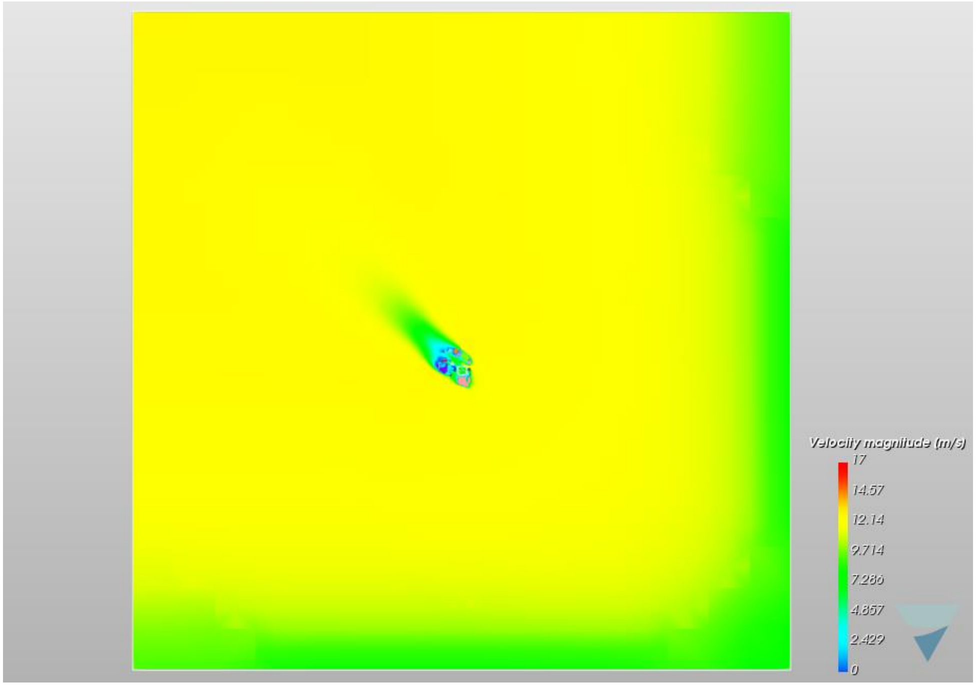


Figure 58: Velocity magnitude for board effects

During this phase the starting mesh or grid is made which has been implemented through the next steps. There is no need to create a very dense initial grid, as if excessively rich in cells, it could slow down or stop (depending on the computing capabilities of the computer used), the calculations during the simulation. As for this work, the assumed starting grid consists of 8x8 cells in the plane parallel to the ground and 8 cells in height (along the Z axis) (Figure 59). These values represent, following the implementation of the network, the number of cells along the edges of the grid away from the surfaces and where their presence has irrelevant effects for the purposes of the simulation.

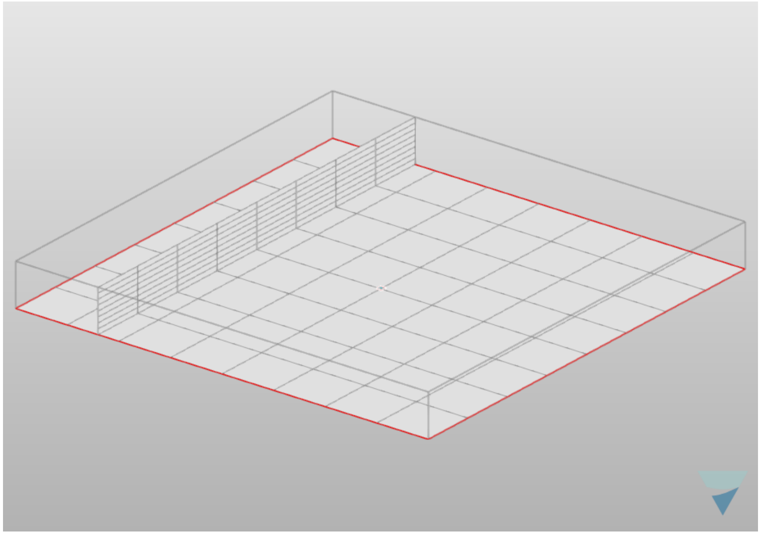


Figure 59: Preliminar grid

The grid configuration is followed by the addition of the surfaces submitted to the analysis. When the *.obj* file from Rhinoceros has been imported into the program, all surfaces are automatically converted and saved to *.stl* format files (STereo Lithography interface format or acronym for "Standard Triangulation Language"). This type of file is very similar to the . *obj* previously described and is the final format adopted by Vento. To the lower face that's parallel to the XY plane of the domain as well, Vento attributes by default the *ground* function, the model therefore, if not already in place, it must be rotated and translated in such a way as to make the ground level of the model coincide with that of the domain and in order to center the site. The translation of the model along Z must be done by virtue of the fact that any surface intended as outside will have to be at a Z altitude greater than zero. According to what has been said, the underground pipes made for the Azzano model have been placed under the ground and therefore appear outside the box and are not taken into account during the analysis.

Once the surfaces concerned have been imported into the model and positioned correctly, to simplify the reading of the results and the assignment of some key parameters for the simulation, families are produced to which associate all the surfaces of the model, through the *surface selection* tool. This is done considering criticality assigned to the surface, importance in the accuracy of the results and proximity to the source of risk.

Conventionally the whole model has been divided into:

1. Digestor;
2. biogas piping;
3. biogas facilities (the component of the plant responsible for the treatment of biogas extracted from digesters);
4. garage;
5. silo;
6. trench;
7. cellar;
8. residential/office buildings;
9. barn;
10. stable_0;
11. stable_1;
12. stable_2;
13. stable_3.

With the new families of newly made surfaces, the program updates the *.stl* files producing only one file for each family. For time optimization, these files are copied and imported into all domains of all simulations carried out with biogas and biomethane as a contaminant.

4.2.1.1 Implementation of geometries and grid

Simultaneously with the creation of *the bounding box,* VentoAEC reproduces the first *refinement window* automatically associated with the plane called *ground*. The *refinement window* corresponds to a specific area delimited, in fact, by this refinement window in which the cells that are made afterwards are thinner and denser so as to make the resolution of the problem more precise. These elements can be assigned to volumes of different shapes, to surfaces or, as is useful in this case, directly to the surface that the software recognizes as *ground*. For the creation of this *window* the program requires the definition of a height assigned to the *refinement window* and the characteristic dimensions X_{ref}, Y_{ref}, Z_{ref} that characterize the size of the cells in the three directions.

These three values represent the maximum size of the cells contained in the *boxes* and which must be guaranteed during the realization of the grid.

The subdivision of surfaces into families performed previously is exploited at first during the initial setting of the maximum size of cells in direct contact with all surfaces both in *the normal* and *tangential* direction (this corresponds to further refinement of the cell size). These two values can, therefore, be assigned at once to all the surfaces belonging to the same family, greatly reducing the time of realization of the model. Surfaces number 1 to 5, which are considered more critical as they represent a greater source of danger due to the equipment present, the processes carried out and possible failures, are characterized by a smaller normal cell size (2m). As for the remaining surfaces, the *normal* has a larger size (3m). This second measure leads to a lightening of the load during the calculation and computation since the number of cells adjacent to the *less critical* surfaces is lower. For the elements mainly under study, a thickening of the cells in this direction is imposed because with the progressive approach to the surface, the wind speed is reduced to the point of canceling out and precisely in the first layers of air in contact the gradient of the air speed is very high. Subsequently, for all surfaces a single *tangential* value is also set, this factor sizes the cell in a tangential direction to the surfaces with which it is in contact (10m). In this case, since there is no prevailing direction for surfaces and there is no wind flow in a single direction, a larger size than *normal* is resorted to because the thickening of this type leads to an overload of cells. Otherwise, for the analysis of bodies having surfaces with a main orientation and placed inside a wind tunnel or in contexts where the wind blows only in one direction, it would be more appropriate to also reduce the tangential component with values lower than those chosen for this case.

For what concern the geometries to be included in the model, the latest development is related to the realization of the *surfaces* to which the task of emitting the gas in a controlled manner will be assigned as to simulate the continuous and regular dispersion. This task is given to circular or rectangular surfaces depending on the geometric conformation of the dispersing point, of variable dimensions (which will be explained below). The realization of these sections takes place in different ways according to the type of dispersion hypothesized:

- in the case of pipes such as *airlift*, *pipe* and *cogen*, a rupture is assumed to have occurred due to the impact caused by the wheel loader operating in the digester area. The pipeline, for this reason, is separated and emitting gas in both directions due to the operating overpressures. The realization within the software takes place through a circular surface set in the software as an *inlet* surface and characterized by *velocity magnitude* and *temperatures* and having the same orientation as the real critical section (Figure 60).

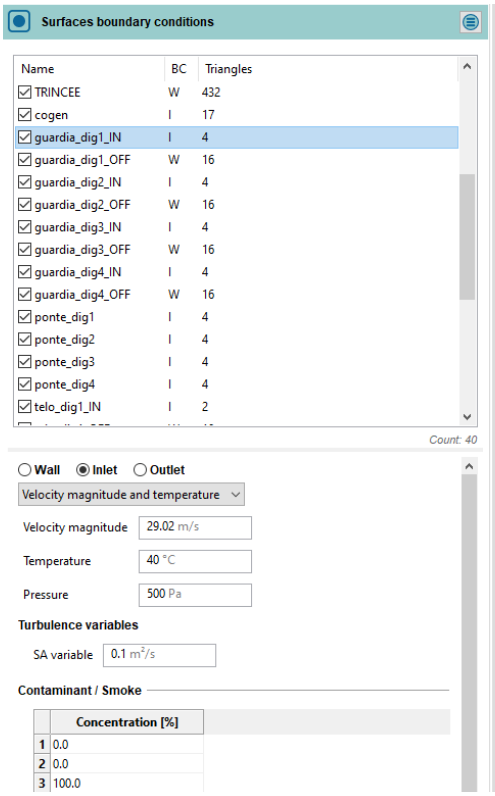


Figure 60: Surface boundary conditions setup

In doing so, the software considers that the section emits the gas with a constant velocity equal to the one set, in the direction normal to the surface (for both sides of the surface) and with a constant temperature. The next image shows a section of this type associated with a representation of the speed of fluids (the surface emits gas in both directions and with the same speed) (Figure 61).

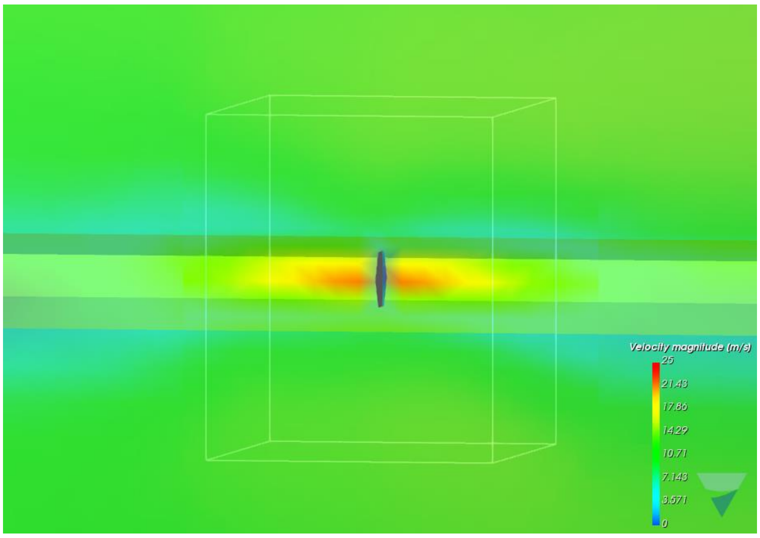


Figure 61: Velocity magnitude for dual-emitting surface

- regarding the pipe connected to the *safety flare*, it is hypothesized that due to a disfunction of the ignition, gas conducted towards the flare is released but not immediately burned, so as to create a cloud with a high concentration of potentially flammable and explosive gas. For the realization of this surface, considering that it is intended to emit in a single direction directed upwards, a cylinder was made. The upper circular face was assigned the task of emitting the gas with constant speed in the positive Z direction and with preset constant temperature (*velocity magnitude* and temperatures) the remaining surfaces of the cylinder were indicated as *walls* so as not to allow the passage of any gas and thus allowing the emitting surface to disperse the gas in only one direction. The image below shows the surfaces just described associated with the safety flare. The gas, in this case, is released in only one direction. The presence of the underlying surface means that in the lower face of the emitting surface there is no fluid. (Figure 62)

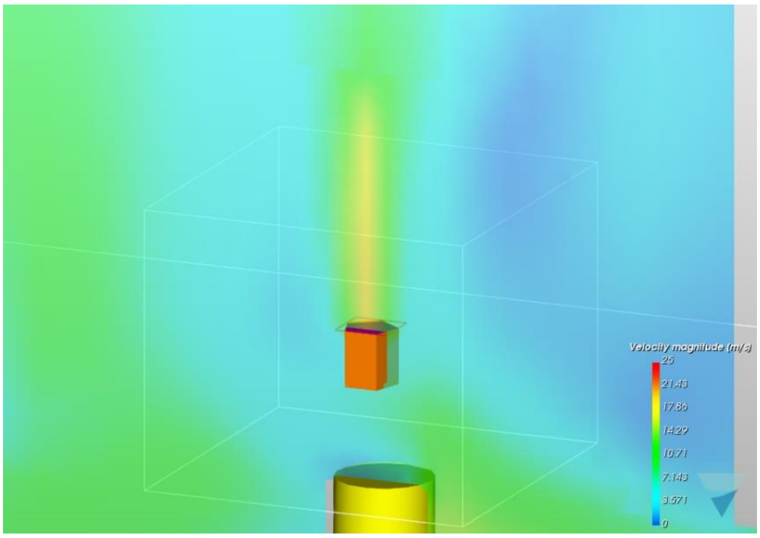


Figure 62: Velocity magnitude for single-emitting surface

- the surfaces made to simulate a dispersion due to the rupture of the tarpaulin-masonry junction have been designed in the same way as the *flare*. The causes associated with such a break are traced back to poor maintenance of the tarp that due to UV rays loses its elastic properties or to the efforts induced by extreme weather conditions. The section, however, has been modeled as a parallelepiped.

Below are the dimensions of the sections adopted for the emission of biogas or *contaminant*. (Table 7)

Table 7: Emitting surfaces geometry

Element	Critical point	ID	Shape	Dimensions [cm]
Digester 1	Air lift	1	Circular	22 Ø
	Extraction Piping	2	Circular	20 Ø
	Hydraulic seal	3	Circular	20 Ø
	Tarp	4	Rectangular (box)	1.5 x 0.2 x 0.1
Digester 2	Air lift	5	Circular	22 Ø
	Extraction Piping	6	Circular	20 Ø
	Hydraulic seal	7	Circular	20 Ø
Digester 3	Air lift	8	Circular	22 Ø
	Hydraulic seal	9	Circular	20 Ø
	Tarp to silo	10	Rectangular (box)	1.5 x 0.2 x 0.1
	Extraction Piping	11	Circular	20 Ø
Digester 4	Air lift	12	Circular	22 Ø
	Extraction Piping	13	Circular	20 Ø
	Hydraulic seal	14	Circular	20 Ø
	Tarp to silo	15	Rectangular (box)	1.5 x 0.2 x 0.1
	Tarp	16	Rectangular (box)	1.5 x 0.2 x 0.1
Cogenerator	Cogenerator	17	Circular	20 Ø
Flare	Flare	18	Circular (box)	10 Ø x 0.1

All the above surfaces have been assigned a *refinement window with the 0.5m side and with X, Y* and *Z refinement* equal to 0.1m in order to ensure a surface coverage of at least 2 cells. The following is the *refinement window* of the critical point *Extraction pipe* from Digester n°2. The emitting surface corresponding to the impacted tube is placed in the center of the box and is covered by at least two cells in all three directions. The lower level of the domain is also made visible, that is, the *ground* and the pipes that circulate below it, as mentioned above these elements are not considered during the simulation because they are isolated from any effect of the wind. (Figure 63)

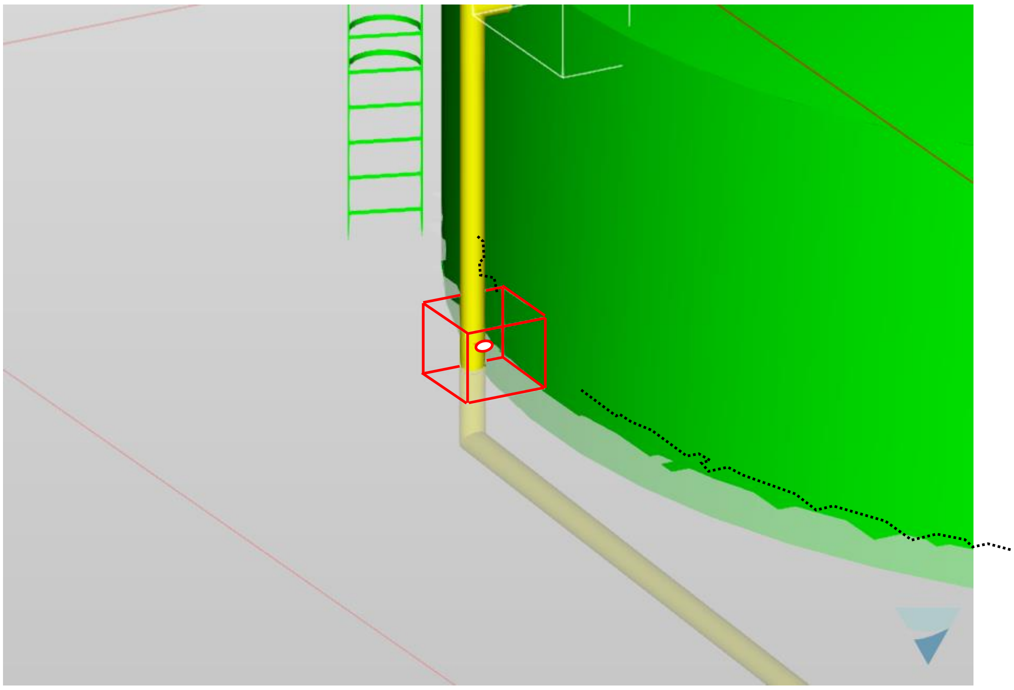


Figure 63: Refinement window for biogas piping

The second last step before starting the creation of the final grid consists in the insertion of a *refinement window* for the surfaces that are part of the D*igester* macro group, that is, elements that represent surfaces of strong interest during computational analysis. This is done by applying an offset of 3 meters to the windows so as to include even a small surrounding volume. (Figure 64)

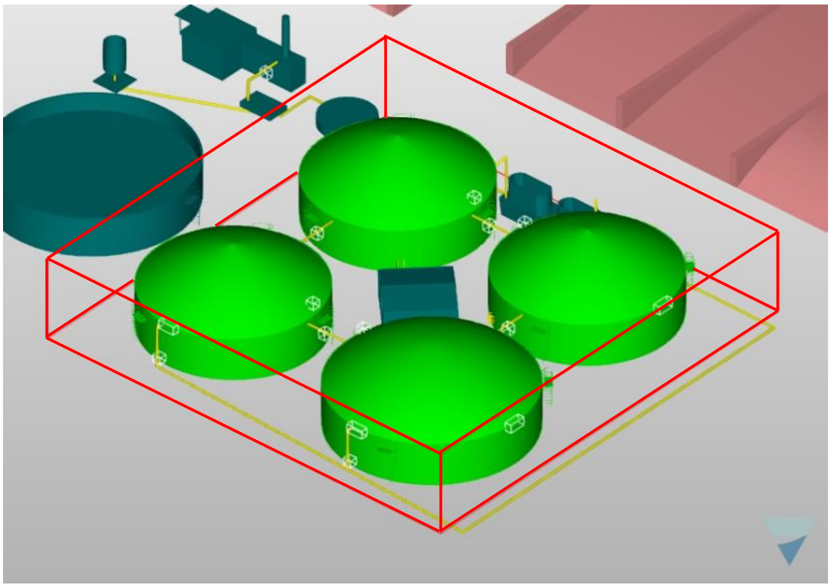


Figure 64: refinement window for surfaces assigned to digestors

The implementation phase of the starting grid (8x8x8) concludes by defining how gradually the cells vary in size as they move away from the surfaces. The software offers different degrees of *density* from the “rawest” to the most "refined": minimum – low – medium – high – maximum. As far as this project is concerned, it was decided to proceed with a *high* density which allows to obtain a sufficiently gradual trend while maintaining, however, an acceptable and workable number of cells.

Below is a planimetric comparison between a *minimum* and *maximum* grid density extracted directly from Vento (Figure 65 and Figure 66)*:*

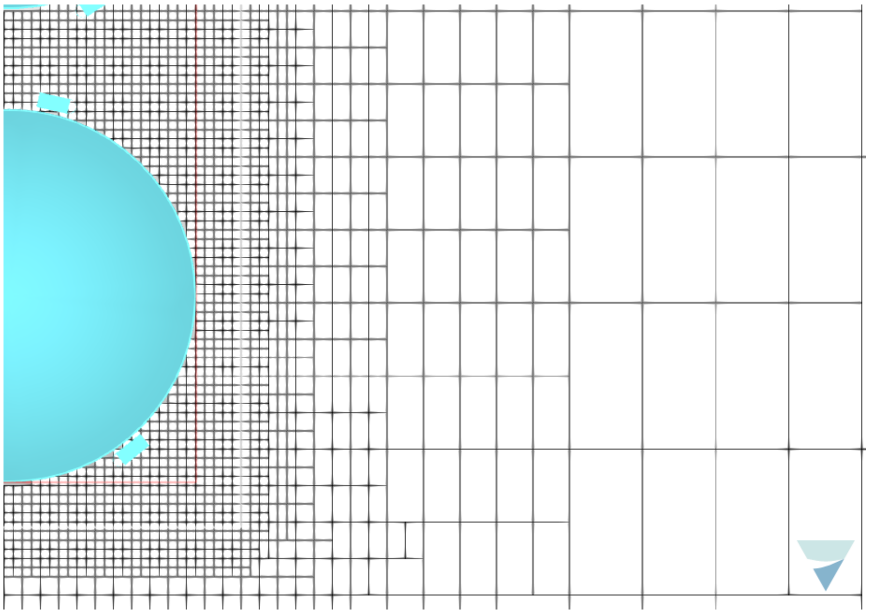


Figure 65: Minumum grid density

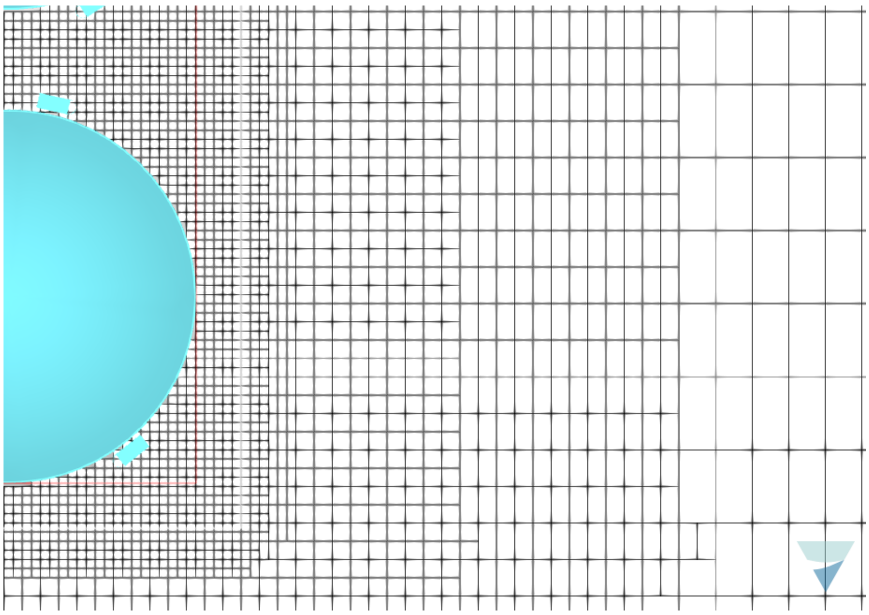


Figure 66: Maximum grid density

It is possible to see how small cells tend to thin out more easily with a minimum level.

At this point the final grid is achievable. The tool that allows to generate it is called CGG (Cartesian Grid Generator). During this process, the software makes visible a written and progressively updated report (called Grid Generator Log) that shows information regarding the number of cells on surfaces and Refinement Windows. The report (or *log*) lists what are referred to as *fluid* cells and *solid* cells. The former, which normally represent the vast majority, are those used for the discretization of the atmosphere while the latter are those associated with all surfaces.

During the grid setting processes some considerations have been done on what was the most suitable quantity of cells for the purpose. For this type of model, with the help of the VentoAEC team, it was agreed that a number of cells between 1 and 3 million is sufficient for a good definition of surfaces.

The choice of the optimal number of cells to carry out the simulations of the site of interest was made through considerations relating to computer power, accuracy of the results and relative processing times. To have a comparison sample, two identical simulations were performed for boundary conditions and .stl model but different in number of cells; the first with about 1.5 million cells and the second with 3 million cells.

The conditions applied are as follows:

- emitting surfaces: Airlift digester 1 and Digester pipe 1;
- biogas concentration: both 100%;
- biogas emission speed: 25 m/s;
- emitted biogas temperature: 36°C;
- wind speed: 17 m/s;
- wind direction: North-West;
- atmospheric temperature: 5.3°C;
- atmospheric pressure: 99797Pa;
- aerodynamic roughness: 0.1m;
- reference height (for logarithmic wind profile): 10m;
- Von Karman's constant: 0.41;
- iterations: 1500;
- CLF Number: 100.

The simulation with 1.5 million cells, managed by a PC with a RAM memory of 8Gb, took about 7 hours and on average 18 seconds per iteration against the simulation of 3 million cells that required 16 hours of processing (with a computer with excellent performance) and 38 seconds per iteration on average.

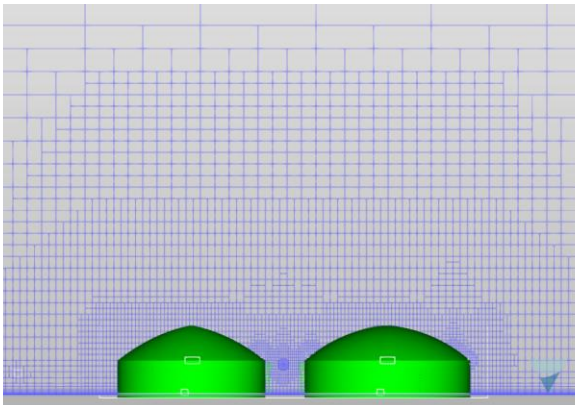
The choice to adopt an average dense grid (1.5 million cells) has clear consequences on the accuracy of the results. The machines available for the execution of the various simulations have made it almost mandatory to choose the aforementioned grid as a thicker mesh would have led to much longer processing times than those spent on the simulations that are analyzed in the next part of the work. This work, in fact, aims to study how an engineering approach of this type could be applied to a sector where most of the plants are very similar and for which the regulatory approach is the most used, using a software that for this type of studies has never been adopted.

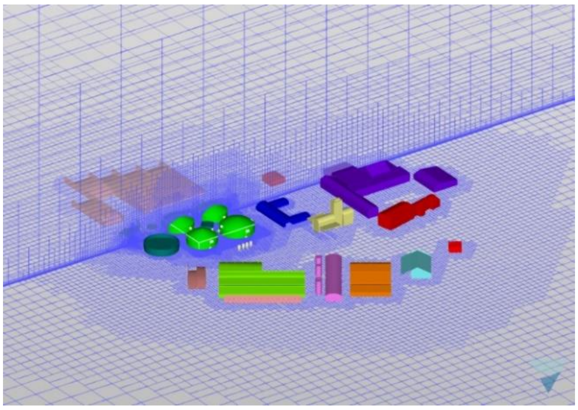
For the reasons given in this pragraph and for needs related to the capabilities of the computers used during this work, the accuracy of the results plays an almost secondary role, giving greater importance to the proposed method.

The time spent during the grid creation, of course, depends on the number of cells that will compose it, the CGG is able to produce a dense grid with a few million cells in a matter of minutes. Recalling what has been said in the paragraph on the creation of surfaces, once the mesh is ready it is necessary to make sure again that the model is made so that all the volumes conceived as *closed* are such. To do this it is recommended to reduce the opacity of the surfaces, this will allow to look *through* them and check that the grid was made exclusively outside all closed bodies. If this does not happen, it is preferable to better define the model to take advantage of 100% all the cells created and make the creation of the grid more effective, thus avoiding working even on unnecessary cells.

Opening, therefore, the grid display it is observable the results of the variations on *density*, *normal*, *tangential* and everything that has been set previously. It is also possible to translate and rotate the grid just to observe the development of the cells both on the XY, XZ and YZ planes. As mentioned above (and visible in the images concerning the *grid density*, Figure 65, Figure 66) the size decreases and the number of cells increases, as a surface is approached, the settings adopted previously mean that the dimensions of the cells in contact with the surfaces are not all the same but change according to the *normal* assigned to each surface.

Below are some views extracted directly from the software to help clarify how cells are distributed across all floors (Figure 67). Getting closer to the different surfaces the cells start increasing in number and decreasing in size, this variation becomes more evident once close to *the refinement windows*. All this applies both horizontally and vertically.





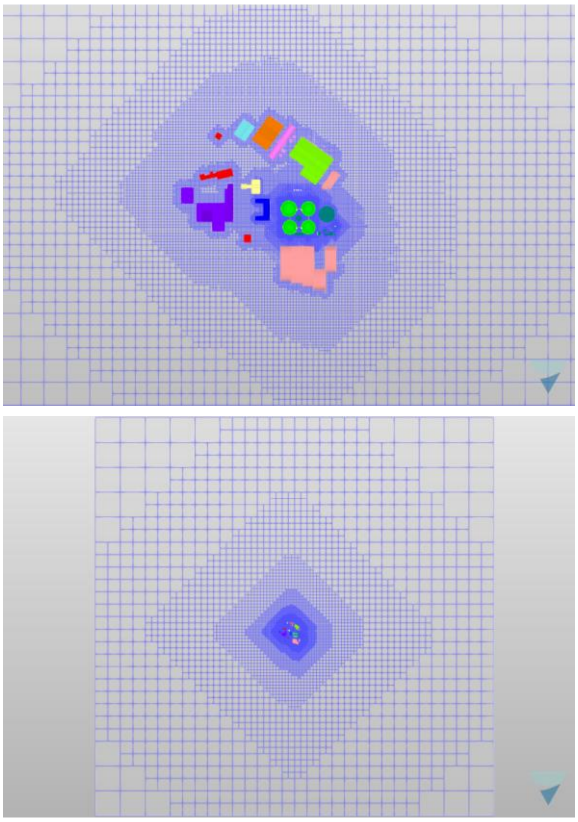


Figure 67: Definitive grid view

4.2.1.2 Definition of Boundary Conditions

With the completion of the grid definition, move on to the setting of the first boundary conditions for the resolution of the fluid dynamic calculation such as gas characteristics, wind and air conditions.

Starting from the *fluid* section it is possible to set which model to adopt for the simplification of possible turbulent motions. The program offers two possible choices between the *K-espilon* and *Spalart-Allmaras* models.

The first option (K-epsilon) allows to approximate the turbulence also using two equations related to the dissipation of the energy of turbulence and the kinetic energy of turbulence, this is often used as it represents one of the most long-lived and still adopted models.

The second method (Spalart-Allmaras) is among the most recent models and is also the most suitable for the work in question as it is widely used in the most disparate sectors thanks to its stability. With this method, based on an equation, it also arrives at the resolution of a balance equation linked to *turbulent viscosity.*

Remaining in the same section, it is essential to demand the program to consider what is called *buoyancy*. With this tool it is made so that during the simulations the software considers all the effects deriving from the attraction of gravity, the motions of the different fluids with different densities and of the layers of fluid with different temperature and therefore different specific gravity.

The last phase related to the characterization of the fluids involved concerns the modelling of gases or *contaminants*. To do this it's necessary to select in this section the item: *coupled*. This tool means that in addition to the air already considered, the software also takes into account the presence of additional gases (intended as ideal gases). In fact, selecting *coupled* becomes accessible a predefined list of gases (in the software they are referred to as *contaminant/smoke*) characterized by their molecular mass. It is possible to implement this catalog with "customized" gases simply by indicating their molecular mass and assigning it a name.

As far as this simulation is concerned, biogas is considered as *a contaminant.* And if it is a mixture composed of a large number of gases with almost 99% represented by the CH_4-CO_2 mix, only these two species are considered, approximating biogas to a mixture consisting of 60% CH_4 and 40% CO_2. The molecular mass of this biofuel is obtained by weighing the molecular weight of the respective components based on their presence as a percentage.

Considered a mass expressed in UMA (Atomic Mass Units), the molecular weights considered are the following: (45):

- molecular weight Carbon Dioxide: 44.01 *uma*;
- molecular weight of methane: 16.04 *uma.*

The molecular weight of the CO_2-CH_4 mixture is calculated as follows:

$$(44.01uma \times 0.4) + (16.04uma \times 0.6) = 27.2uma$$

The value of the average molecular mass of biogas with the above concentrations is therefore 27.2 *g/mol* or *kg/kmol*.

For this type of analysis, considering the time required for each simulation, it was decided to create and adopt n°6 distinct biogases equal in chemical characteristics but different only in nomenclature: from 1 to 6. This measure has been taken in order to reduce the time taken for each simulation. Following initial attempts, it was found that the times for each simulation expand, even by several hours, if the number of gases is high. Six gases were made because it is the minimum manageable number for obtaining readable and unambiguous graphic results. For each simulation, in fact, all the critical points listed above are analyzed and to avoid those outgoing flows from nearby points can mix each other, not allowing a precise analysis of the dispersion of the gas from each critical point taken individually, it was decided to associate the various gases in an arbitrary way trying to keep the points that emit the biogas with the same identifier as far as possible. During the choice of gas-critical point associations, possible "interweaving" between the flows under different wind conditions was considered.

The last phase of fluid characterization concerns the definition of the *air* model. The software inserts by default, in the atmosphere of the domain, an air with characteristics measured in what are called standard conditions (100000Pa and 25 ° C). During this work, the air characteristics proposed by the program were maintained. The latter, if necessary for the purpose of analysis of a very different type from the current one, also allows to modify these characteristic values such as *viscosity, Prandtl number and specific heat*.

4.2.1.3 Definition of atmospheric conditions

The definition of the boundary conditions continues with the characterization of the wind acting on the model. Based on this factor, following the model setup phase, the different simulations are carried out.

In the *Flow condition* section, it's possible to set: temperature, speed, wind direction, pressure and variable SA (Spalart-Allmaras variable, used to characterize turbulence and assumed equal to 0.00001). The desire to analyze the most disparate representative cases led to the decision to perform an analysis of the climatic conditions of the place so as to define realistic and most varied scenarios possible.

One of the fundamental steps of this simulation is the choice of atmospheric conditions to be attributed to the context under study.

4.2.1.3.1 Wind speed

The first element analyzed within the *.epw* file. concerns the choice of weather conditions attributed to the different simulations performed. This is done by giving importance, in the first place, to the *speed of the wind*.

Particular importance is given to the effects that the more or less high speed of the wind having an influence on the dispersion of the gases in play, (with the same gas flow rate and time interval, a wind with greater intensity allows a wider distribution of the *contaminant* but with lower concentrations while a wind with a lower speed will lead to the accumulation of gas in less extensive areas and closer to the source but with much higher concentrations).

The values searched among all those recorded were:

- 17 m/s (detected on 9/Aug at 01:00), corresponding to the maximum speed recorded and reported in the climatic file;
- 2.67 m/s corresponding to the average speed between all recorded and non-zero values and approximated to 3 m/s (recorded on several days during the year) (wind speed values are expressed in whole figures);
- 0 m/s (recorded on several days during the year) as the absence of wind combined with the leakage of gas with speed could lead to very interesting scenarios for this type of analysis.

Below is the wind rose chart with the representation of the different wind directions reported on the .epw file (Figure 68).

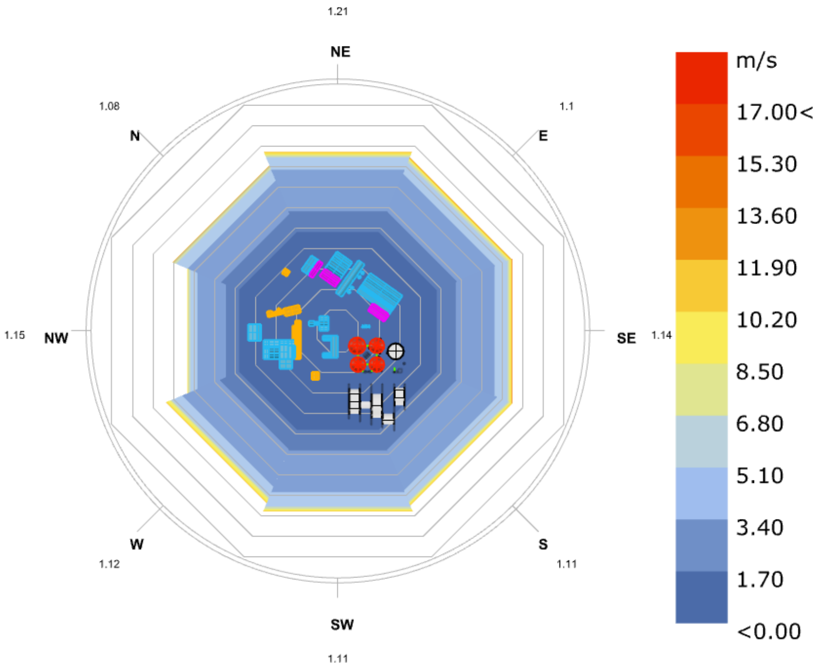


Figure 68: Wind rose characteristic of the production site

The graph attached above shows the wind rose oriented according to the cardinal axes and complete with representation of the average speeds calculated for each selected orientation. Being an arithmetic average, in this case the situations in which the wind is zero are also taken into account: for this reason, the values next to the cardinal signs can appear very low.

As visible from the graph, among the various orientations shown never stands out a particularly unfavorable value from the point of view of speed (i.e. "unfavorable" if the intent to analyze the *worst possible scenario* is considered), moreover the wind blows more frequently in the direction of areas where the presence of people and buildings is practically nil. With the will to analyzing the *worst possible case*, the direction of the winds was therefore assumed arbitrarily so as to simulate scenarios that most affect those that have been identified as *critical points*. In this regard, the selected directions will be North, North-West, North-East.

4.2.1.3.2 Outdoor temperature

One of the last boundary conditions that are imposed concerns the atmospheric temperature which, at the time of emission of the gas, will lead to a variation in the temperature of the biogas affecting the density of the latter. For this reason, the different simulations were carried out taking into account this additional condition. For this purpose, the two extremes of temperatures are considered, namely the summer case and the winter case.

Based on the previously carried out climate analysis, the selected temperatures are:

- the maximum recorded: 32.6°C, on 12/July at 14:00;
- the minimum recorded: -9.3°C, on 10/January at 07:00

The decision to take two temperatures at the extremes is made in anticipation of the fact that the effects of the temperature of the air-gas mixture over the two days could lead to different dispersions of the mixture due to their difference in density. This difference will be observed during the analysis of the results.

4.2.1.3.3 Atmospheric pressure

The atmospheric pressure assumed and used in the model is equal to 99797Pa and is considered constant throughout the year.

4.2.1.3.4 Definition of the simulations

The configurations of the simulations that have been performed are showing the table below (Table 8):

Table 8: Scenarios configurations

Temperature	Air pressure	Wind speed	Wind direction	ID simulation
-9.3°C	99797 Pa	17 m/s	N-O	1
			N	2
			N-E	3
		3 m/s	N-O	4
			N	5
			N-E	6
		0 m/s	/	7
32.6°C	99797 Pa	17 m/s	N-O	8
			N	9
			N-E	10
		3 m/s	N-O	11
			N	12
			N-E	13
		0 m/s	/	14

In addition to the primary factors considered, in a simulation in which the wind acts, the effect of the soil on it and its speed must be considered. To this end, inside the VentoAEC control panels it is necessary to set the parameters that influence the logarithmic profile of the wind speed assumed for the calculation of the average wind speed at the height *h,* like:

- adiabaticity of the ground;
- aerodynamic roughness: the program suggests some ranges of values depending on the type of context surrounding the surfaces under study. A value of 0.1m can represent a value appropriate to the rural context in which the plant is situated;
- the reference height, equal to 10m;
- Von Karman's constant: assumed equal to 0.41.

This type and type of profile are used to estimate the average wind speed at a given height and is based on a logarithmic profile approximation limited within 100 meters of ground level. The scale of representation adopted in this graph divides into colors a range that starts from 0.1m/s, defined by the color blue, to 31 m/s represented with red (Figure 69).

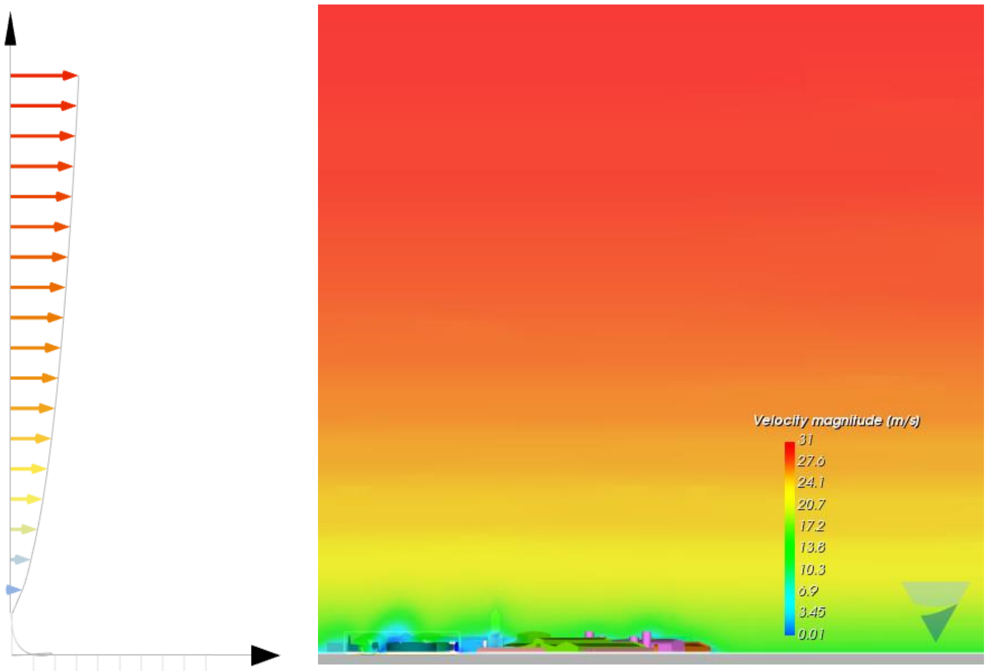


Figure 69: Logaritmic wind profile

As anticipated in the paragraph concerning the realization of the emitting surfaces (4.2.1.1), these must be indicated in the *surface b.c. section.* as *inlet* surfaces. Each of these elements will be assigned a gas outlet speed (the exit direction corresponds to the normal of the emitting surface), a temperature of the emitted gas and factors not useful for the purpose. Each *leak section* was assigned 29.02 m/s as speed and 40°C temperature.

The numerical value of the gas outlet velocity was defined thanks to Bernoulli's Theorem, i.e. the fluid dynamic relationship that binds together the sliding velocity, pressure and density of a fluid:

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

Where the terms:

- *p1* and *p2* represent the fluid pressures in section 1 and section 2, respectively;
- *ρ is the density of the fluid. For biogas it corresponds to 1.1 kg/m^3;*
- *v1* and *v2* represent the fluid velocities in section 1 and 2, respectively;
- *h1* and *h2* represent the altitudes of the two sections.

Imposing some initial hypotheses such as:

- *h*1 and *h*2 correspondents;
- *p1* equal to 5mbar + *p2;*
- *v2 equal to zero.*

the equation, if elaborated, leads to the numerical quantification of the gas emission velocity, in this case it is equal to 29.02 m/s.

The temperature was assumed to be 40°C by virtue of the fact that the anaerobic digestion process practiced in the Azzano Decimo plant corresponds to a mesophilic process with a temperature range between 35°C and 40°C.

Finally, the *inlet* surface must be characterized by the concentration of gas from which it is crossed. Considering a flow of only biogas inside the pipelines and bio-digesters, the concentration is 100%.

For all remaining surfaces, the section on the element type falls on *the wall*. In this way the software considers this object as static and not traversable by any fluid. The only customizable values concern the roughness of the surface finish and a possible flow of heat through it.

As far as roughness is concerned, a zero value is chosen for all surfaces considering that the finish of the buildings is more or less homogeneous and for the purposes of the work has no particular influence on the masses of moving air. As far as the heat flow is concerned, it is necessary to make considerations related to the period of analysis and the type of building. Each surface can be characterized by imposing a constant heat flow or temperature. In this case, all open buildings (such as *stables* and *garage*) which therefore have an internal temperature very similar to the external one, are referred *to as adiabatic*. Considerations made at the beginning on the possible influence of the surface temperature of the buildings around led to the choice to adopt as "adiabatic" also *residences, offices and cellar* simplifying the process on the prediction that the influence of these surfaces is not detectable at this level of detail. The gas distribution system consists of well thermally insulated pipes that are only partially above ground (so only that small amount of pipes is inside the *domain box*), this leads to a very low heat loss, even with very high temperature gradients. Considering the mass of gas constantly present inside the digesters and the thickness of insulation used along the entire wall, only the *digesters* were characterized by a constant temperature of 25°C.

If during one or more of the steps explained above, a geometry or a characteristic factor of the grid has been modified, the creation of a new and updated mesh is an obligatory step in order to a truthful and accurate analysis.

4.2.1.4 Starting of the simulation

The simulation phase performed by VentoAEC consists of an iterative process of solving the following partial and discretized differential equation:

$$\frac{\partial Q}{\partial t} = -\frac{\partial F(Q)}{\partial x_j} + S \equiv RES$$

where Q represents the vector of dependent variables: velocity (all three of its components), pressure and temperature and possibly the equation related to the model for turbulence (as mentioned above, in this case the model is Spalart-Allmaras) and the equation of the passive scalar where S it is a source term, dependent on molecular and turbulent viscosity, as well as on the average vorticity and distance from the wall and RES corresponds to the *Residue* that is the one that can be approximated as *an error*. VentoAEC is therefore designed with the aim of solving this equation for a static condition (*steady-state condition*) through the resolution of $Q(x,y,z)$ and that tends to satisfy the condition $RES(Q)=0$. To do this, an iterative *Gauss-Seidel* resolution algorithm is applied.

In the *simulation* section there are some parameters to set.

- *Iterations*: Introduced previously, correspond to the number of steps for the resolution procedure. Once the iterations are complete, the calculation process stops, whatever the convergence. For all simulations, 1500 iterations were adopted following the analysis of the results in terms of convergence;

- *cores*: number of processors used for parallel computing (parameter dependent on the computer used). The simulations have been carried out by two computers both equipped with 4 cores processors;
- *CFL (Courant-Friedrichs-Lewy condition*): this parameter controls the rate of solution of the iterative algorithm. The higher the CFL number, the lower the resolution time of the iterations required to conclude the simulation. The use of a high CFL is not always a guarantee of a solution found in a short time because often the stability of the numerical process is not always ensured with nonlinear equations. A CFL around 20 saves 50 to 90% of the computation time; in this case CFL 100 was adopted;
- *convergence stops*: this value, [*rms*, root mean square] allows the program to control *convergence*. It is a measure of the approach to zero of the residue and is calculated by considering the ratio between the *residue* of the first and last iteration calculated during the current simulation. With a *convergence stop* equal to 5, the program is asked to stop as soon as the *residue* has been reduced by 10^5 times compared to the *initial residue*.

$$CON = \log_{10} \frac{RES^{1st\ iteration}}{RES^{current\ iteration}}$$

This last paragraph concludes the simulation setup phase; therefore, one can move on to the resolution of the equations relating to the deadness of fluids. To do this, the program must be allowed to identify a sufficiently high number of solutions characterized by a gradually lower error and tending to zero. For this purpose, the simulation is started by asking to follow a number of iterations in the order of thousands (in this case the iterations were 1500).

During the first phase of the simulation the software proceeds with a collection of all the input data entered during all the phases previously described the analysis of the geometries and all the applied boundary conditions. This process for the incidental analysis of Azzano Decimo took an average of 1 and a half minutes (Figure 70).

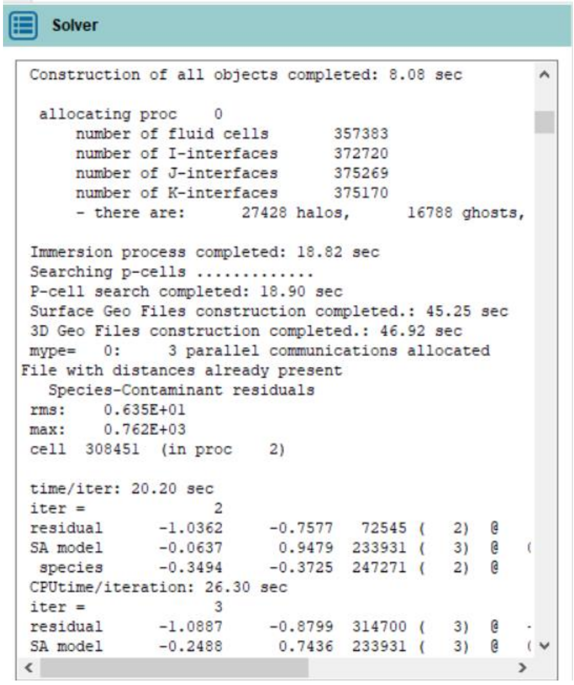


Figure 70: Simulation log

Once the analysis of the model created in all respects is completed, VentoAEC begins to iterate, progressively updating the *simulation log*, showing for each iteration the time spent and the residue obtained.

The high number of iterations will lead the PC to work for some time (the processing time varies widely based on the number of cells created and the number of gases and gas sources present, in the case of this project a PC took an average of 10 hours against the 13 of the less performing PC). The use of a more performing calculation, compared to the one used, would also have greatly reduced the timing.

During all the simulations it arose that while keeping the *.stl* model unchanged, with the same emitting surfaces, the times for the simulations expand even just by changing the wind speed.

During the simulation the software provides a series of customizable charts where their progressive trend is reported. One of the most useful for verifying a correct modeling of the problem is represented by that *Iterations-Convergence*. With a correct simulation this graph has a downward trend with the residue increasingly decreasing. A graph that, on the contrary, shows an increasing residue is a sign of a bad model where there are imperfections or where the grid is not dense enough. Another possible result is represented by a graph that has a descending trend and that reached a certain iteration has a wavy development (sinusoidal like), in which case the effects of some turbulence have come into play.

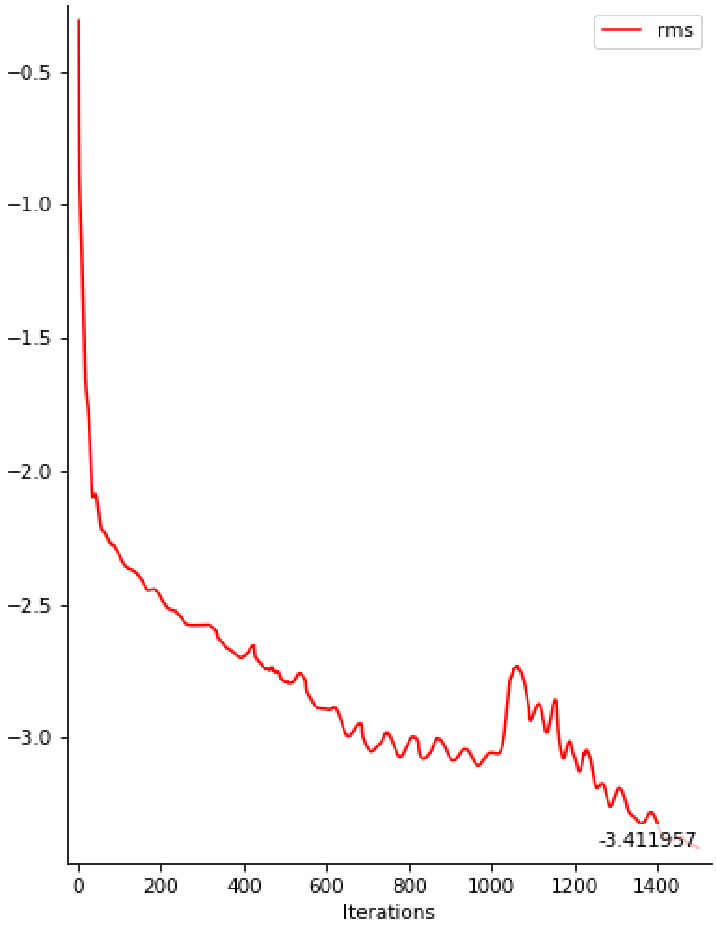


Figure 71: Convergence chart

The graph proposed above (Figure 71) represents the value of convergence as a function of the iterations carried out by the software. In this case a condition of strong wind is represented and the wave trend, although descending, represents the interference due to small turbulences present in the model. In addition, the peak reported between 1000 and 1200 iterations is due to an interruption of the simulation intended for example purposes. In this case, once the simulation was stopped, a convergence of about -3.0 rms was reached. If the simulation is resumed, the path of the graph does not continue in a uniform way but is subject to a steep increase that brings the convergence to about -2.6rms with subsequent resumption of the decreasing trend until reaching -3.44rms at the 1500 iterations.

4.2.2 Simulation and results analysis

In this section the results of the individual simulations carried out under all different conditions are represented and commented. Each simulation is first presented according to the characteristics that distinguish it from the others and evaluated considering the position of the non-ATEX devices and the surfaces intended to be critical.

4.2.2.1 Simulation 01

- Wind speed: 17 m/s
- wind direction: North-West
- atmospheric temperature: -9.3°C
- *LEL*: 61.87 g/m^3
- *UEL*: 1000 g/m^3

Recalling what has been said in chapter 4.4.4.2 of this work, according to CEI EN 60079-10-1 it is not essential to define the maximum explosive value for en plain air conditions. For the purpose of the graphic representation of the results, however, it is necessary to impose a concentration range of the contaminant that to be shown. Therefore, once it has been established that for all gases within the entire set of simulations the maximum limit is around 1000 g/m^3 it has been established to represent a range of concentrations that has as its highest value, in fact, 1000 g/m^3. This factor is adopted in all biogas simulations regardless of the outside temperature.

To support this assumption, the assumption of a cloud with a range greater than the maximum available value would lead to a minimum variation of the represented clouds located near the biogas emission point, affecting only a small part of the results obtained and the considerations made.

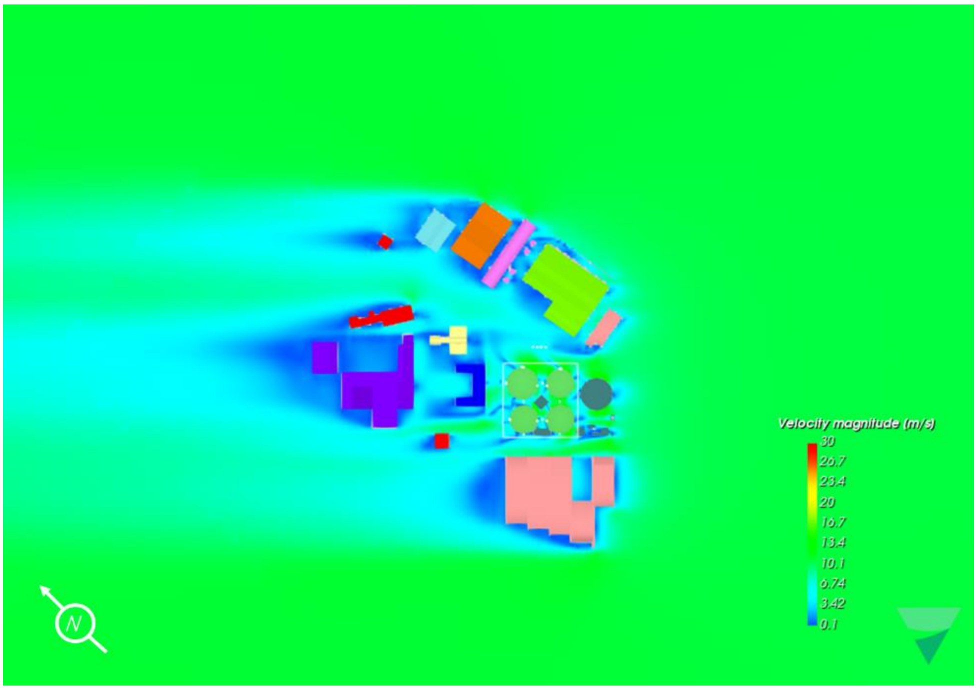


Figure 72: Velocity magnitude Simulation-01

Figure 72 represents the graphical display of the *velocity magnitude* at ground altitude and extracted directly from the software as part of the current simulation. As can be seen, even for subsequent simulations, this view represents the first starting point of the analysis. From this it is possible to immediately notice how the wind speed at ground level is not equal to 17 m/s due to the effects of aerodynamic roughness exerted by the type of soil selected (*rural ground* with roughness equal to 0.1m). From the blue trails that represent a movement of the air at a speed close to zero (see legend) it can be guessed the origin and direction of the wind.

Subsequently, through this value it is possible to compare in a first analysis the differences between simulations performed in the same wind conditions but with different temperatures.

- Convergence: -5.4682 *rms* (root mean square)

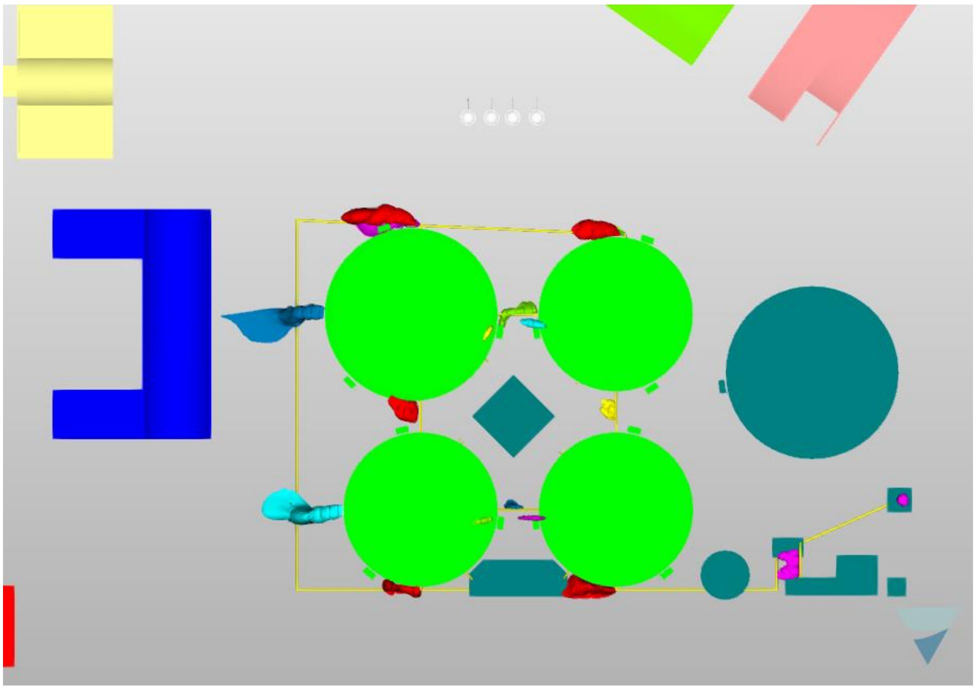


Figure 73: X-Y plan view of gas clouds Simulation-01

In Figure 73 is shown the plan view of the plant together with the *clouds* depicting the volumes of air with a concentration of gas within the range described above. This view is shown for all simulations performed as it represents the first real step in the analysis of the results obtained. With the configuration adopted in this simulation, it is clear that a possible risk can come from the spread of biogas (in this case it is the blue cloud) towards the garage. It should also be noted that between the digesters and the garage runs a small service road traveled mainly by a wheel loader in service to the plant. An unlikely, but still possible, risk can derive from a fortuitous ignition of the gas due to the rubbing of the metal bucket with the ground consisting of beaten ground and gravel in small quantities, as shown in the following image.

An in-depth analysis of the expansion share of the cloud is shown in Figure 74 . From this it is clear that the danger of infiltration of biogas inside the garage is low for two reasons:

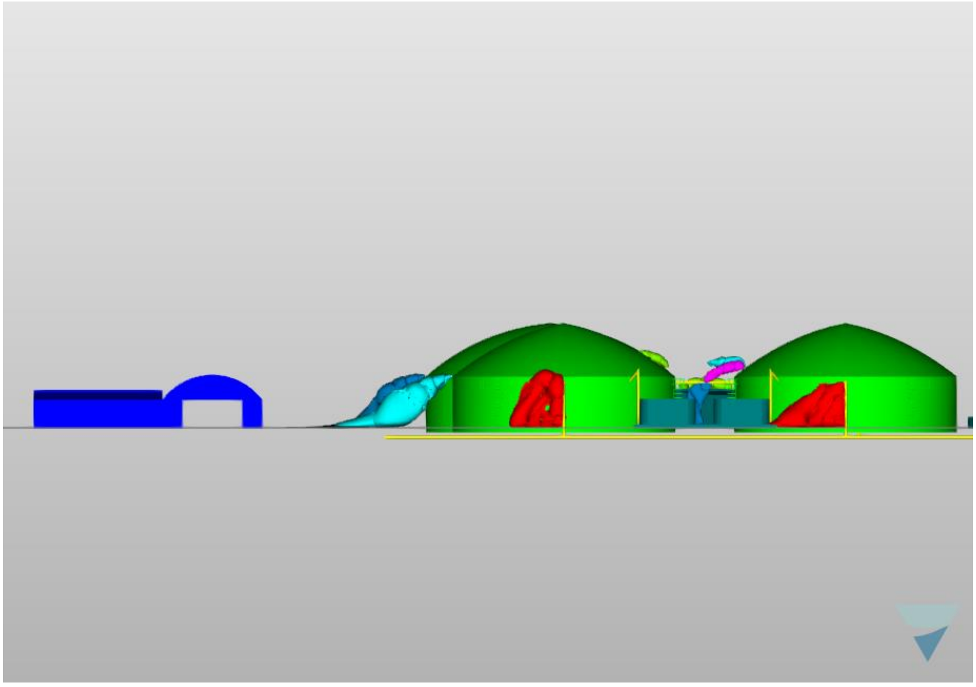


Figure 74: Elevation side view Simulation-01

- the expansion of the gas is limited and does not allow the volume of flammable fluid to reach the garage in a horizontal direction;
- imagining that the cloud can extend until it reaches the perimeter of the garage, this would not be able to invade the garage as at ground level there are no openings of any kind.

Figure 75: Contiguous critical sources

The diffusion of biogas downwards is due to the thrust of the wind coming from South-East, due to the conformation of the digesters the moving air mass runs along a curvilinear path that near the dispersing surface pushes it downwards, also bringing with it the biogas. In a windless situation, the *blue* cloud takes on an ascending parabolic trait. Considerations regarding the development of vertical clouds are made in the chapter on conclusions.

4.2.2.2 Simulation 02

- Wind speed: 17 m/s;
- wind direction: North;
- atmospheric temperature: -9.3°C;
- *LEL*: 61.87 *g/m*³;
- *UEL*: 1000 *g/m*³.

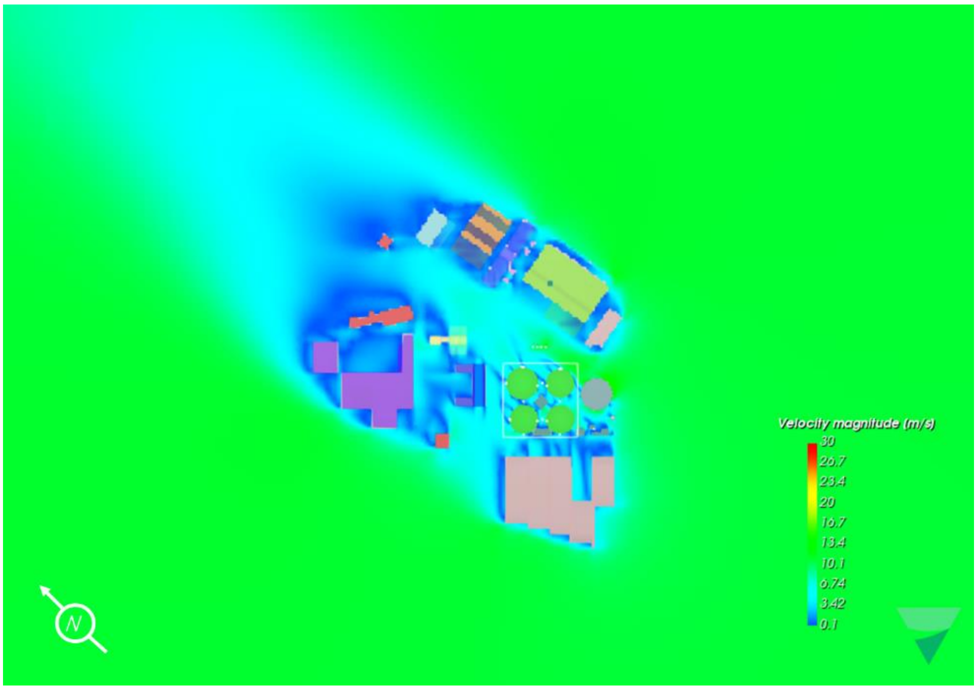


Figure 76:Velocity magnitude Simulation-02

- Convergence: -5.5143 *rms*.

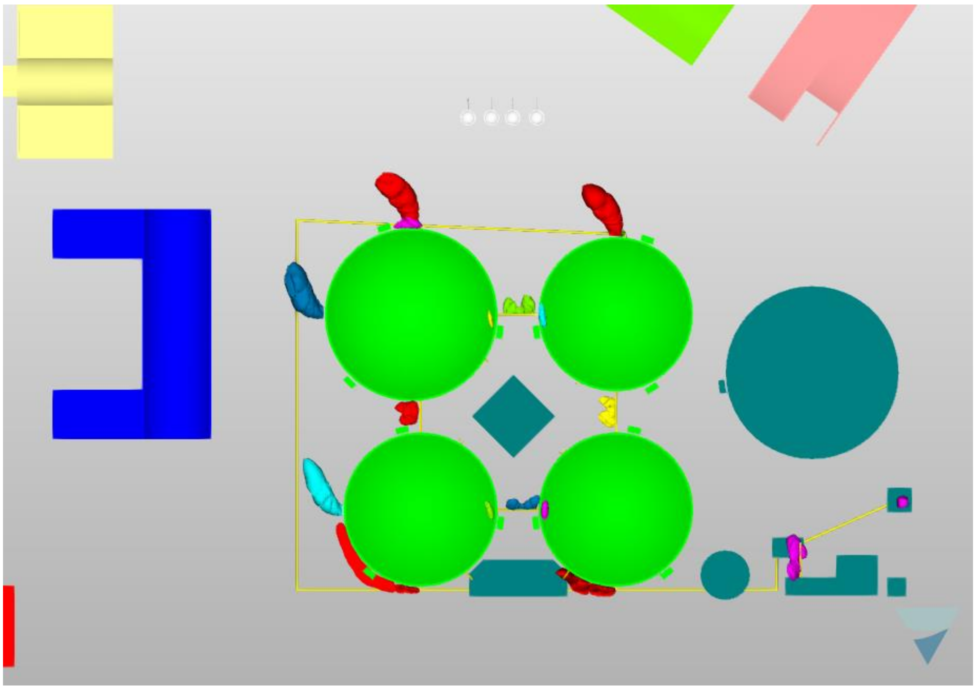


Figure 77: X-Y plan view of gas clouds Simulation-02

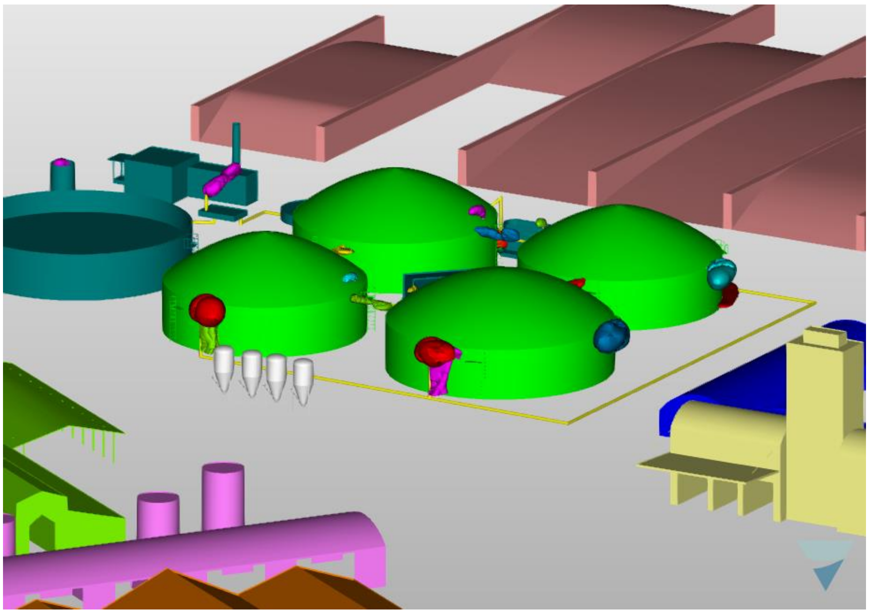


Figure 78: 3D view of the results

As confirmed byFigure 77, Figure 78, Figure 81 and Figure 80, in the first analysis there are no significant risks related to gases in contact with hazardous surfaces. From this, it can be concluded that with this configuration, both wind and gas, with regard to the dangers of a possible explosion the distances between the various elements are sufficient to provide a good degree of protection.

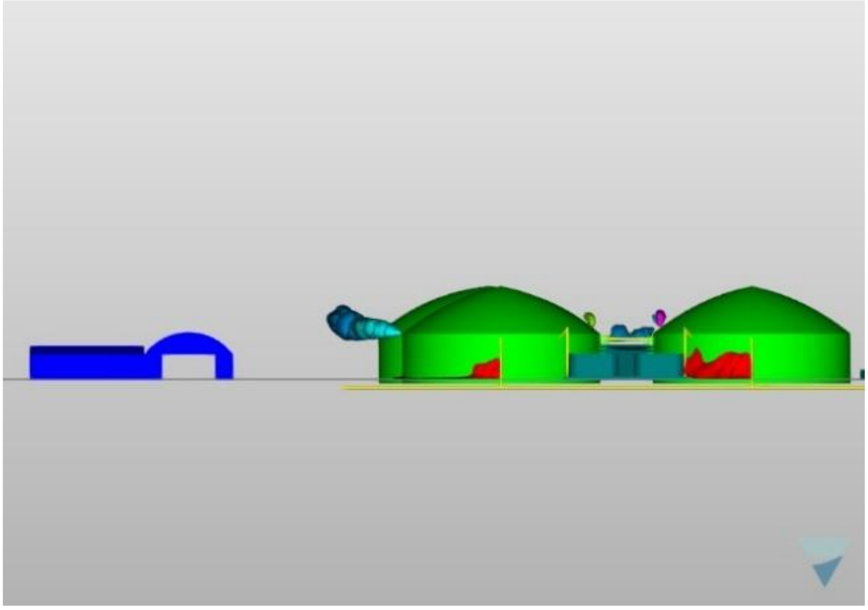


Figure 79: Elevation side view Simulation-02

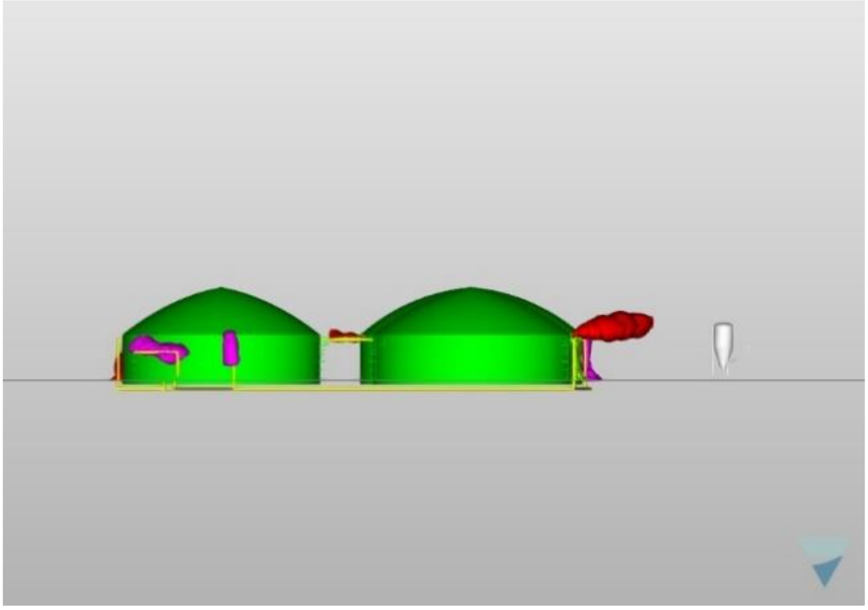


Figure 80: Elevation side view Simulation-02

These two further side views confirm that the risk of gas ignition is not present (remembering that by definition the risk can never be zero), not even for what concerns a possible ignition due to the passage of vehicles nearby.

4.2.2.3 Simulation 03

- Wind speed: 17 m/s;
- wind direction: North-East;
- atmospheric temperature: -9.3°C;
- *LEL*: 61.87 g/m^3;
- *UEL*: 1000 g/m^3.

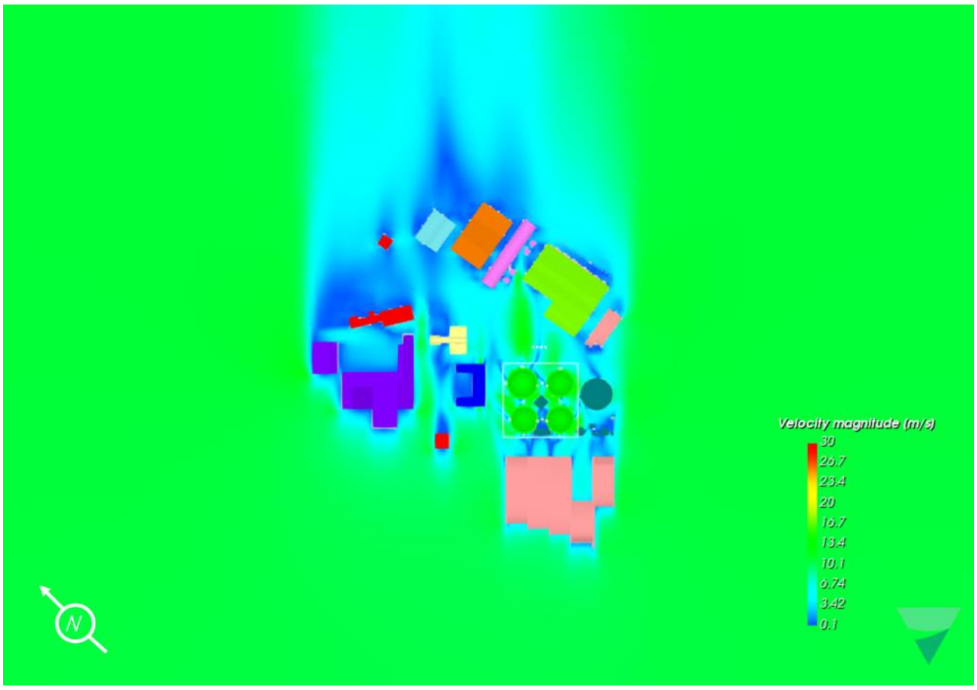


Figure 81: Velocity magnitude Simulation-03

- Convergence: -3.8516 *rms.*

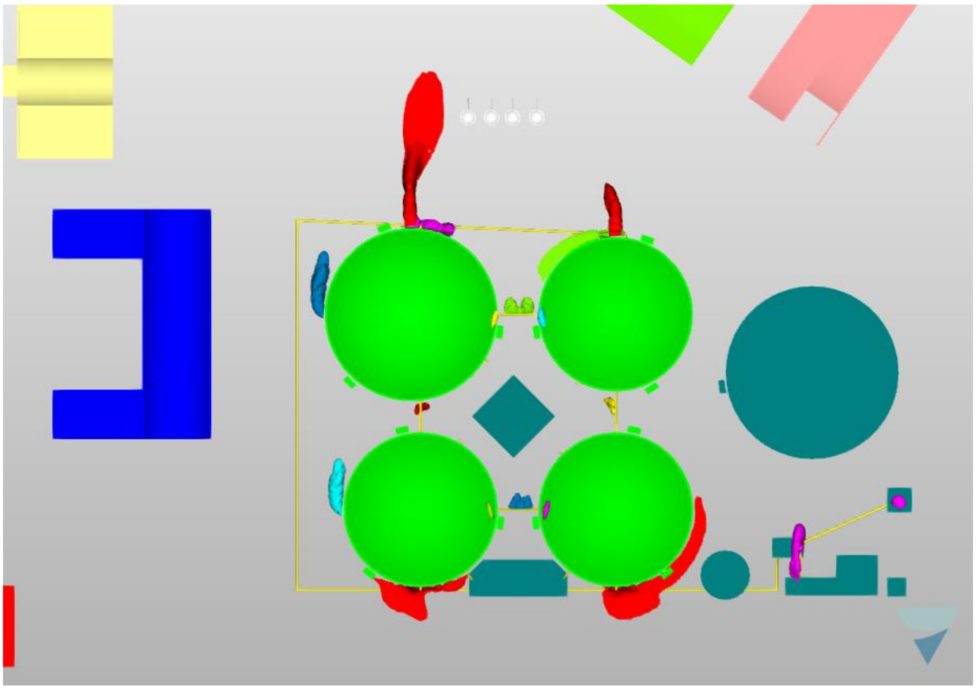


Figure 82: X-Y plan view of gas clouds Simulation-03

From the plan view (Figure 82) it is evident how the strong wind coming from South-West pushes a cloud in particular towards the silos, as if to reach them. The cloud in question is coming from a critical surface that simulates a leak due to the rupture of the Digester 4 tarp. The loss is proportional to the size of the gas outlet area, it is precisely for this reason that in this and in the next simulations with winds parallel to the normal surfaces of the *tarp* and *tarp surfaces towards silos* the clouds that most expand are precisely those produced by these critical points.

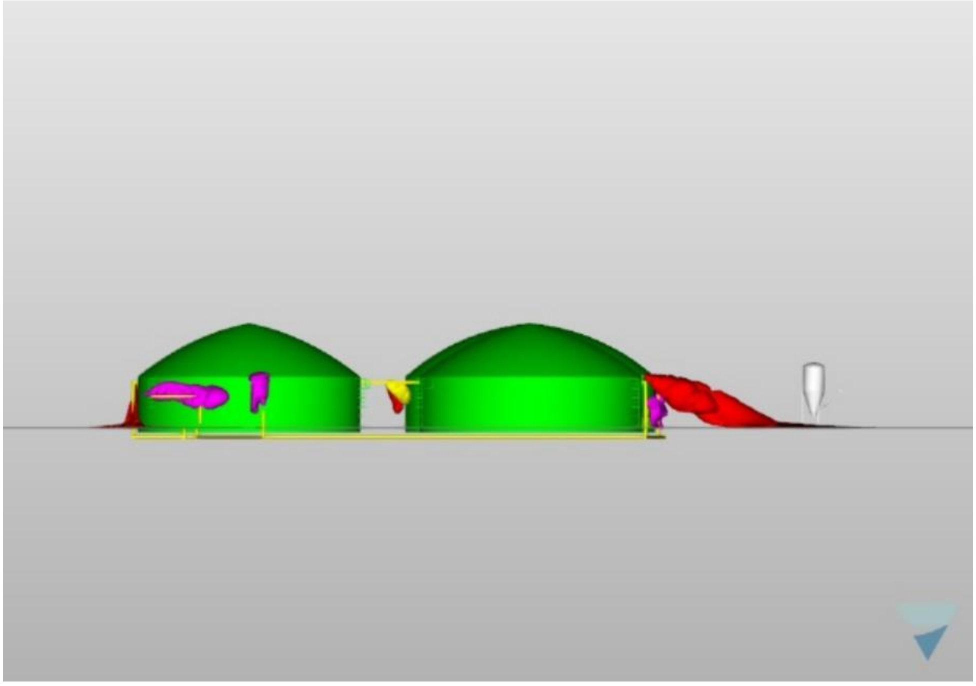


Figure 83: Elevation side view Simulation-03

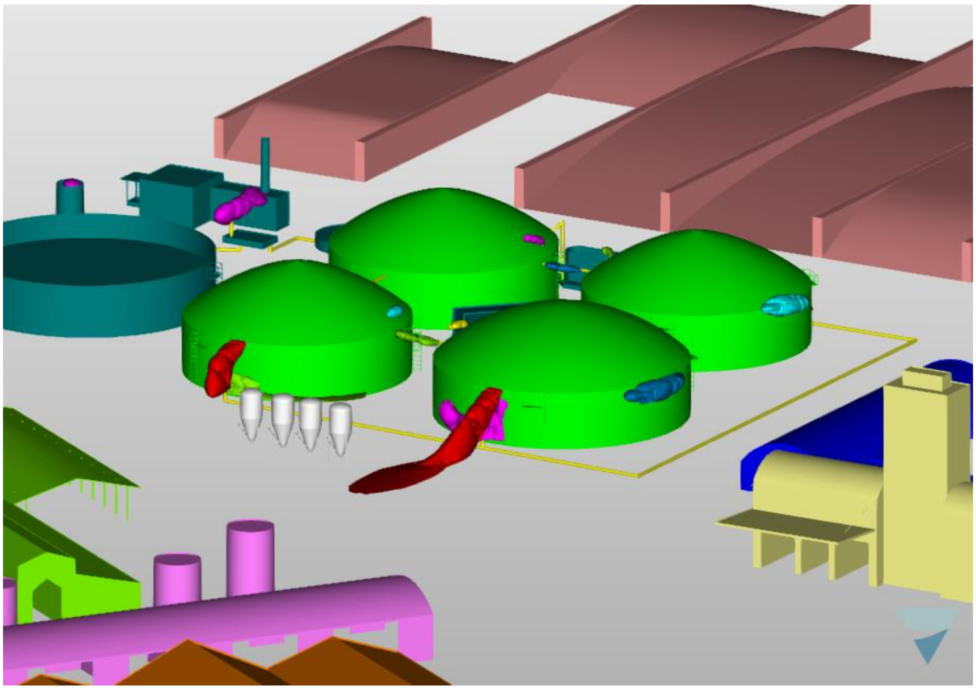


Figure 84: 3D view of the results

In the conditions previously dictated, what is shown in the Figure 84 represents a scenario that apparently could be risky but that has little probability of happening because, as already mentioned for simulation 01, the wheel loader could ignite the gas only through the friction of the blade with the ground. Another possible trigger could derive from the contact of the gas with the exhaust system of a motor vehicle passing through that area, the high temperatures of the metal constituting the exhaust system in contact with the cloud could start an adverse and sudden reaction. As for the contact with the silo, this does not happen because of the height of the gas flap in correspondence of the non-ATEX engines supplied with the silos. These two are very distant from each other vertically, so it is difficult to contact gas-engines.

4.2.2.4 Simulation 04

- Wind speed: 3 m/s;
- wind direction: North-East;
- atmospheric temperature: -9.3°C;
- *LEL*: 61.87 *g/m*^{3};
- *UEL*: 1000 *g/m*^{3}.

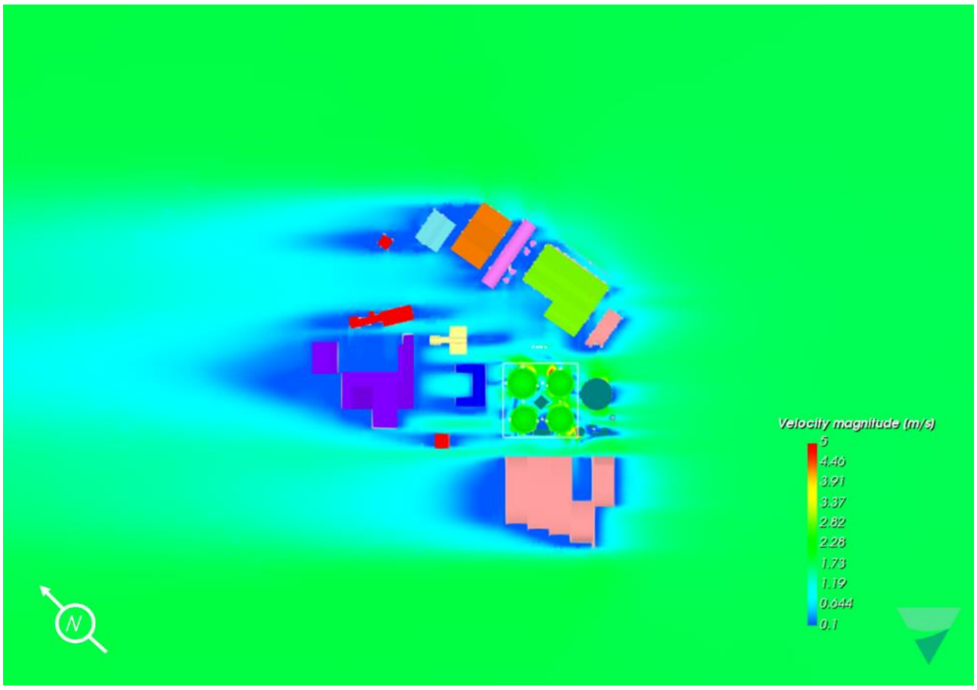


Figure 85: Velocity magnitude Simulation-04

- Convergence: -4.4549 *rms.*

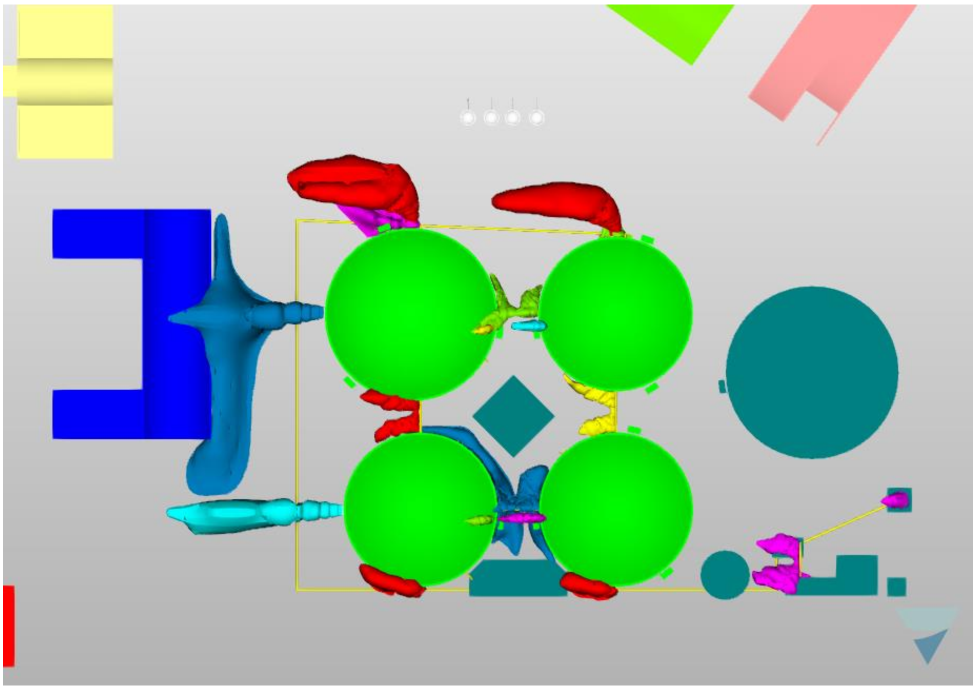


Figure 86: X-Y plan view of gas clouds Simulation-04

This simulation is very significant because it represents in a very good way the difference between the effects of a fast wind with that of reduced speed. The fluid pushed by the air coming from the North-East can collect itself in a certain area at high concentrations. On the contrary, with winds of higher speed the gas is able to reach more remote areas but with much lower concentrations than this case. There are two interesting views to analyze:

- North-East prospective view: to observe the *blue* cloud contact (leakage from the digester 4 membrane) towards the garage.

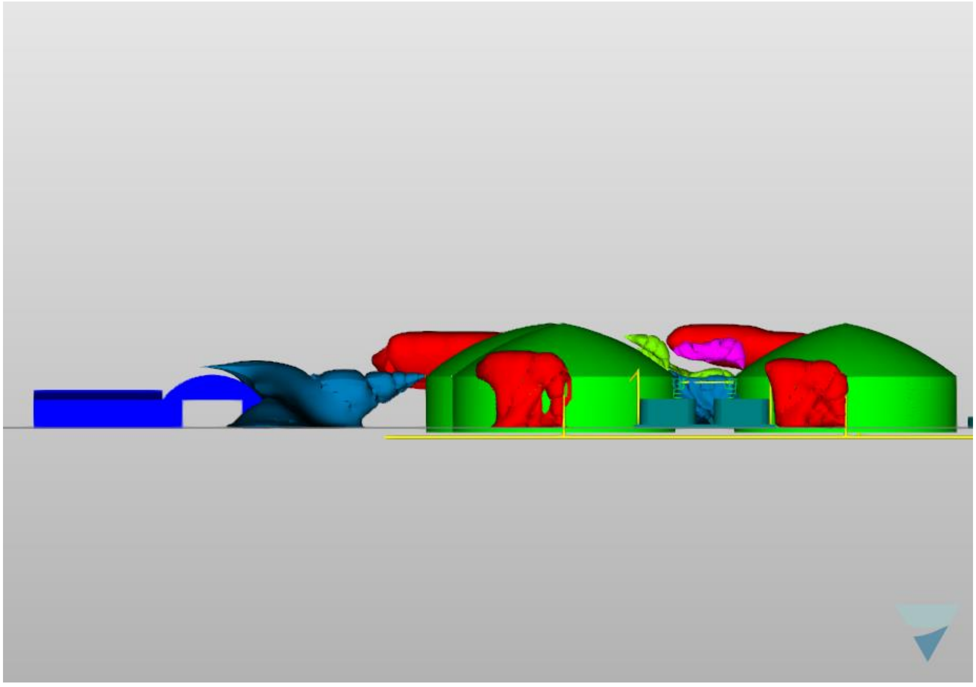


Figure 87: Elevation side view Simulation-04

The garage is almost completely covered by a cloud of gas that is flammable for his own concentration. This represents a critical scenario as the machines contained and the processes carried out inside the building could involve sources of heat, open flames or sparks that would represent an excellent ignition source for a violent reaction by the gaseous mass.

- North-West elevation view: to observe the share of expansion of *the red* clouds towards the silos (loss from the rupture of the digester 3 and 4 membrane).

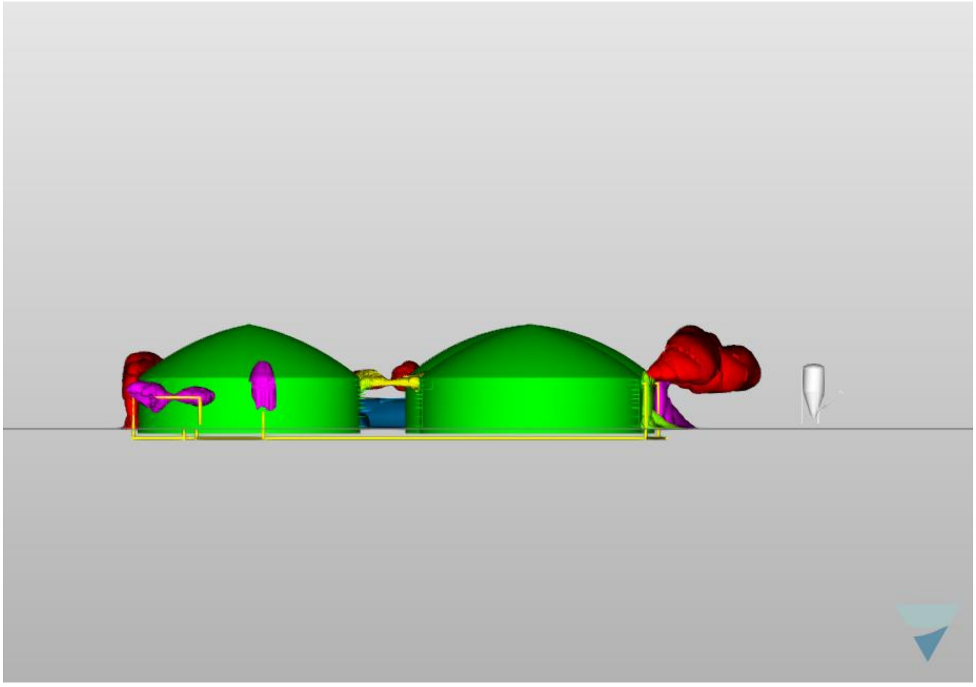


Figure 88: Elevation side view Simulation-04

The altitude reached by the cloud does not allow any moving machinery in the circumstances of the digester to represent a trigger factor for a fire.

In conclusion, for this simulation the element from which the greatest risk factor derives is the garage hit by a gas leak due to the breakage of the membrane. Also to be considered is the possibility of a possible contact with the vehicles of passage on the service road, parallel to the garage.

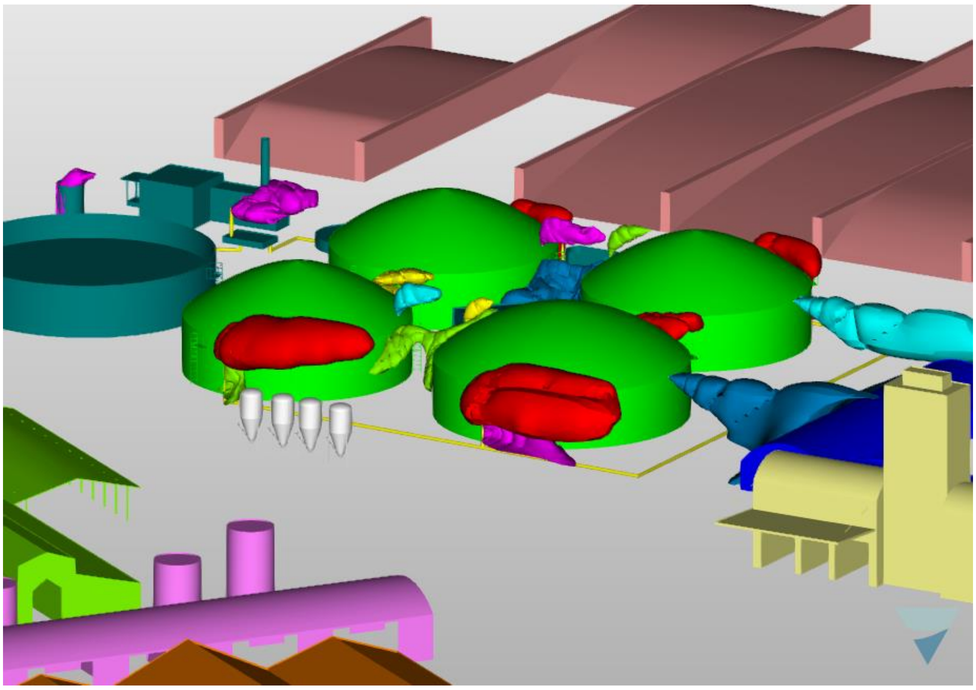


Figure 89: 3D view of the results Simulation-05

4.2.2.5 Simulation 05

- Wind speed: 3 m/s;
- wind direction: North;
- atmospheric temperature: -9.3°C;
- *LEL*: 61.87 g/m^3;
- *UEL*: 1000 g/m^3.

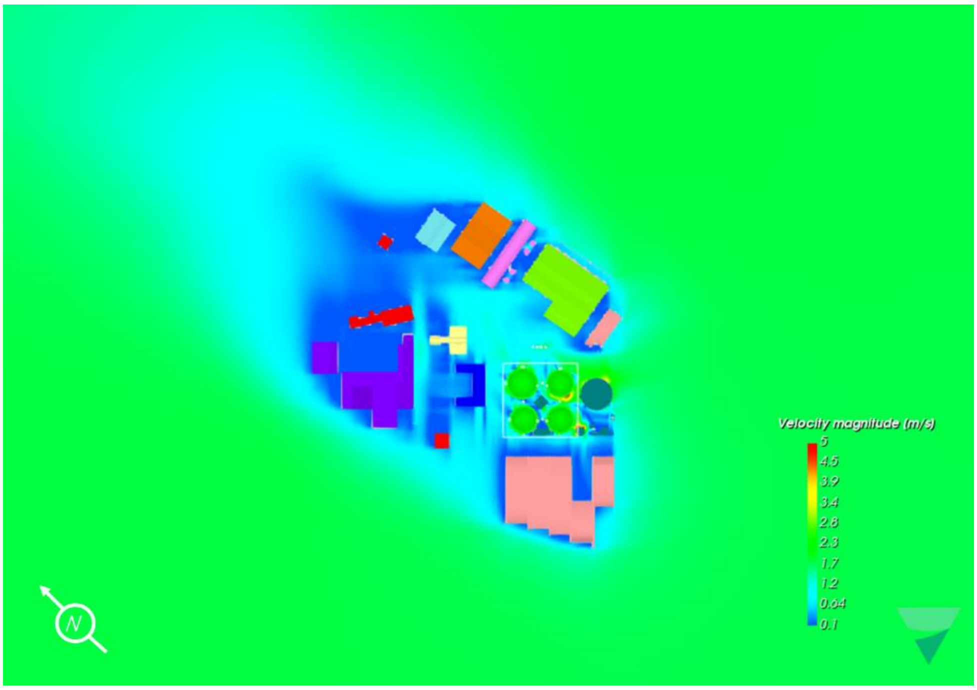


Figure 90: Velocity magnitude Simulation-05

- Convergence: -4.2494 *rms.*

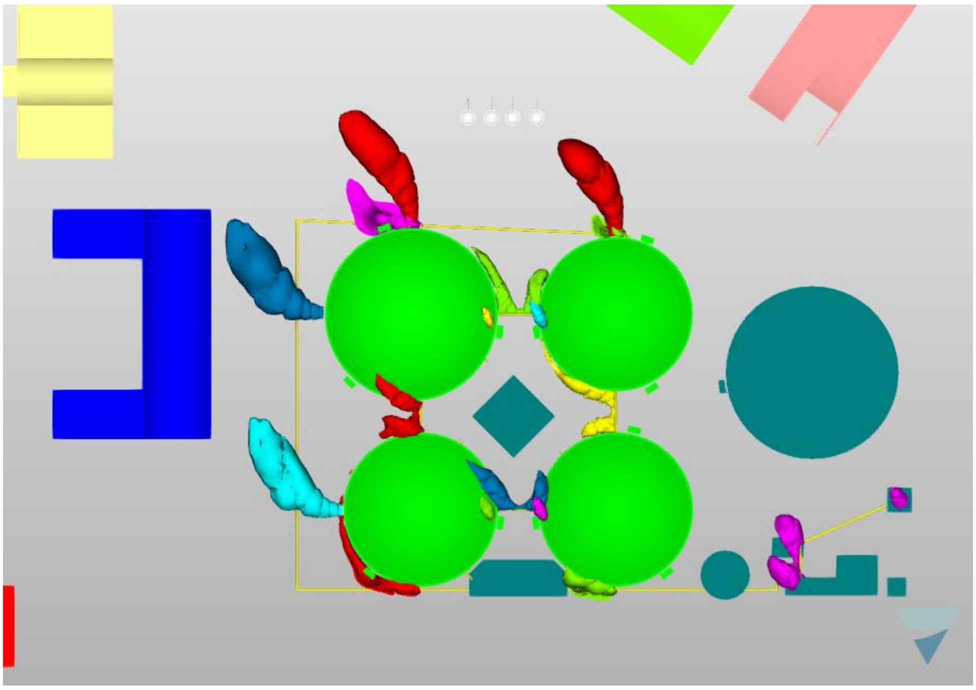


Figure 91: X-Y plan view of gas clouds Simulation-05

Even if in this case the clouds are not able to reach any dangerous surface, it is still necessary to analyze the elevations, in order to understand at what level the mass of gas moves and identify possible risks due to the contact of the hot surfaces of moving vehicles with exhaust pipes or linked to a possible change in wind direction.

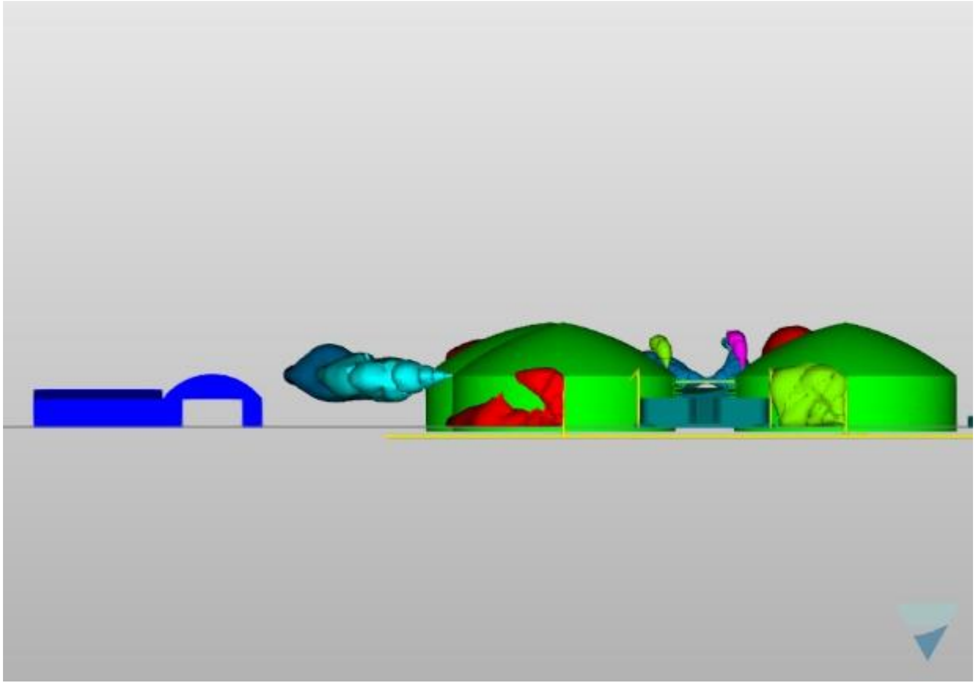


Figure 92: Elevation side view Simulation-05

As for the *blue* and *cyan* gas, at the bottom of the image, (respectively leaving the critical point of the digester tarp 1 and 4, in Figure 92) in the direction of the garage, these do not represent a source of significant risk because of their altitude, in fact, it would not allow it to cross the openings on the walls of the garage or even to come into contact with exhaust pipes of the shovel or other operating machines.

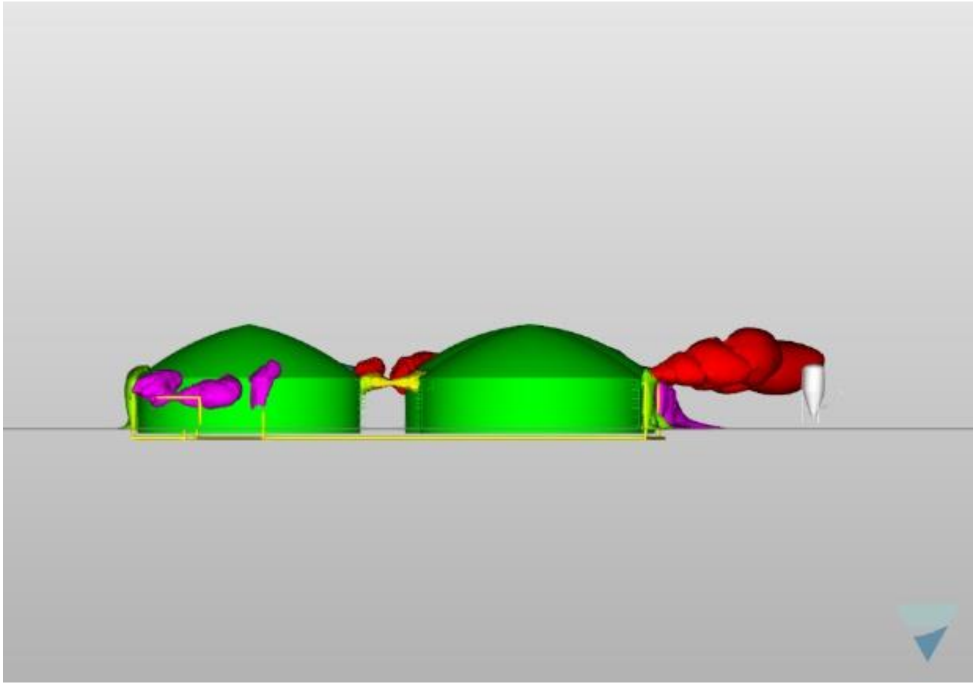


Figure 93: Elevation side view Simulation-05

On the contrary, in Figure 93 there is a mass of gas coming out of the tarp of digester 4 (*red*) which, although not moving in the direction of the silos, is placed at such an altitude that if there were to be a change in wind direction in the direction of the silos, this cloud would risk coming into contact with the NON-ATEX components of the engine connected to the silos.

From this elevation view and from the following image it is noticeable how the gas leaving the critical point *digester pipe 4* (*magenta* cloud) develops downwards (despite the lower density of the air) because of the motion of the air. In this case the ignition of this mass could be due to the passage of motor vehicles that have an exhaust at a height close to the ground.

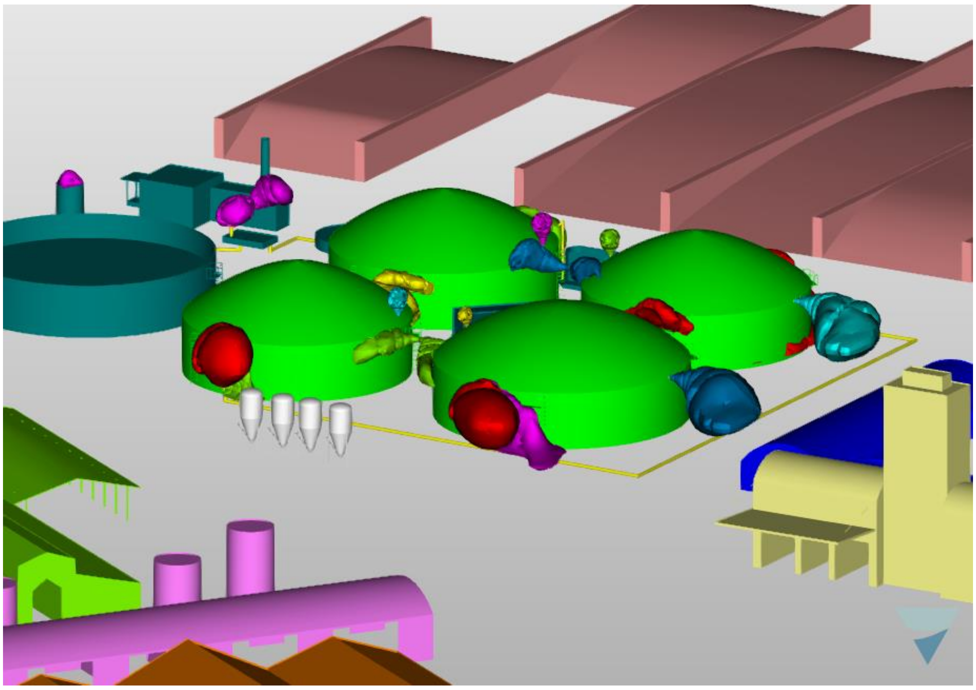


Figure 94: 3D view of the results Simulation-05

4.2.2.6 Simulation 06

- Wind velocity: 3 m/s;
- wind direction: North-East;
- atmospheric temperature: -9.3°C;
- *LEL*: 61.87 g/m^3;
- *UEL*: 1000 g/m^3.

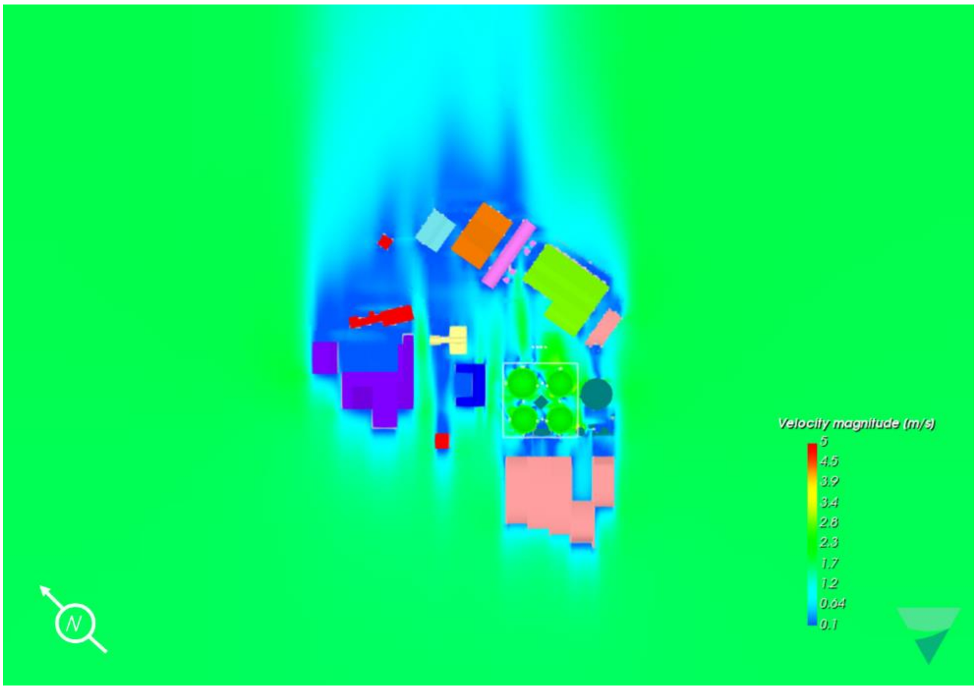


Figure 95: Velocity magnitude Simulation-06

- Convergence: -4.1280 *rms.*

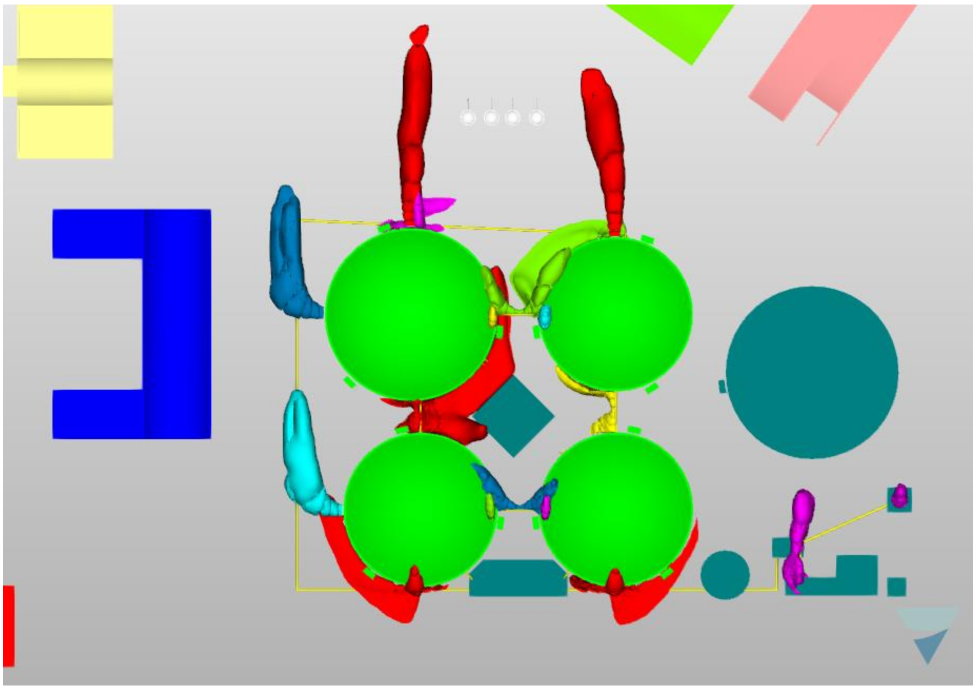


Figure 96: X-Y plan view of gas clouds Simulation-06

Similar to the 4.2.2.5, if the possibility of a change in wind direction towards one of the two buildings is considered, there could be a real risk of explosion. If, on the contrary, the analysis is limited of the current position, then it is only necessary to study the position along Z of the clouds.

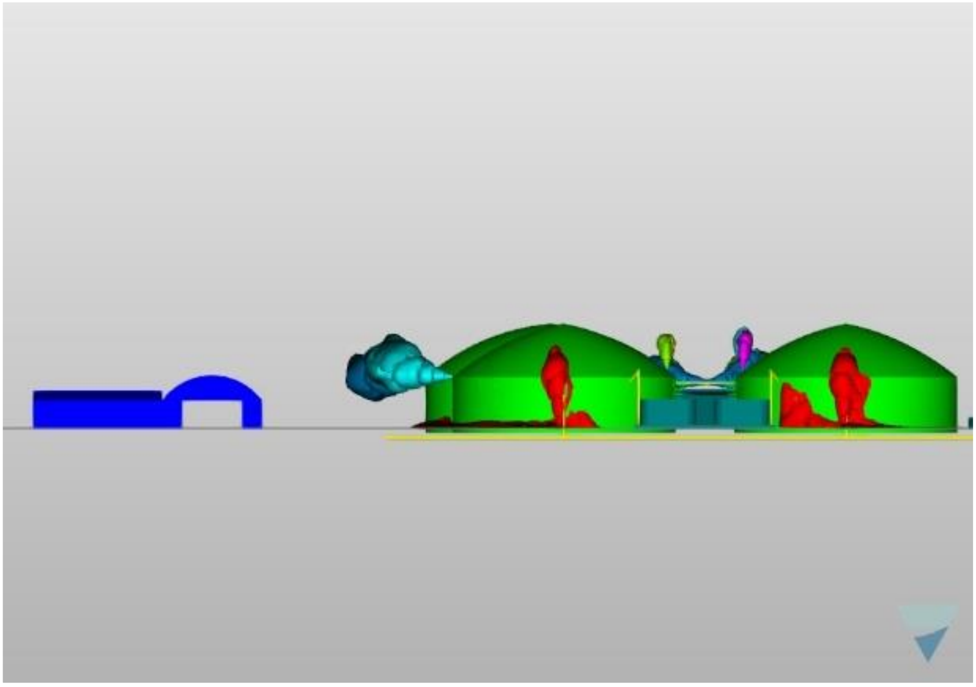


Figure 97: Elevation side view Simulation-06

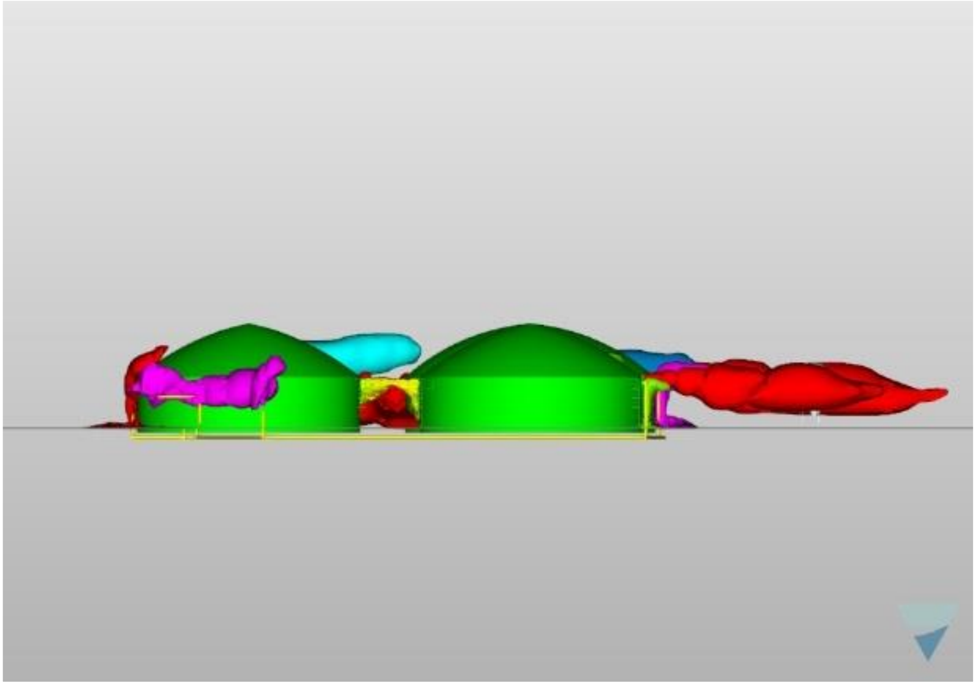


Figure 98: Elevation side view Simulation-06

From Figure 97 and Figure 98 it is possible to define that in a stationary static situation such as that reached by the various simulations, the dangerous cloud is not able to directly reach any of the surfaces. The danger could, however, derive from the contact of the gas with very hot surfaces such as exhaust pipes of moving vehicles in those areas. In this case, the leakage from the *cogenerator* pipe that extends several meters towards the North-West is also important.

4.2.2.7 Simulation 07

- Wind speed: 0.1 m/s;
- wind direction: North;
- atmospheric temperature: -9.3°C;
- *LEL*: 61.87 g/m^3;
- *UEL*: 1000 g/m^3.

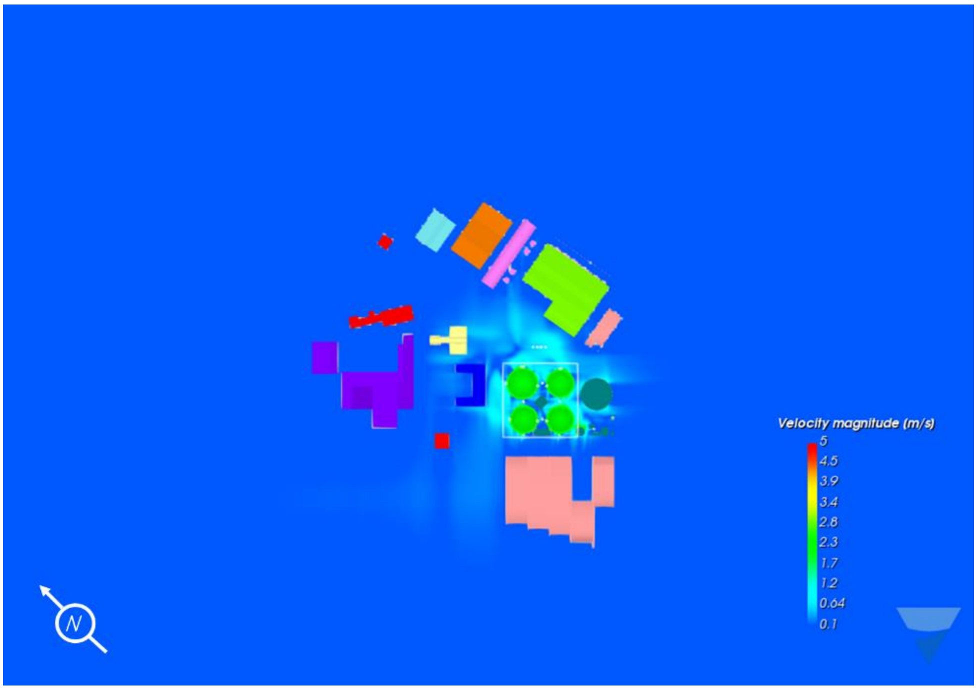


Figure 99: Velocity magnitude Simulation-07

This simulation is aimed at studying the propagation of gas in the total absence of wind, so as to define which paths are traveled by clouds free to move without any external constraint. Since the simulation is set *outdoors*, the VentoAEC software requires, to carry out the CFD analysis, that inside a model is present what is defined as *forcing*, that is an element that cause the movement of the entire fluid mixture inside the *domain box*. The effect of the gases leaving the *critical* points has no influence on the entire air mass such as not to allow the software to perform a simulation in an acceptable time. Therefore, it was established (as a result of attempts with lower speeds but which required very long and unmanageable timings) to assign the wind a very low speed, i.e. 0.1 m / s. To obtain a result as balanced as possible, considering that the orientations analyzed are North-West, North and North-East, the North was chosen as the direction of the *breeze* in question. This measure can have more or less impactful effects on the result of the simulations: considerations are also made on this possible problem.

Looking at Figure 99, the colored trails differently from the surrounding of the plant indicate that the air is characterized by a speed greater than zero, this difference (very visible only with wind at zero speed) is due to the thrust exerted by the fluids coming out of the different biogas emission surfaces.

- Convergence: -3.9509 *rms.*

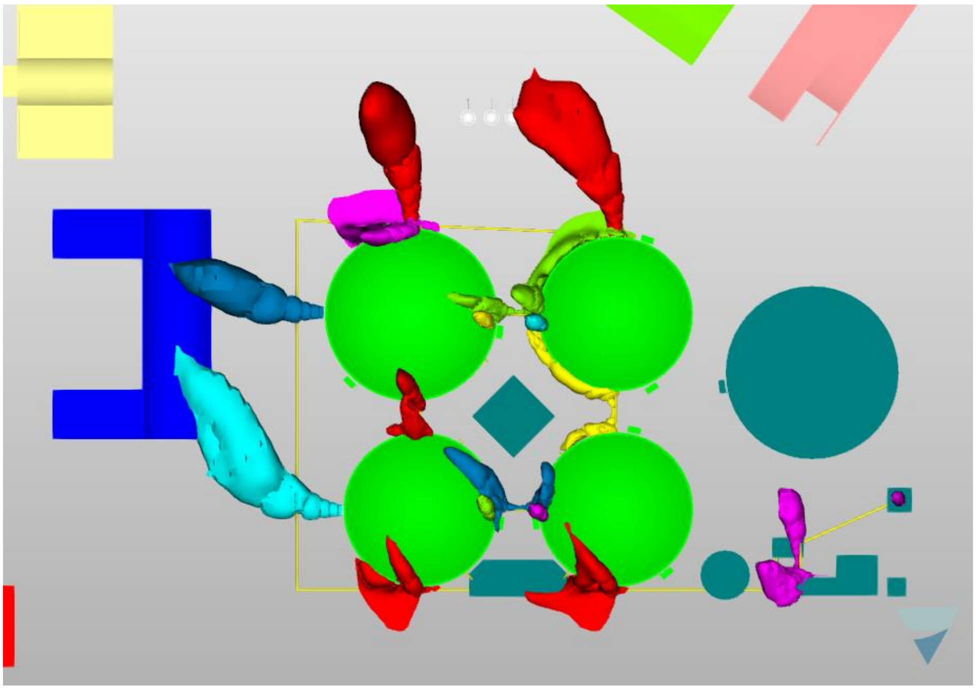


Figure 100: X-Y plan view of gas clouds Simulation-07

This configuration represents what until now could be the most dangerous as three clouds of gas would be able to reach the two most critical elements (garage and silo). Also in this case it is mandatory to deepen the knowledge about the current position of the different clouds. The deviated movement of the *blue* cloud in the direction of the garage is due to the characteristics of the wind that have been adopted. In the total absence of wind this would have continued parallel to the normal of the emitting surface.

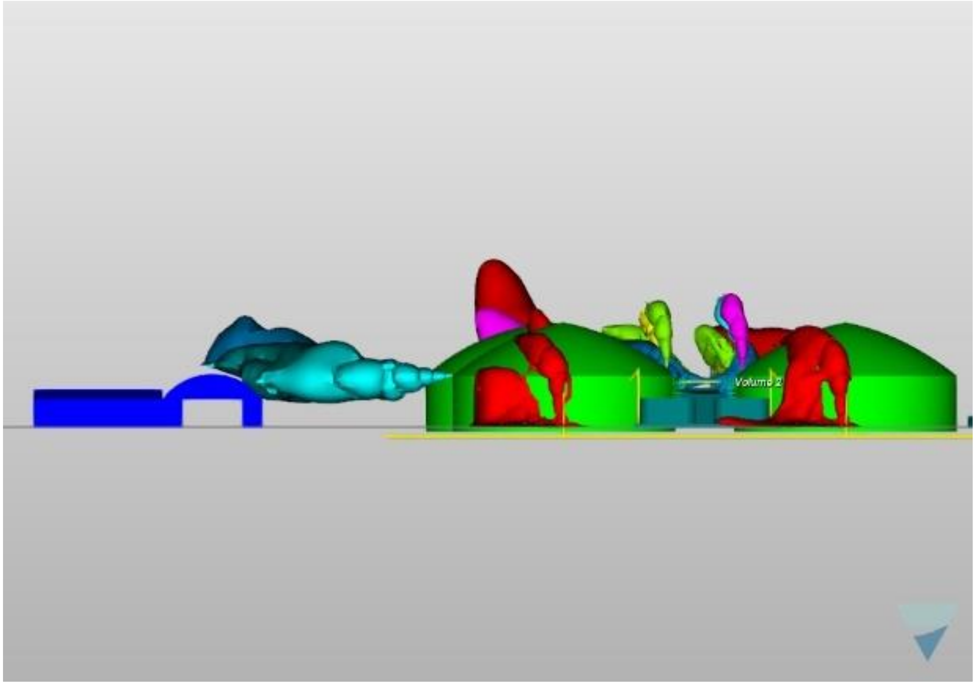


Figure 101: Elevation side view Simulation-07

The *blue* and *cyan* clouds (respectively leaks due to the breakage of the tarp of the digester 4 and 1) in the direction of the garage reach the building only at the level of the lower ridge of the roof thus avoiding entry into the premises.

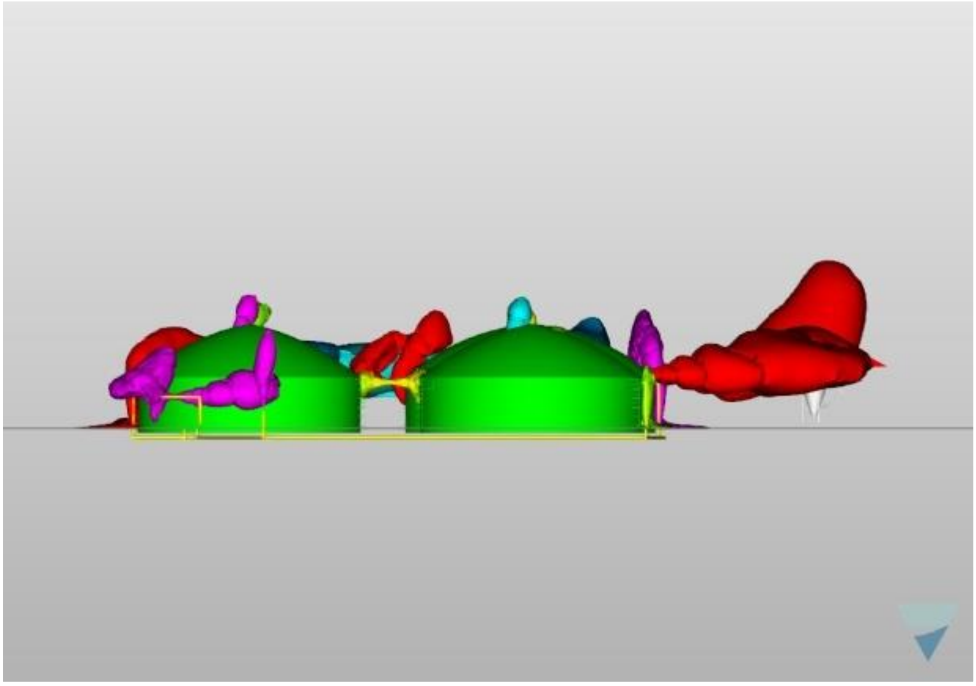


Figure 102: Elevation side view Simulation-07

As for the *red* clouds in the direction of the silos (failure of the tarp of the digester 3 and 4) the same considerations apply as for the previous simulation, 4.2.2.6. For both clouds the passage of a vehicle with exposed hot parts could represent a danger. Even in this case a special attention deserves the leakage from the *cogenerator* that assumes more and more importance in terms of extension. This is surrounded by ATEX equipment which reduces the risk in a very effective way.

4.2.2.8 Simulation 08

- Wind speed: 17 m/s;
- wind direction: North-West;
- atmospheric temperature: 32.6°C;
- *LEL*: 61.87 *g/m*³;
- *UEL*: 1000 *g/m*³.

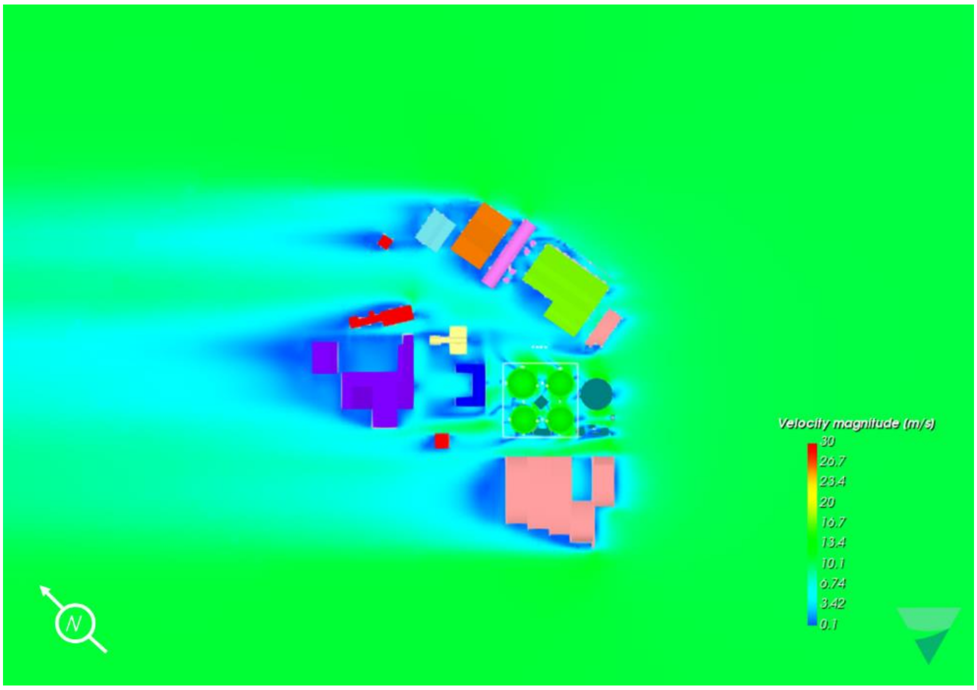


Figure 103: Velocity magnitude Simulation-08

- Convergence: -5.4679 *rms*.

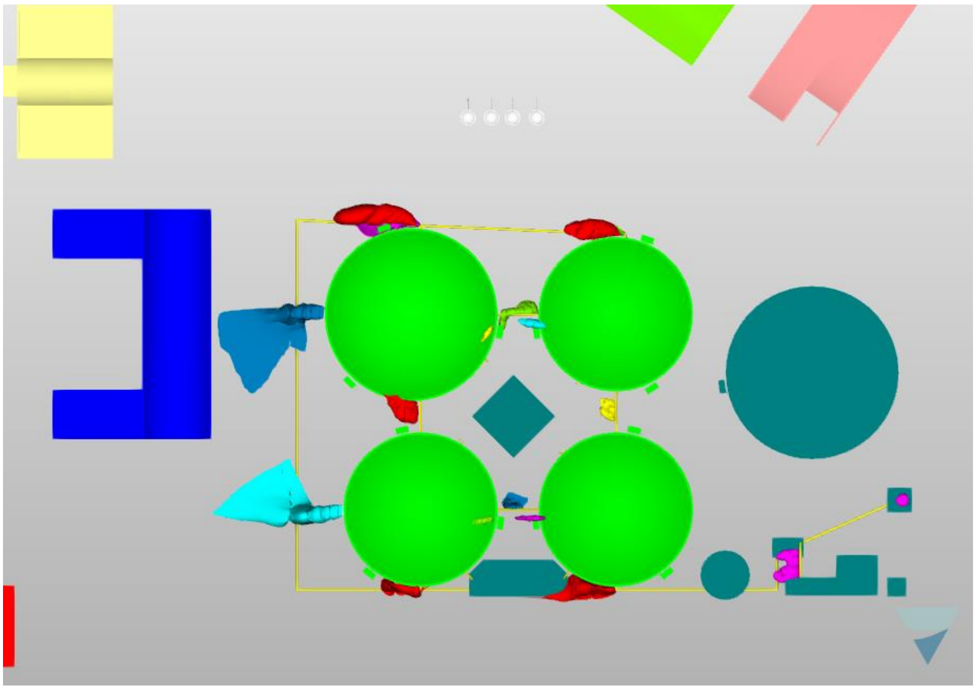


Figure 104: X-Y plan view of gas clouds Simulation-08

This and subsequent simulations represent elements of further interest as they represent a means of comparison between identical simulations for all boundary conditions but the external temperature, which is expected to have an influence on the densities of fluids and their motions.

Comparing this image with the one captured for the first simulation in conditions of much lower temperature (-9.3°C against the current 32.6°C, Figure 73) it is noted that in general all clouds develop in the same way, the only visible difference concerns the dispersion of gas at ground level in the garage direction, as shown with the following image.

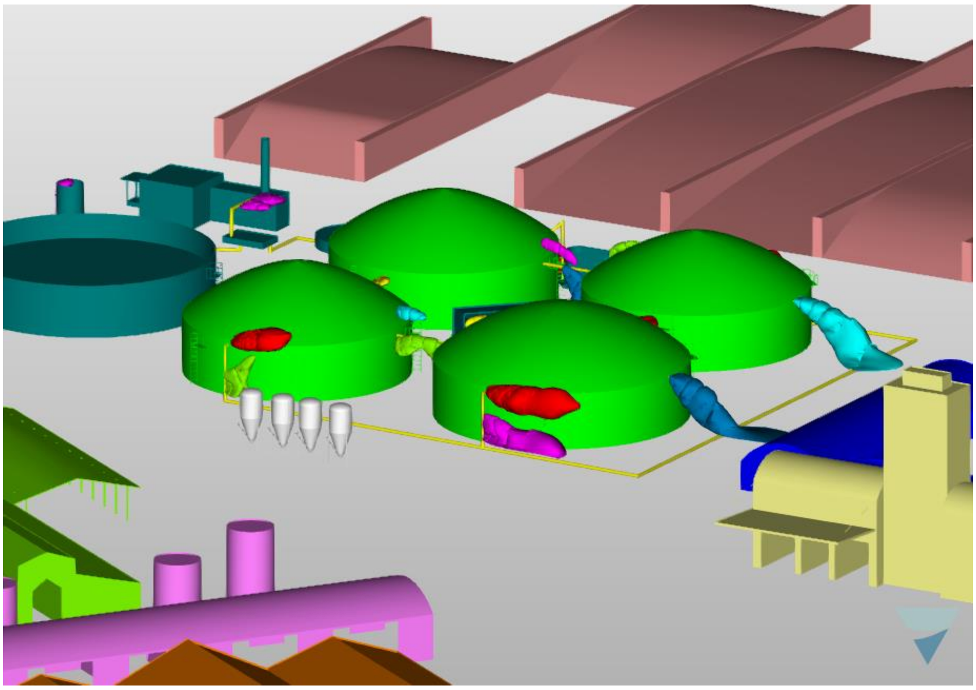


Figure 105: 3D view of the results Simulation-08

From this view, in addition to the two *blue* and *cyan* clouds (leakage the tarp of the digesters respectively 4 and 1) it is possible to see the dispersion due to a rupture of the pipe digester number 4 (*magenta* cloud). This moves horizontally at low levels. In this case the danger of contact with hot surfaces of motor vehicles does not exist as it is contained within the perimeter of a small rise between the road and the support surface of the digesters, similar to the sidewalk.

4.2.2.9 Simulation 09

- Wind speed: 17 m/s;
- wind direction: North;
- atmospheric temperature: 32.6 °C;
- *LEL*: 61.87 g/m^3;
- *UEL*: 1000 g/m^3.

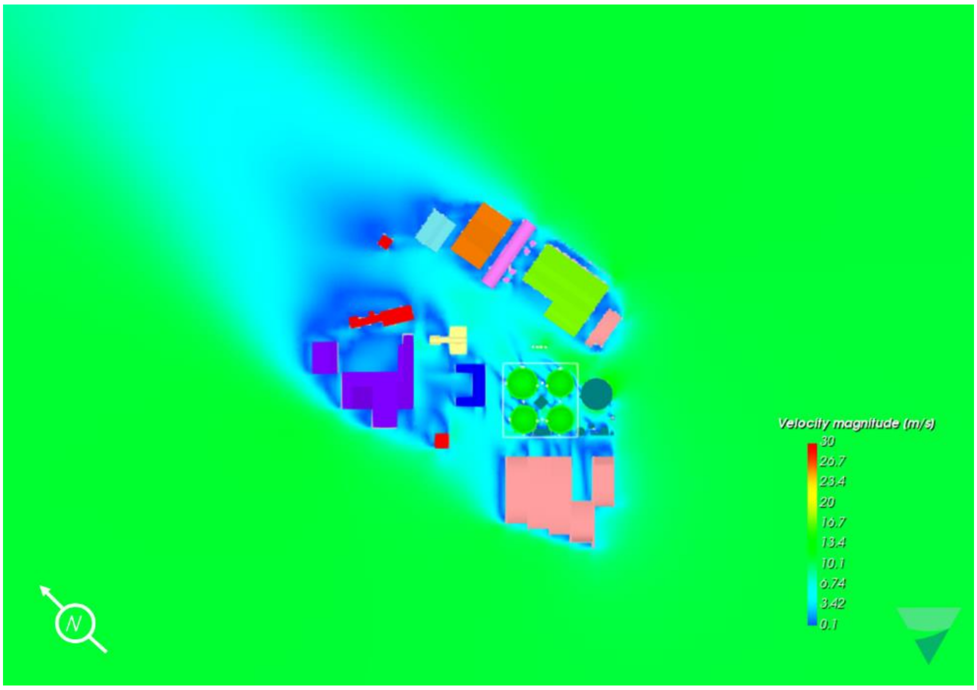


Figure 106: Velocity magnitude Simulation-09

- Convergence: -5.5523 *rms.*

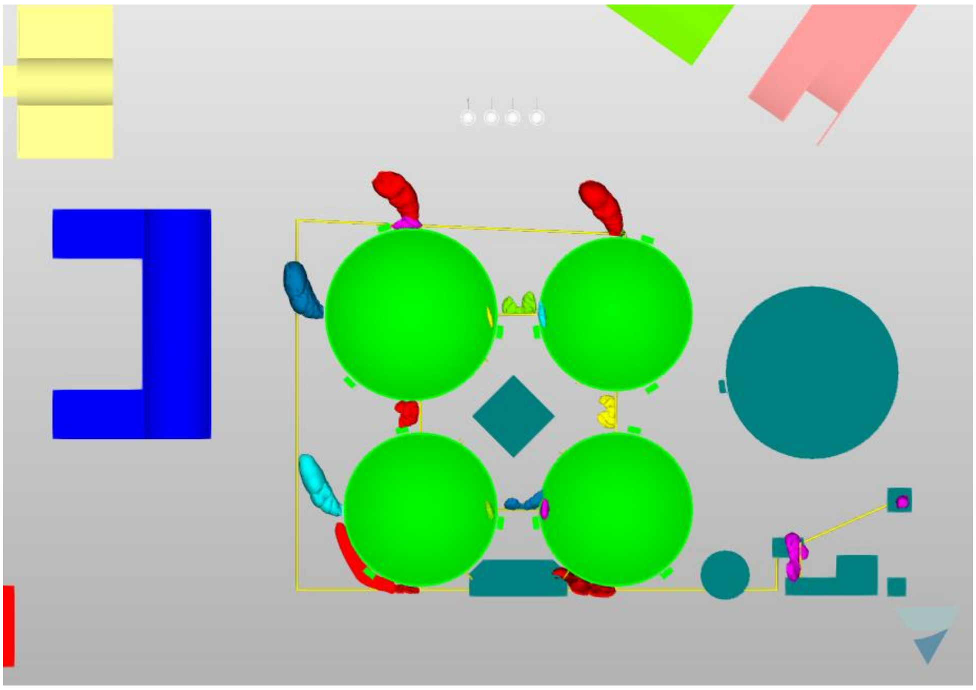


Figure 107: X-Y plan view of gas clouds Simulation-09

No risk has been identified with regard to this simulation. A very similar result for cloud conformation and identified risks is obtained for 4.2.2.2.

4.2.2.10 Simulation 10

- Wind speed: 17 m/s;
- wind direction: North-East;
- atmospheric temperature: 32.6°C;
- *LEL*: 61.87 *g/m³*;
- *UEL*: 1000 *g/m³*.

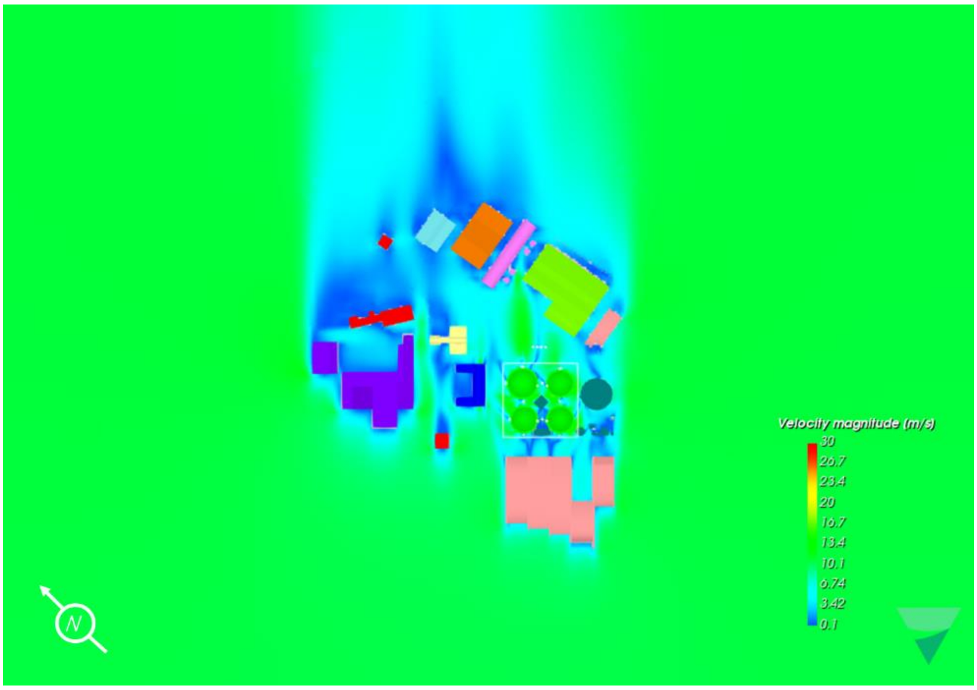


Figure 108: Velocity magnitude Simulation-10

- Convergence: -3.8743 *rms.*

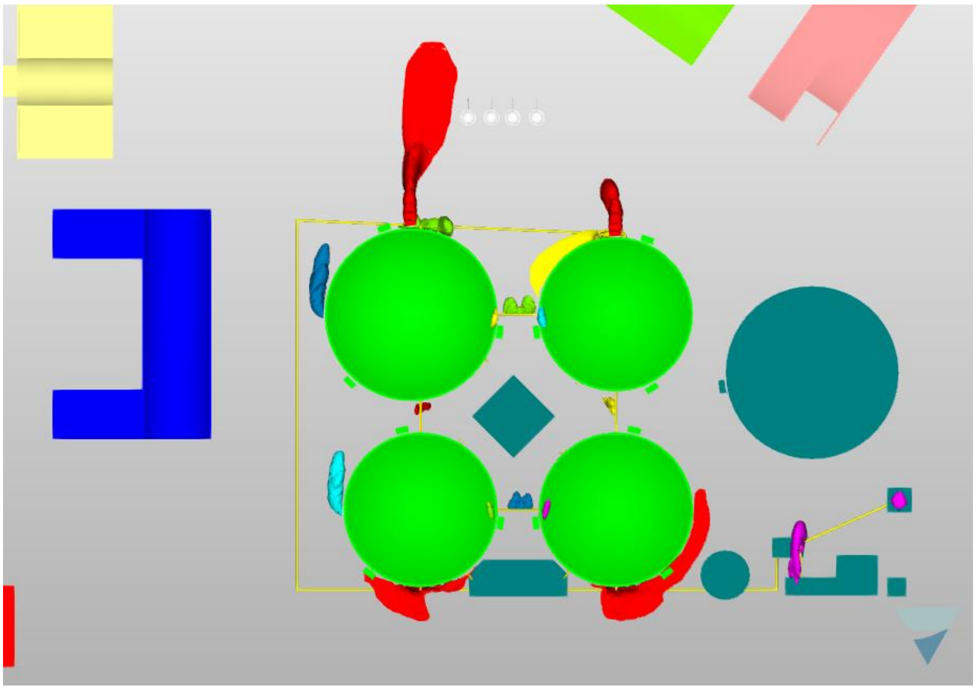


Figure 109: X-Y plan view of gas clouds Simulation-10

Again, the analysis of these results requires further detail so as to convey in what a unique way the extension of the red cloud coming out of the tarp of digester 4.

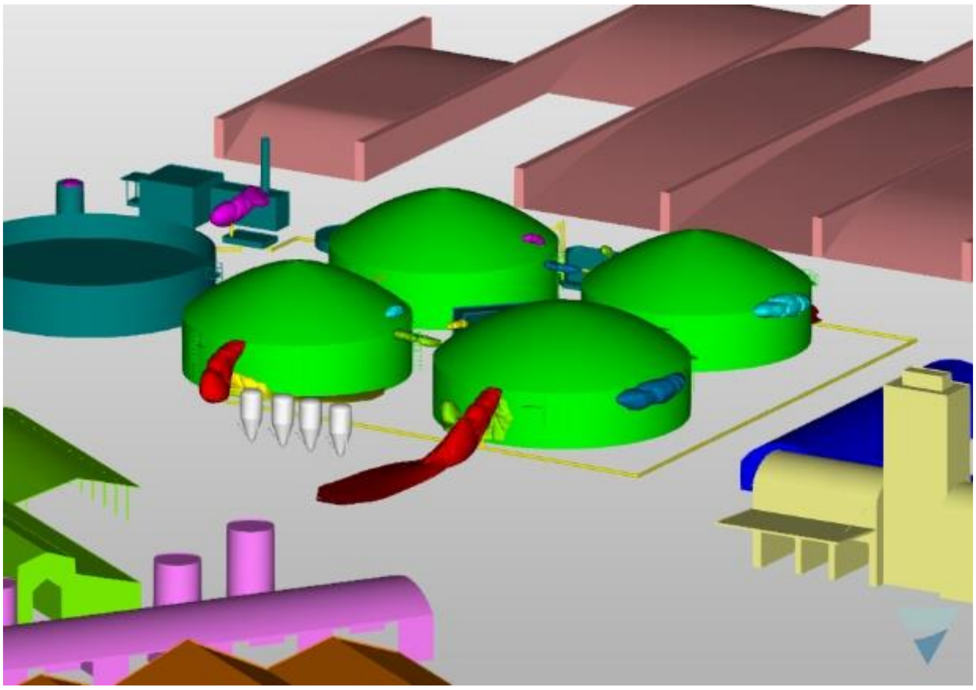


Figure 110: 3D view of the results Simulation-10

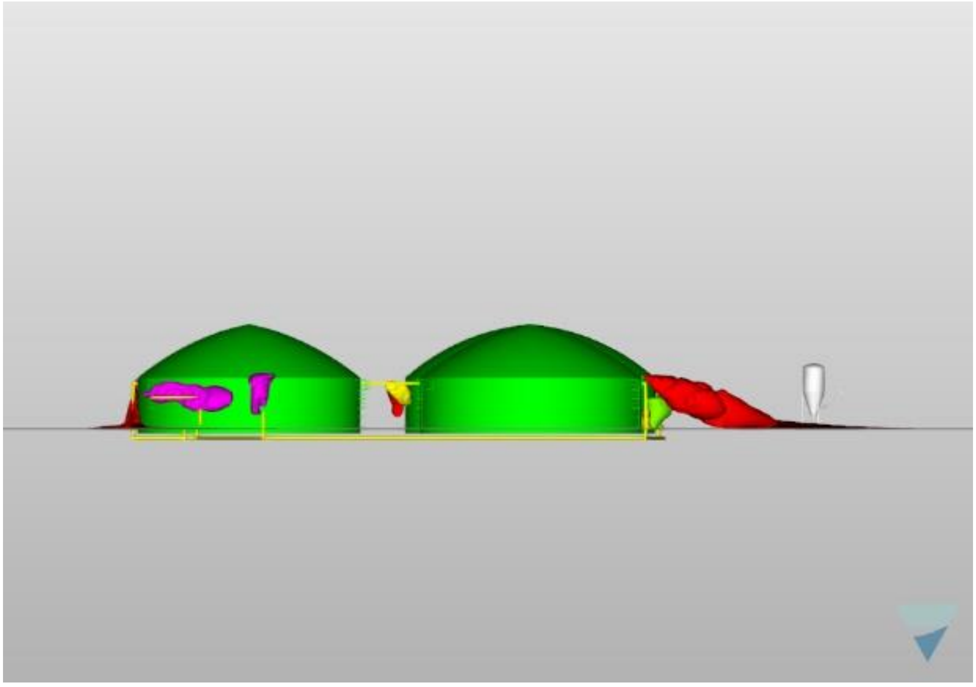


Figure 111: Elevation side view Simulation-10

Figure 110 and Figure 111 make it very clear that the expanding red cloud does not represent a danger as regards contact with the engines of the silos, as it is for a possible trigger due to the passage of machinery with very hot surfaces or, even rarer, the trigger due to the rubbing of the blade with the ground. The same considerations were made for 4.2.2.3.

4.2.2.11 Simulation 11

- Wind speed: 3 m/s;
- wind direction: Nord-Ovest;
- atmospheric temperature: 32.6°C;
- *LEL*: 61.87 g/m^3;
- *UEL*: 1000 g/m^3.

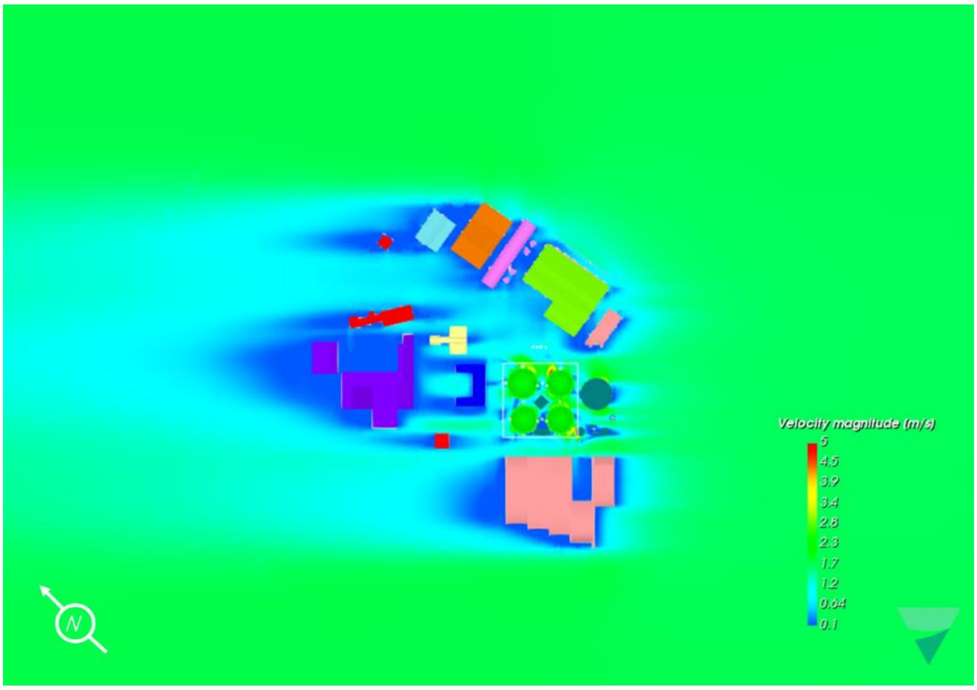


Figure 112: Velocity magnitude Simulation-11

- Convergence: -4.4971 *rms.*

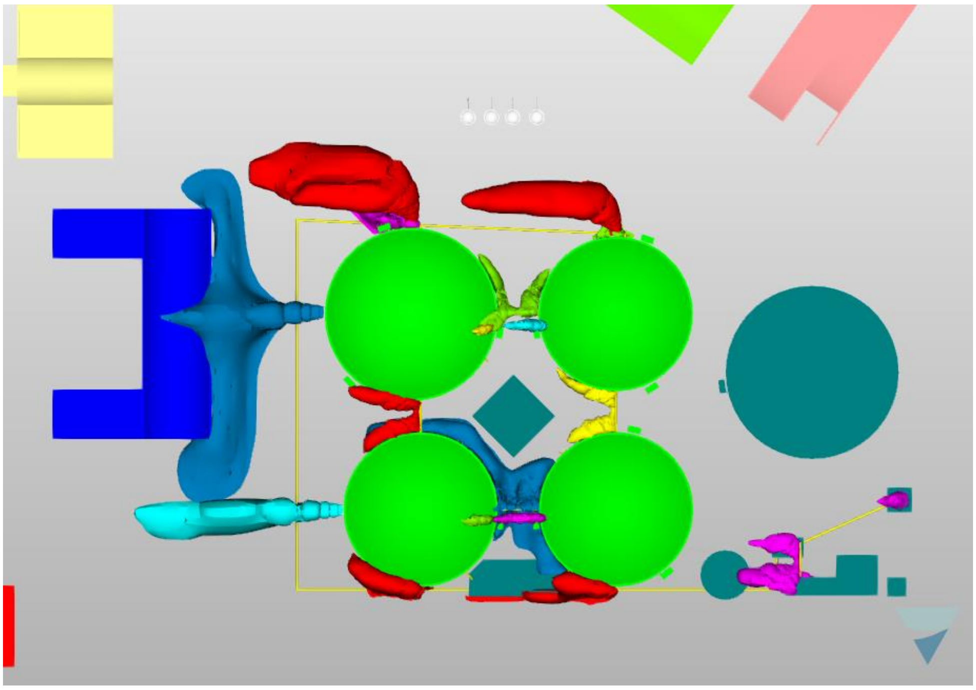


Figure 113: X-Y plan view of gas clouds Simulation-11

The comparison between this simulation and the 4.2.2.4 leads to the conclusion that the temperature, in this specific case, begins to cause differences in the conformations much more evident than the previous ones, especially for what concern the clouds coming out of the tarp of the digesters.

Just like 4.2.2.4, the criticality is represented by the cloud that almost covers the garage bringing inside, if there are open or not perfectly insulating fixtures, the biogas emitted. The danger linked to this scenario is mainly due to the processes carried out and the machinery contained within it.

It is also interesting to highlight the *red* masses of gas that almost completely invade the roadway. The next two images are useful to understand at what level the gas floats above the road.

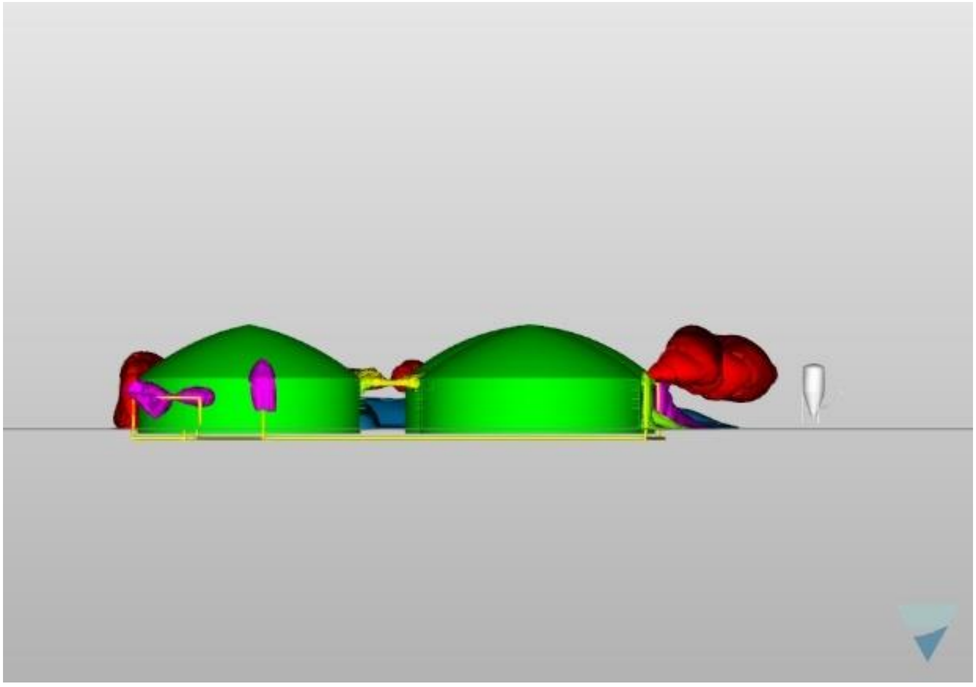


Figure 114: Elevation side view Simulation-11

These two clouds certainly represent a critical issue, especially for the extension that mainly characterizes the one coming from digester 4.

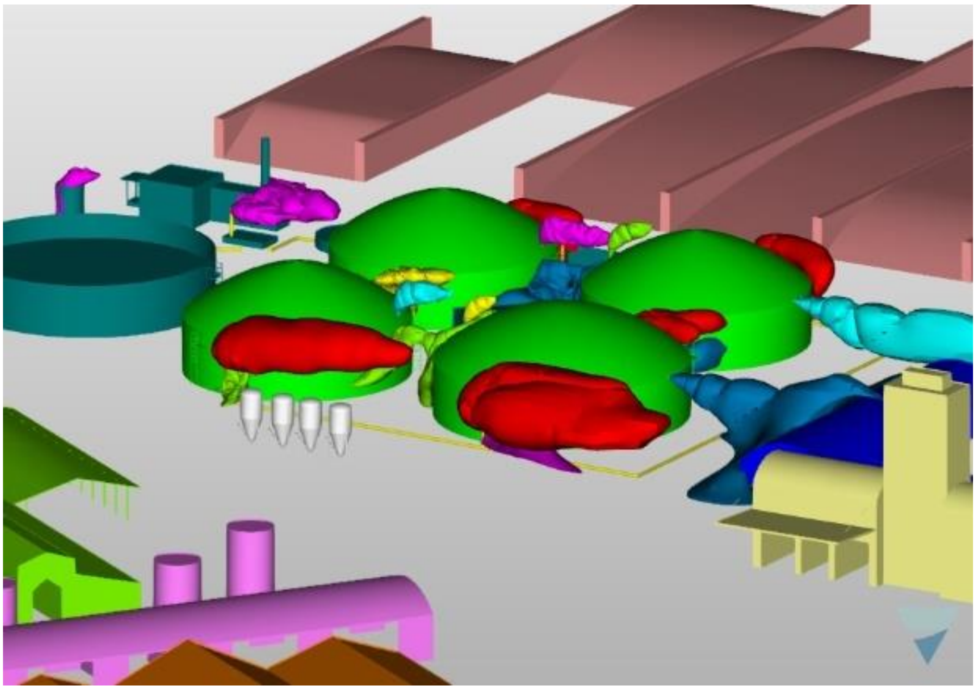


Figure 115: 3D view of the results Simulation-11

4.2.2.12 Simulation 12

- Wind speed: 3 m/s;
- wind direction: North;
- atmospheric temperature: 32.6°C;
- *LEL*: 61.87 g/m^3;
- *UEL*: 1000 g/m^3.

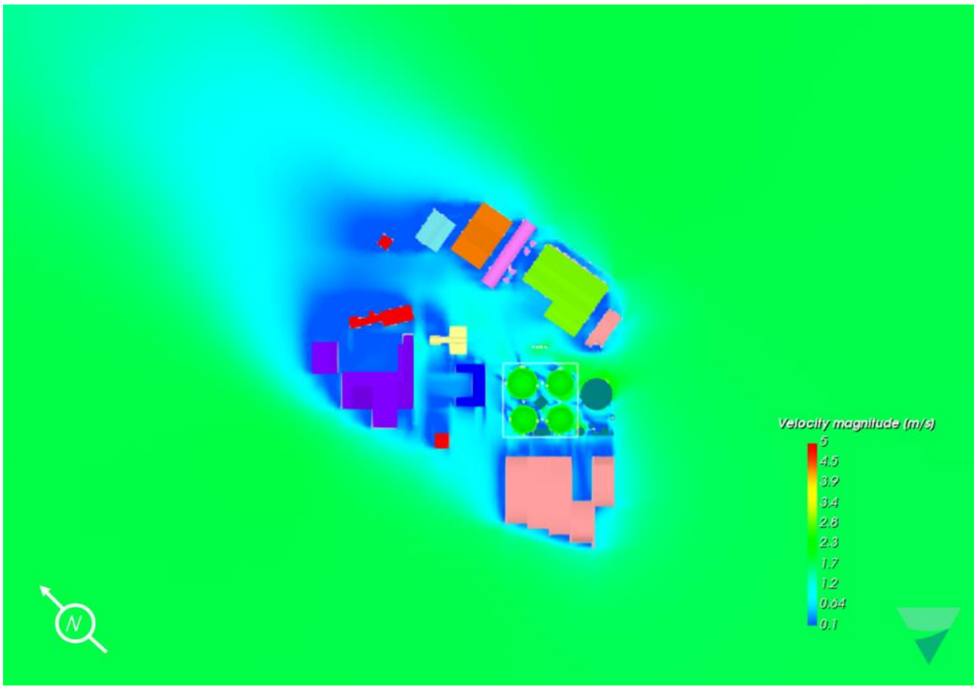


Figure 116: Velocity magnitude Simulation-12

- Convergence: -3.9593 *rms.*

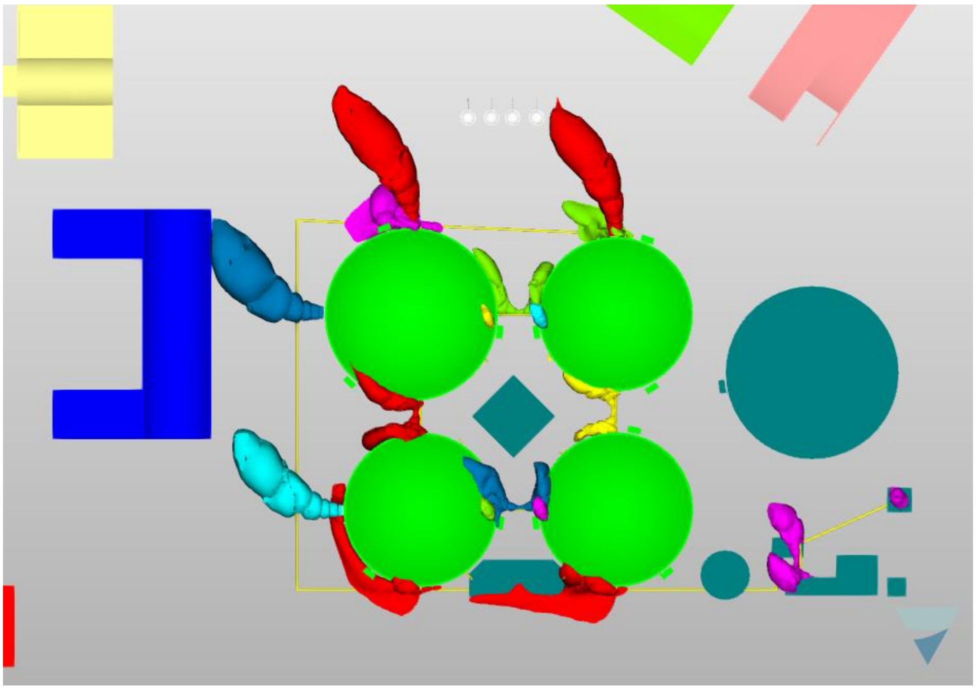


Figure 117: X-Y plan view of gas clouds Simulation-12

The worst-case incidental scenarios in this case concern a possible penetration of gas into the garage and contact with hot surfaces along the two driveways.

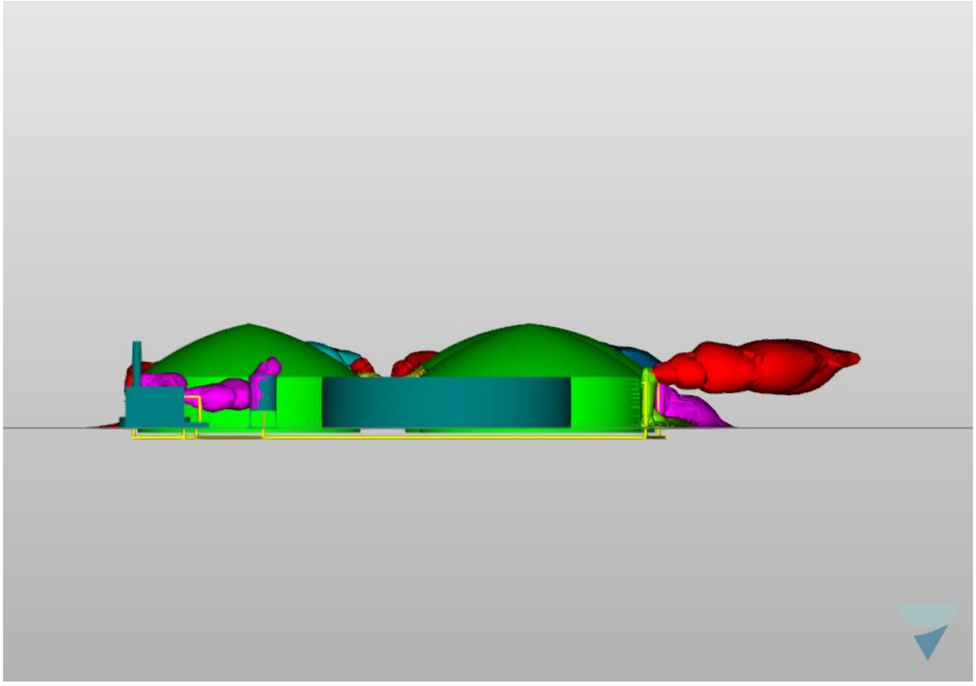


Figure 118: Elevation side view Simulation-12

A further risk derives from the *magenta* cloud coming out from the point of rupture of the pipe of digester 4, the hypothesized trigger is the same as the *red* cloud, with the difference that for what concern this new volume of fluid, the latter develops at heights easily accessible even from an exhaust pipe of a conventional vehicle (rarely passing through).

4.2.2.13 Simulation 13

- Wind speed: 3 m/s;
- wind direction: North-East;
- atmospheric temperature: 32.6 °C;
- *LEL*: 61.87 g/m^3;
- *UEL*: 1000 g/m^3.

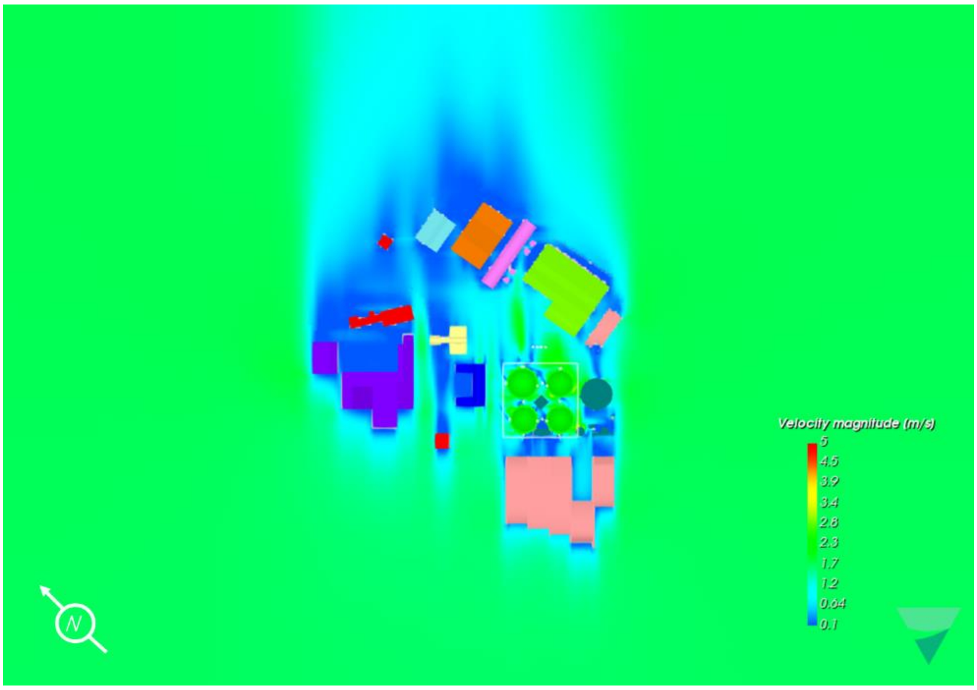


Figure 119: Velocity magnitude Simulation-13

- Convergence: -3.9712 *rms.*

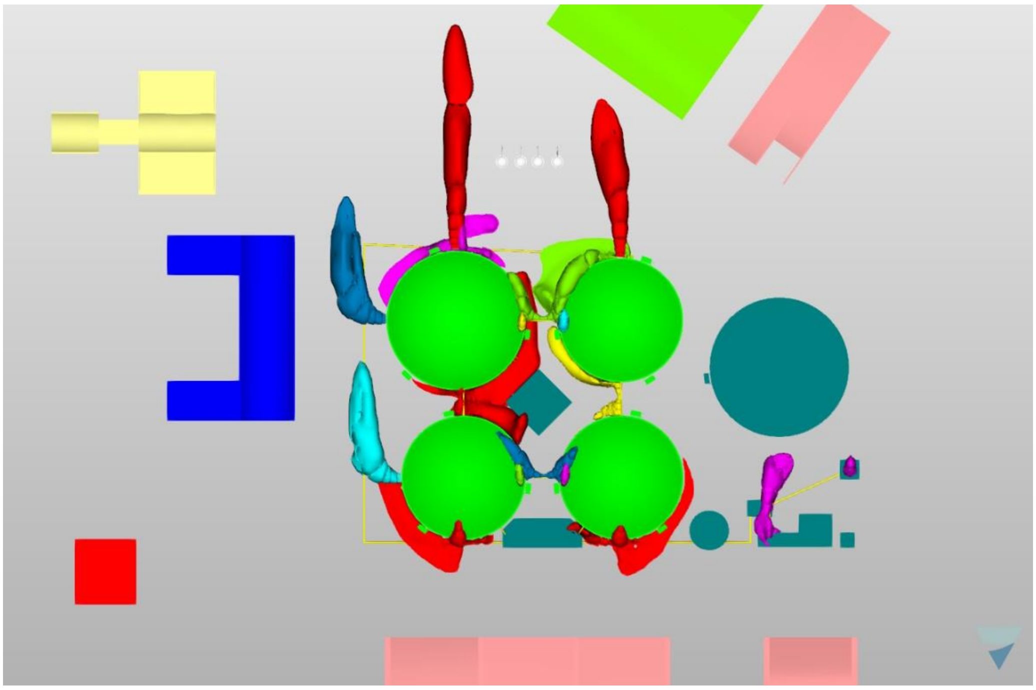


Figure 120: X-Y plan view of gas clouds Simulation-13

With this setting the wind facilitates the distribution of a large mass of gases at a dangerous concentration capable of reaching important distances and, if associated with a change in the direction of the wind, could lead to critical scenarios characterized by the gas that comes into contact with surfaces or machinery such as those seen in previous analysis. Also with regard to this type of configuration, it is crucial to identify any dangers by studying the share of cloud spread so as to assess the possible danger deriving from the contact of passing machinery and their surfaces.

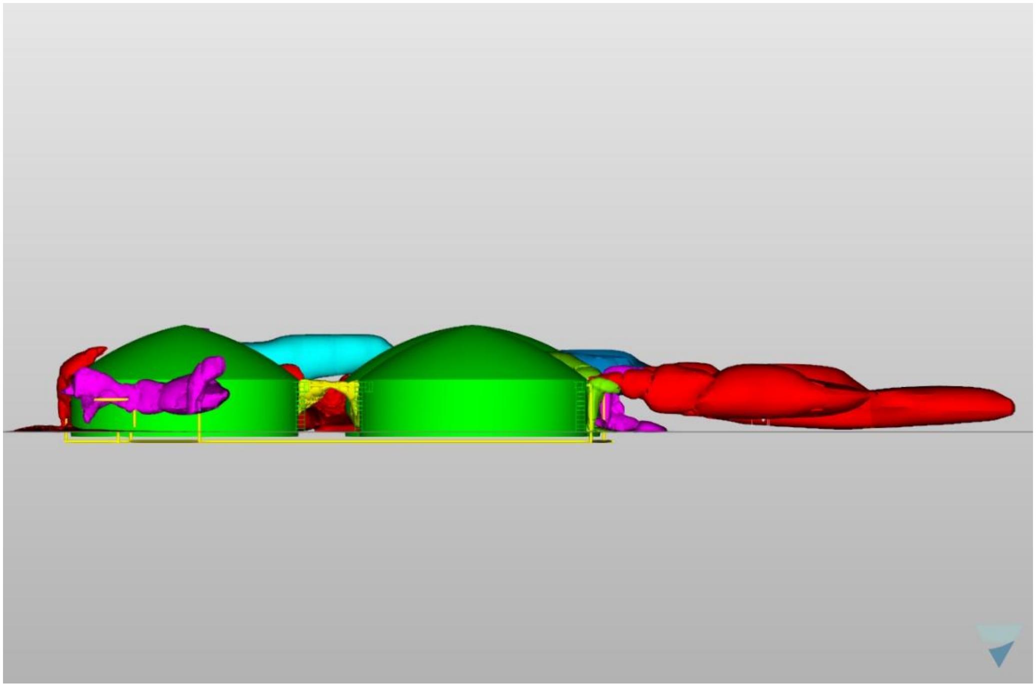


Figure 121: Elevation side view Simulation-13

Figure 121 concerns a North-West elevation view: it is easily noticeable the danger of the cloud (*red* mainly) due to a distribution altitude that also reaches the ground exceeded a short distance from the digester.

4.2.2.14 Simulation 14

- Wind speed: 0.1 m/s;
- wind direction: North;
- atmospheric temperature: 32.6°C;
- *LEL*: 61.87 *g/m*^{3};
- *UEL*: 1000 *g/m*^{3}.

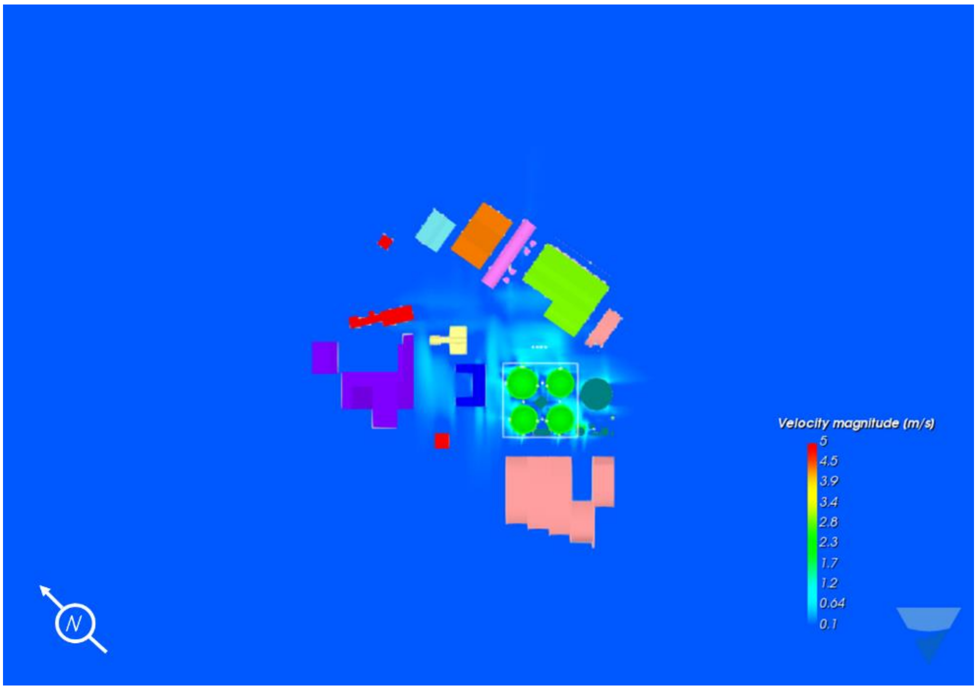


Figure 122: Velocity magnitude Simulation-14

As for *4.2.2.7*, a wind with a speed of 0.1m/s in a northerly direction was adopted. Also in this case the effects of this choice are considered.

- Convergence: -4.2929 *rms.*

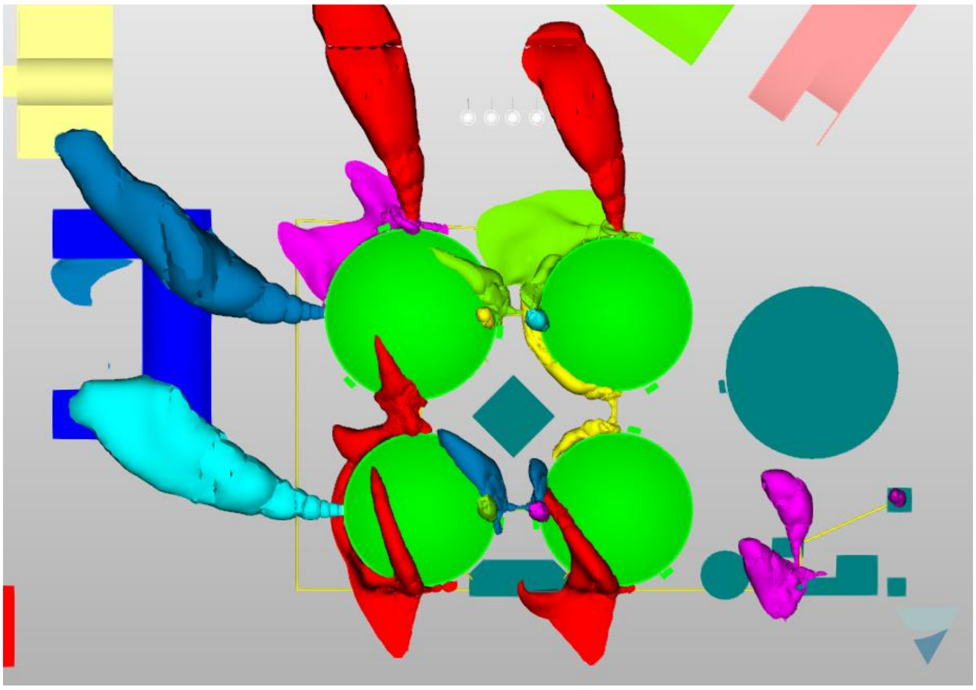


Figure 123: X-Y plan view of gas clouds Simulation-14

If Figure 122 is compared with that of simulation 7 (no wind and temperature of -9.3°C), it is evident that in this case the gas has dispersed much more than 7. From this one can draw the conclusion that when there is no forcing of any kind, what regulates and influences the diffusion of gases most is their density. On the contrary, when there is a mass of air moving with an appreciable speed at stake, the motions related to the different densities take on less importance until they appear without any influence on the model.

As far as this simulation is concerned, the critical points identified through this view are many. These include the loss of gas from the flange downstream of the cogenerator (Figure 124).

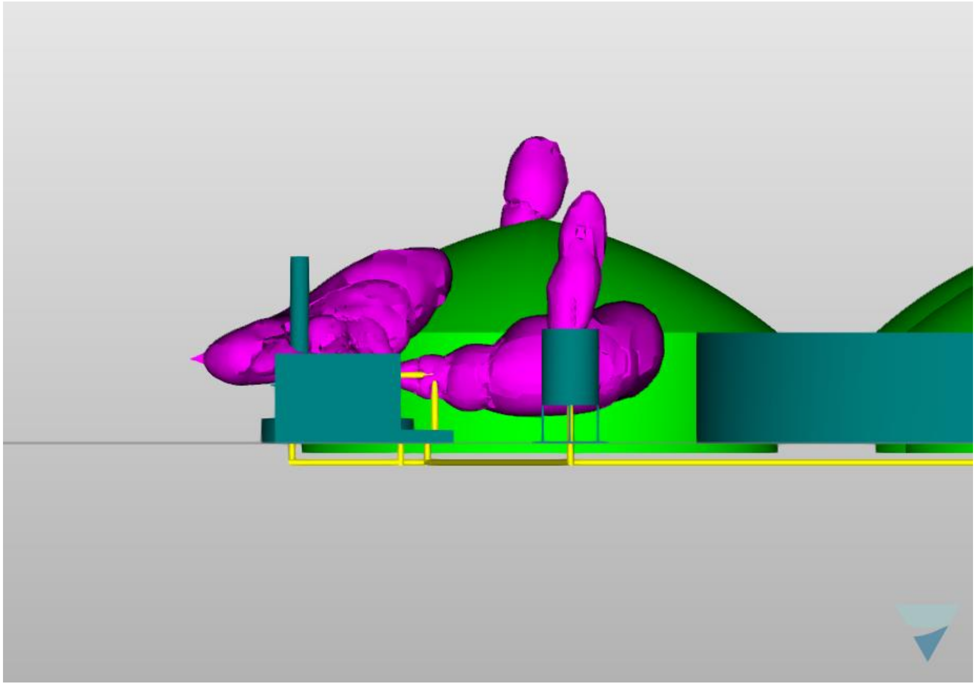


Figure 124: Elevation side view Simulation-14

The clouds under analysis concern those caused by the rupture of the flange located downstream of the cogenerator, its loss occurs in a horizontal direction as already described in the previous chapters. The dispersion of the gas, although it seems critical, is not because the area above which the biogas expands is not crossed by vehicles of any kind and is not in the vicinity of dangerous surfaces. The proximity to the safety flare is not alarming since the external metal wall ensures much lower surface temperatures than those that would cause the gas to ignite. During the operation of the flare it is very difficult for gas to creep into the cylinder and consequently getting directly in contact with the torch flame is hard to happen.

Below, as a summary, a graphic is shown representing the trend of convergences of all the simulations just commented. An unexpected positive peak was reached by simulations 03 and 10 characterized by wind at 17 m / s coming from the South-West and with temperatures respectively equal to -9.3 and 32.6 ° C, this represents a lower precision in the resolution of the iterative algorithm. This particular variation is due to the effect of small turbulences probably caused by the trench geometries.

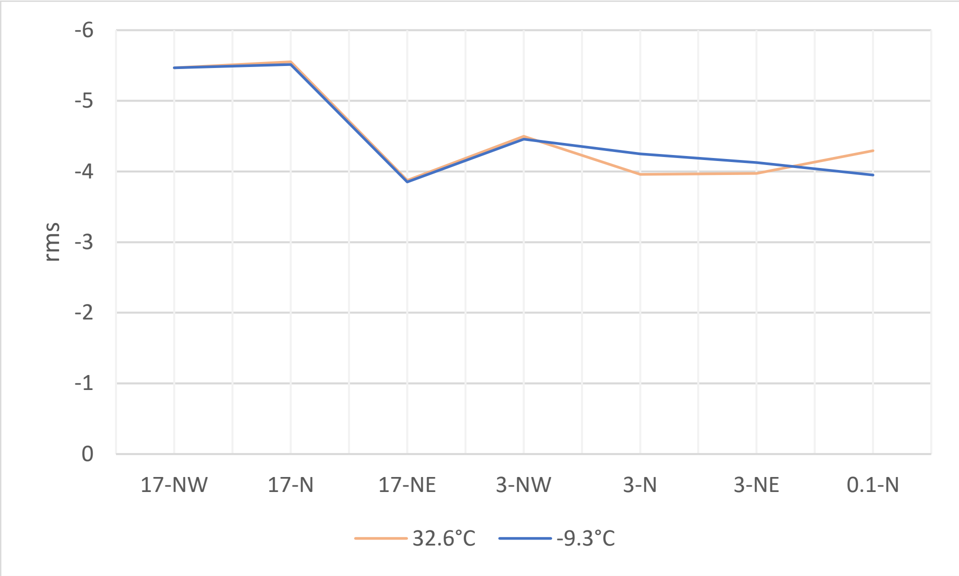


Figure 125: Convergences comparison

The most critical scenarios are represented by wind speed conditions close to zero or in any case with medium/low speed. These cases are made even more realistic considering that in an area such as the one on which the biogas plant in question is built, the winds have very low speeds: for most of the time during the year with the recorded wind speed equal to 0 m/s. In these wind conditions there is also a big difference between simulation 07 and 14; as far as the other simulations are concerned, they are similar to each other due to the presence of a forcing that causes a dilution of biogas in the atmosphere by lowering concentrations. A final conclusion to be drawn from the analysis of these results concerns the effect of temperatures on biogas dispersion. From what can be observed, the air temperature is almost irrelevant, this is because although there is an excursion of almost 40°C between the two macro-classes of simulation, biogas always has a higher air temperature and also a higher density.

4.2.2.15 Conclusions

The analyzes carried out with biogas as *a contaminant* were 14 in total, the goal has been covering all the representative climatic conditions so as to be able to provide a general framework for the observation of the possible risks due to the emission of the gas throughout the year.

At the beginning of the analysis, it was decided to work on two main factors in order to evaluate every possible eventuality: wind speed and atmospheric temperature. This was done in anticipation of the fact that the different values related to these two characteristics of the model would lead to interesting and varied results.

It is important to dedicate a paragraph to what initially represented an important and determining factor for the setting up of the simulations in view of their outcome: the temperature gradient.

The Vento software, used to perform all the simulations carried out, approximates all the gases to ideals. This led to the conclusion that comparing the air and its components at a given temperature (-9.3°C and + 32.6°C) with the biogas, the difference in density and molar mass between this two would have led first to a shift immediately visible of the mass of biogas gas upwards and subsequently to different expansions of the various gas clouds for the two temperatures, very different from each other (ΔT= 41.9°C).

With regard to this first point, so the upward shift of the gas, the explanation can be found in the following representations. By way of example, only a few will be reported, the most representative. The means of representation is the "streamline representation" defined by curvilinear lines that graphically summarize what is the wind path for a given area of the model.

The following images are representative of the gas clouds coming out of:

- Simulation 01: from the opening created in the membrane of the digester 1 and facing North-West.

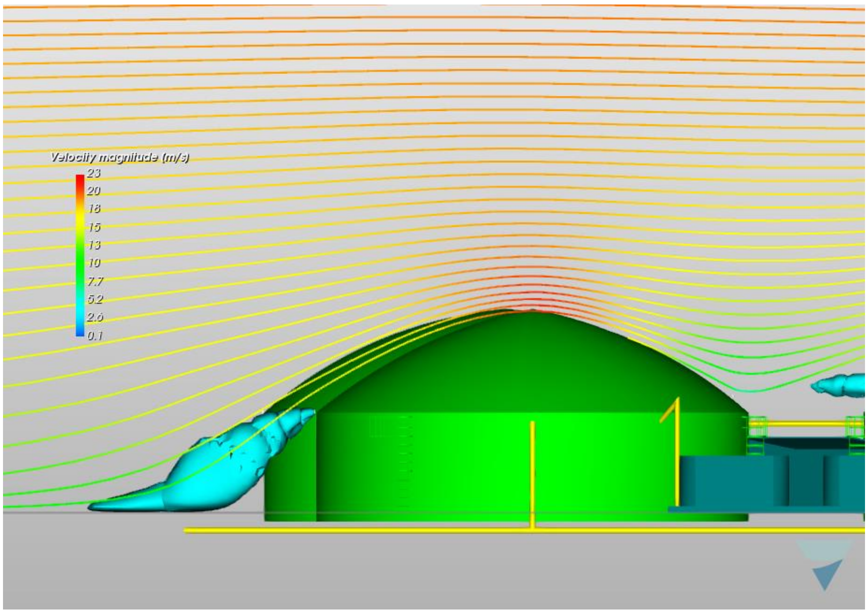


Figure 126: Streamlines Simulation-01

- Simulation 03: from the opening created in the membrane of the digester 4 and facing North-West.

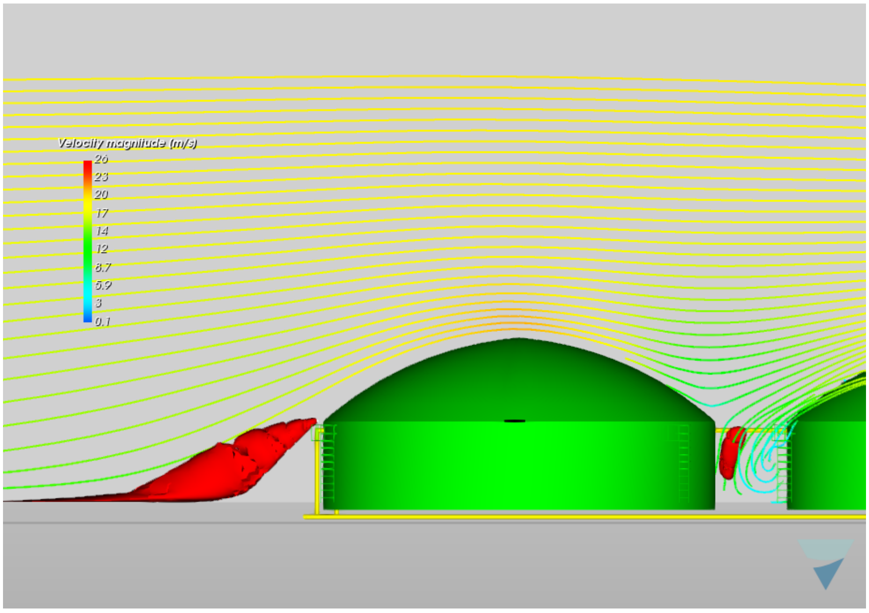


Figure 127: Streamline Simulation-03

- Simulation 08: coming out of the failure created in the membrane of digester 1 and facing the garage (North-East direction).

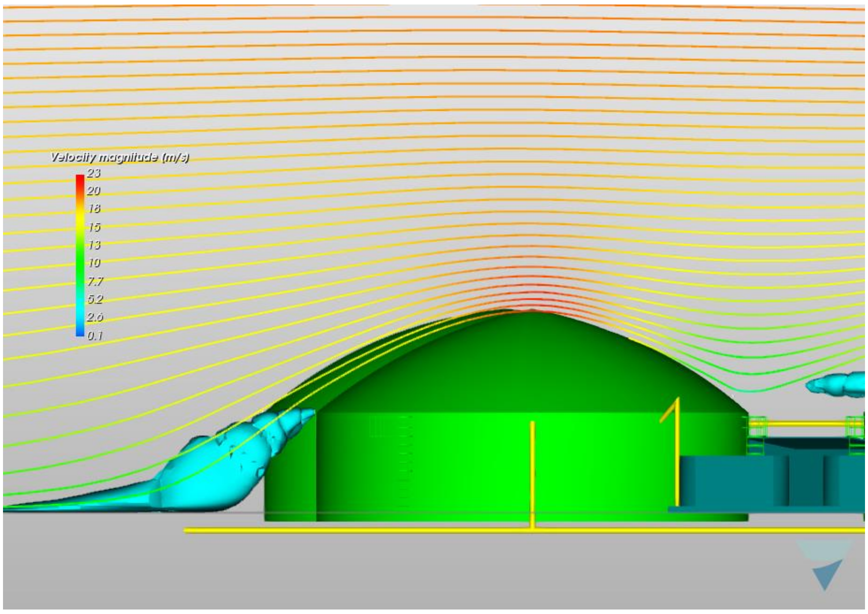


Figure 128: Stremline Simulation-08

- Simulation 13: coming out of the flange of the biogas extraction pipe and connected to the digester number 1 (Figure 129 and Figure 130) and number 4 (Figure 131).

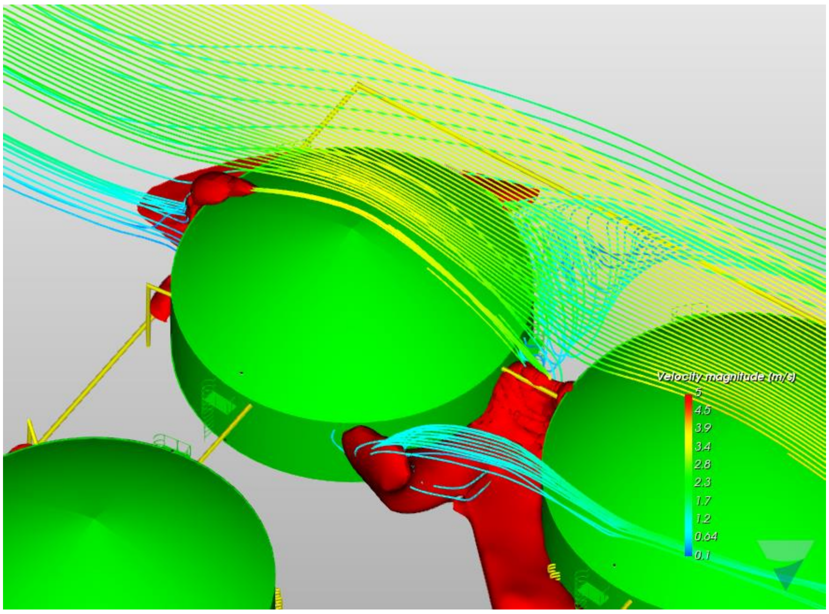


Figure 129: 3D view of streamlines Simulation-13

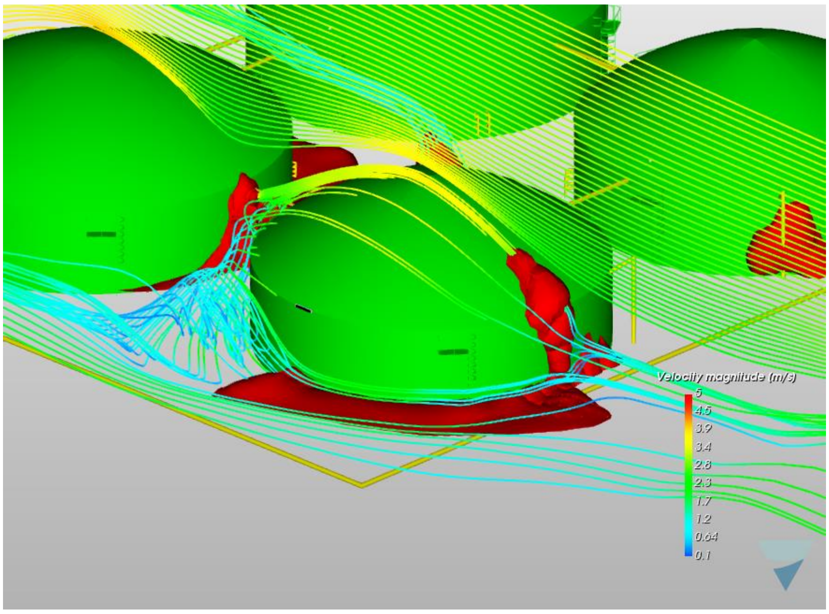


Figure 130: 3D view streamlines Simulation-13

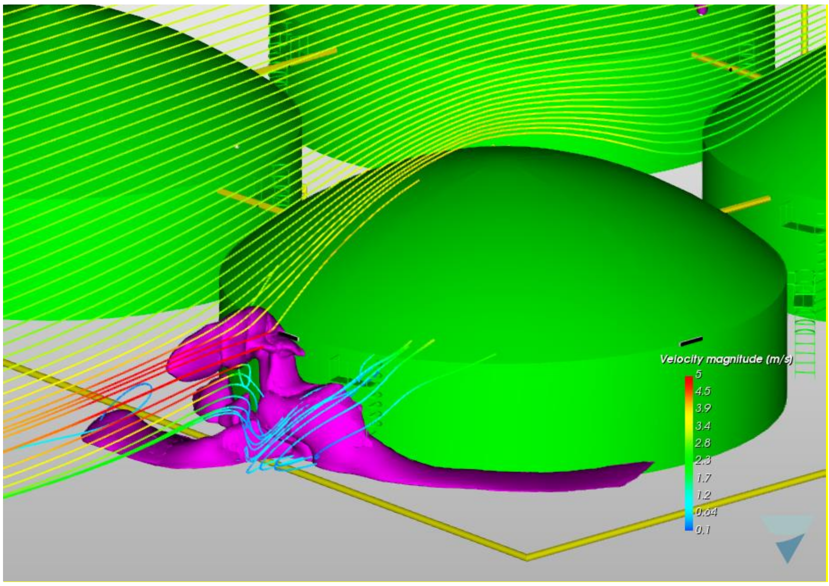


Figure 131: 3D view streamlines Simulation-13

In correspondence of the digesters what leads the wind to push the biogas towards the ground or to follow particular paths (as visible inFigure 130and Figure 131) is the conformation of the tanks and domes themselves that due to pressure and depression effects because of the wind running along the gasometric domes of the digesters heads towards the ground also dragging the biogas with it.

Instead, as far as what is written about the effects of the temperature difference is concerned, authors would like to recall what was commented during the analysis of the simulations. In summary, for most simulations the effect of temperature is only slightly visible. In the remaining cases, in which the wind does not represent the forcing with more influence, the variation between the same *clouds* is very evident and leads to the materialization of more or less critical scenarios.

Below, by way of example, simulations carried out under the exact same conditions but with different temperatures are attached. The criterion used for the choice of the simulations to be exhibited was the desire to show what variation there can be as the wind speed changes; therefore, those selected are characterized by the three different wind speeds:

- simulation 01 and 08;

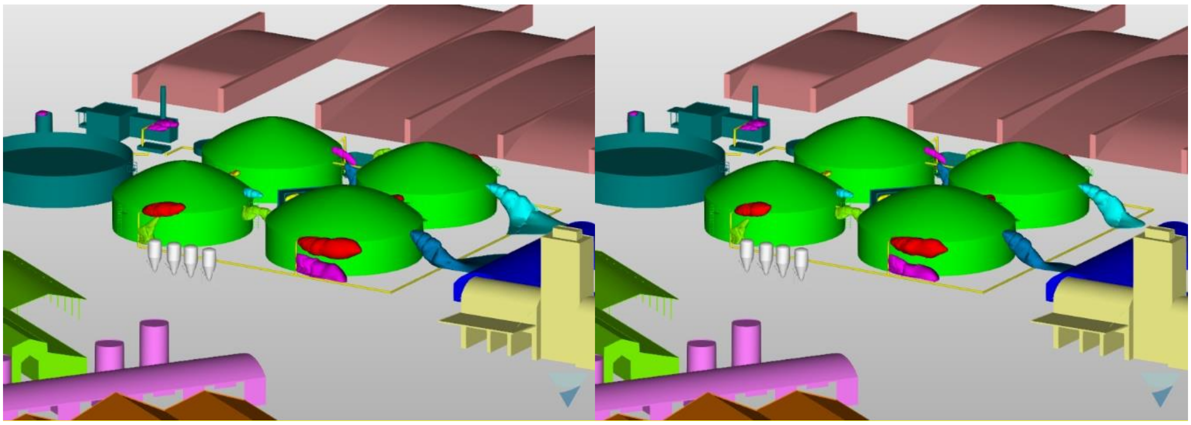


Figure 132: 3D view comparison Simulation 01 -08

- simulation 06 and 13;

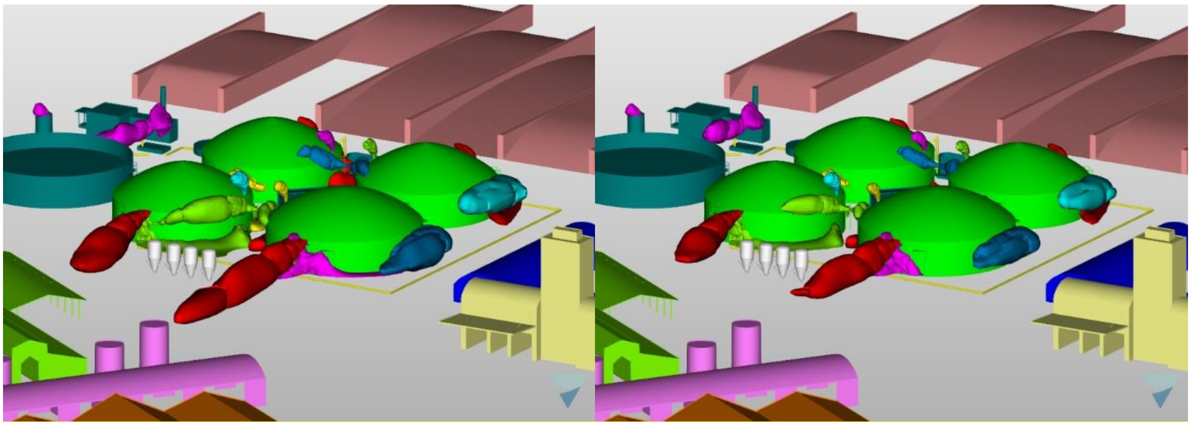


Figure 133: 3D view comparison Simulation 06-13

- simulation 07 and 14.

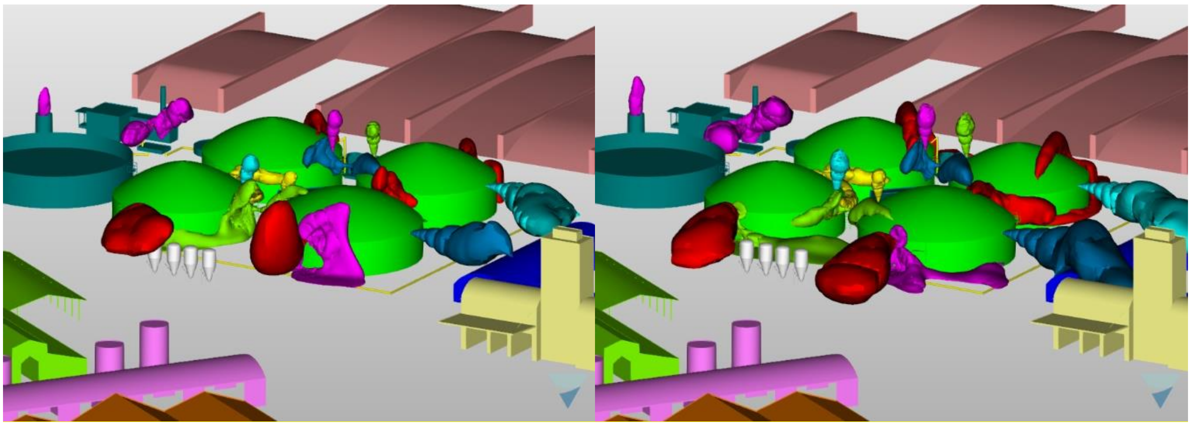


Figure 134: 3D view comparison Simulation 07-14

As possible to observe, as the wind speed decreases the conformation of the clouds diverges more and more, and what matters the most is that their extension follows the same rule. This variation is also accentuated when comparing the case of wind at 3 m/s and 0.1m/s.

Observing, therefore, the simulations reported, and probably also the remaining ones concerning biomethane, the temperature gradient implies a slight difference only for cases in which the acting wind is strong, in fact the volumes and extensions of the clouds are just slightly different, this can mean that despite the important temperature gradient and the difference in density (air density equal to 1,225 kg/m^3 and biogas with 1.18 kg/m^3), the forcings included in the model such as gas outlet speed, orientation and extension of the emission surface, wind direction and speed have such an important effect that the contribution of specific weights is negligible. All this is concerning mainly cases of wind at 17 m/s, if the comparison is made between simulation 07 and 14 the difference between the various clouds is clearly visible to the point that in the configuration with 32.6°C, the risk of penetration of the gas coming out of the digester 4 membrane (blue cloud) is much higher. (simulation 07 and 14 respectively).

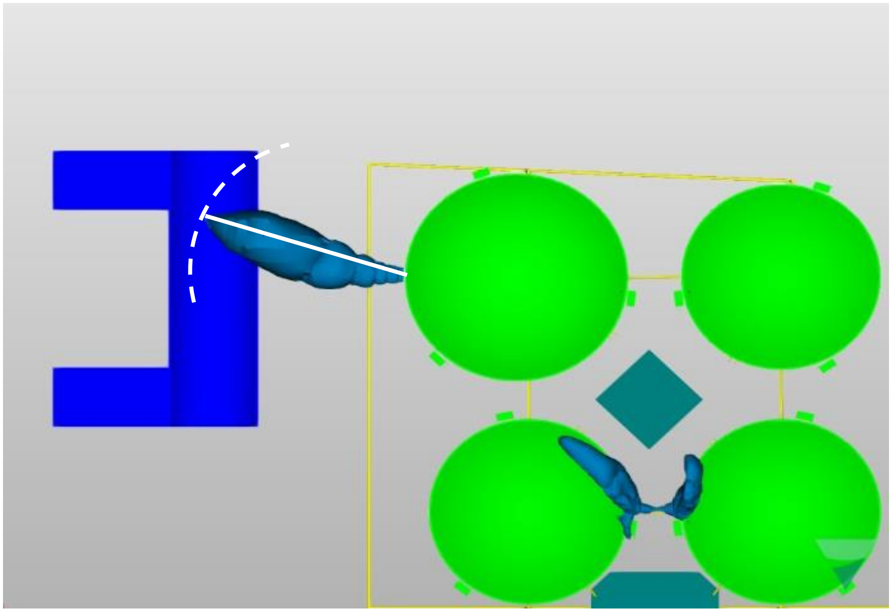


Figure 135: Plan comparison

In the figure are represented, in addition to the respective plants including only the gas cloud of interest, also the views on the south-west side of the cloud escaped from the digester 4 membrane (*blue* cloud) in the direction of the garage.

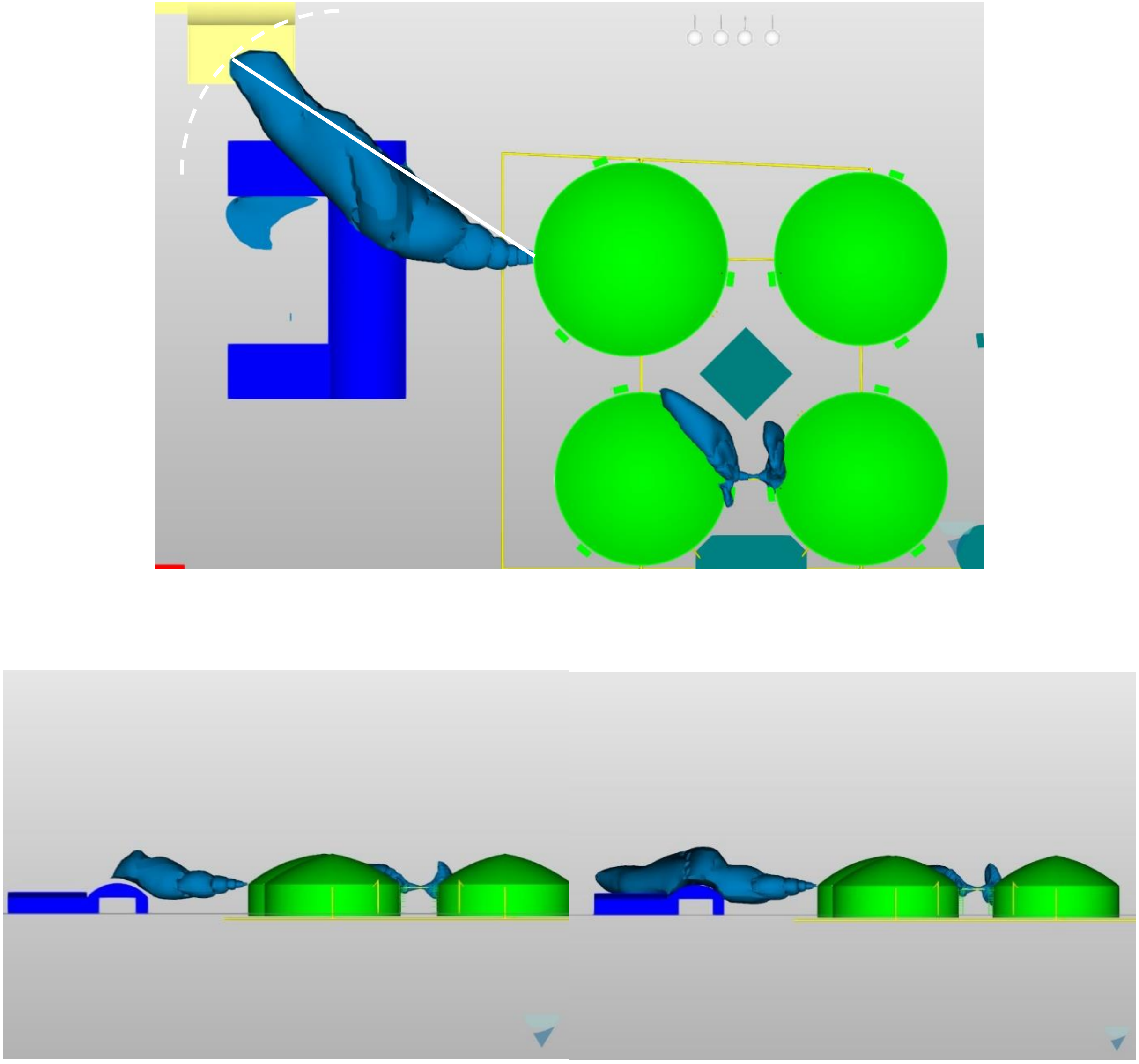


Figure 136: Cloud extension comparison Simulation 07-14

A further detail provided is the extent of the gas cloud subject to analysis. In this case the measurement of the coverage radius taken starts from the center of the emission surface to the end of the cloud. In the case of simulation 07, in fact, the radius measured starting from the emission surface and the extreme of the cloud is about 26.25m while as regards simulation 14 the cloud, although with a more curved trend, has an extension of 53m, more than double.

For the purpose of a realistic analysis, the consideration of an almost zero wind follows what is reported in the .epw file of the area on which the complex stands (on a daily basis, the wind with a speed between 0 and 0.99 m / s covers 71% of the days of the year). If only the climatic conditions of the site are considered, being the condition of calm wind the prevailing one, the results of these analyzes in particular, and assume a relevant importance and that should certainly be deepened with further analyzes characterized by other intermediate temperatures.

From what can be seen from the results of the various analyzes, it is clear that the greater extension of the clouds is the result of calm wind conditions. The reason for this is traced back to the ability of the gas to disperse less easily if with calm wind than with strong, keeping concentrations high. In fact, if studying the extension of air volumes containing even a small part of biogas, this would be able to cover a huge portion of the territory in fast wind condition and a smaller extension with calmer winds. As far as the work in progress is concerned, all volumes of air containing percentage of biogas less than the percentage of explosiveness will not be considered because they are not dangerous for the purposes of fire analysis.

This is a first conclusion about what revolves around the most important extensions of the clouds to critical areas. The results reported both for the extension of the clouds and for the conclusions regarding the reasons for air expansion require further investigation, especially through the use of machines much more powerful than those used so far and also in the next part and would also require more time for the execution of further "intermediate" simulations. The choice of boundary conditions in a work of this type or similar certainly plays a key role in obtaining realistic and reliable results, also for these would need an in-depth study on the climatic conditions of the area immediately surrounding the plant, very detailed assessments on the chemical composition of the biogas and on the type of raw material introduced.

The authors want to remind that what is done whit this work is to propose first of all the use of a rather innovative, effective, intuitive and fast software to use for a purpose for which until now there have been no similar application; then it is to try to propose a useful track to anyone who wants to undertake a CFD analysis of this type and for this purpose. Clearly this work has been based on months of study and refinement and is supported by intense statistical but above all legislative research that would require further refinement on the computational side mainly.

The management of this type of plant is carried out by specialized personnel who, being highly trained on the operation of the plant and on the internal safety standards of the plant, are easily able to repair the possible damage in the shortest time, maintain an excellent level of maintenance and in complete safety. This type of analysis considers only the "worst possible case" that finds realization in accidental events such as complete rupture of the flanges or tearing of the cloth covering the digester. This last consideration led to assume the flow rates and extent of the surfaces visible in the previous chapters.

5 Future scenarios

In the context of the current uncertain geopolitical situation, there is no doubt that the exploitation of agricultural resources for biogas production could represent a strong element in the context of environmental strategies at European level and in the national implementation of the objectives of the *Next Generation EU (PNRR)*. Studies carried out by the Consorzio Italiano Biogas (CIB) show how the development of biomethane production, obtained by maximizing the energy recovery of organic residues of agricultural origin, can be considered strategic for the strengthening of a circular economy based on reuse and at the same time could make a substantial contribution to achieving the European decarbonization targets set in the *2030* AGENDA , i.e. the Programme of Action signed by 193 member countries of the United Nations and approved by the UN General Assembly. In particular, if conveyed in the national distribution network, biomethane could lead to an overall saving of greenhouse gases compared to the life cycle of fossil methane, between 80 and 85% (46). It also shows the status of advanced biofuel, if obtained from the materials listed in Part A of Annex 3 of the Italian Ministerial Decree of 10 October 2014 and subsequent amendments and additions (47).

5.1 Biomethane

Biomethane represents a further step compared to the exploitation of biogas for the production of electricity and thermal energy "in situ". The process for obtaining biomethane involves the refining of biogas, separating the two main components, respectively methane (CH_4) and carbon dioxide (CO_2), allowing a considerable energy improvement. This is promoted, for example, by avoiding the inefficiencies that can occur in the electro-thermal enhancement of biogas where there is a poor valorization of heat, often linked to the intrinsic inefficiencies of a district heating network, due to the distance between users and cogenerator. These distances are often linked to the "rural" nature of these types of system, i.e. relocated with respect to urban centers, which can often lead to the inconvenience of heat exploitation and therefore sees the need to be released in the atmosphere through the radiators integrated into the cogenerator group.

5.2 Current situation in Italy

The approval of the Italian Ministerial Decree of 2 March 2018 issued by the Minister of Economic Development in accordance with the Minister of the Environment and the Protection of the Land and The Sea and the Minister of Agricultural, Food and Forestry Policies, relating to use of biomethane and other advanced biofuels in the transport sector followed the fact that the previous decree dated 5 December 2013 did not lead to significant increases in the implementation of new plants for the production of biomethane. At that date it emerged that in the meantime Italy has already reached the minimum targets required by the European Union to 2020, in terms of overall renewable sources and electricity, while it is lagging behind for the target of renewable sources in the transport sector. In order to promote development in this direction, it was considered necessary to give priority to biomethane to be used in the transport sector, while for the remaining uses a subsequent update decree was provided to be issued downstream of the achievement of the target of renewable sources in transport. The situation that has arisen has therefore created many expectations and has sparked the interest of operators in the sector (48).

While the industrial sector (waste, agro-industrial waste, etc.) has seen a rapid transposition by the market, the agricultural sector has appeared slower due to obstacles that are limiting the development of agricultural biomethane including the too limited duration of the incentive guaranteed in the face of major investments and the strong limitations on the biomass that can be used (livestock waste, triticale or sorghum as cover crops and subsequent to the first harvest feed food, some by-products, but not many), difficulties (and costs) of connection to the gas network, technological complexity of advanced solutions (eg liquefaction), strict constraints related to sustainability (mandatory certification) and, at the base of all this, a business plan that envisages the actual convenience only in the presence of specific conditions (ie a low cost of raw materials) (49).

5.3 Conversion of biogas plants to upgrading

The Ministerial Decree of 2 March 2018, relating to the promotion of the use of biomethane and other advanced biofuels in the transport sector, foresee for the possibility of partially or totally converting the electricity production of existing plants into biomethane, while allowing enhancements contextual to the reconversion. In addition to this, the construction of "relevant" biomethane distribution and liquefaction plants for the production of LNG (related to the investment in biomethane) is also planned. In the first case, the incentive system is managed by the GSE (Gestore Servizi Energetici), i.e. the guarantor of sustainable development in Italy, through the promotion of renewable sources and energy efficiency. Gse is a company controlled by the Italian Ministry of Economy and Finance, deals with economic incentives for the production of energy from renewable sources and high-efficiency cogeneration plants. The incentive provides that for producers of biomethane released for consumption in transport, through road, motorway or private distribution systems, Certificates of Release for Consumption (CIC) are issued, which correspond to a value set at € 375 (50) In the second case, LNG is beginning to be considered a concrete possibility, allowing to create more interesting margins while presenting the disadvantage of the technological complexity of a liquefaction system, characterized by high costs.

5.4 Agricultural plant for biomethane upgrading

The upgrading phase of biogas for the production of biomethane consists of a process of gas separation starting from a raw gases mixture i.e . biogas. In order to be used as a fuel for transport or for immission into the national grid, this biomethane must have well-defined quality and purity characteristics and for this purpose there are several technologies that have proven to be technically and economically valuable. The various technologies have specific advantages and disadvantages and for the economically optimal choice it is necessary to consider several factors, including the quality and quantity of the biogas of origin for upgrading, the quality of the desired biomethane and the end use of this gas, the operation of the anaerobic digestion plant and the types and continuity of the substrates used as well as the specific circumstances at the plant (24).

Figure 137: Biogas upgrading group   Source: AB-energy

The upgrading process, although varying in the specific case according to the raw composition of the biogas etc., mainly includes:

- the removal of the sulfur present by desulphurization process;
- the separation of carbon dioxide (thus increasing the calorific value and the Wobbe index), the drying of the gas;
- the removal of minor components such as nitrogen, oxygen, hydrogen sulfide, ammonia and siloxanes;
- the compression of the biomethane at the pressure necessary for the subsequent use of the gas (different depending on the type of use). If the gas is injected into a local natural gas network at low pressure, at this stage odorization is generally also carried out, i.e. the introduction of additives characterized by a marked odor, eg Mercaptani, which allow to immediately identify the possible presence of methane, normally odorless). If necessary, the regulation of the calorific value is also carried out, by means of propane dosing.

The Figure 138is a conceptual outline of the flows, from biogas to biomethane:

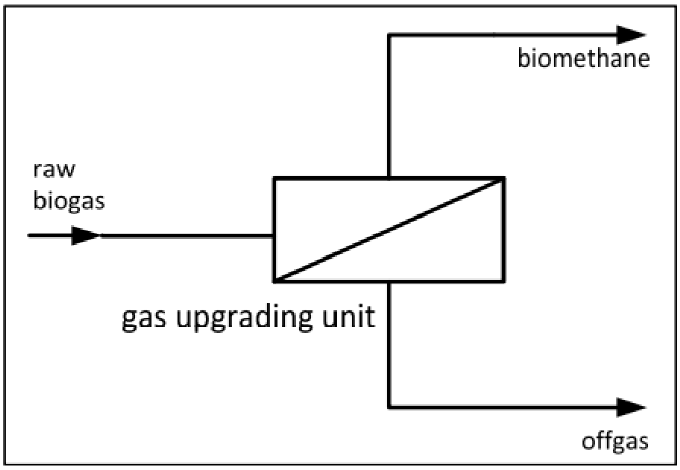


Figure 138: Conceptual scheme of biogas upgrading plant

The biogas stream is subjected to a refining process, as a result of which two flows are derived: a flow rich in biomethane (CH_4) and a flow rich in carbon dioxide (CO_2). It should be noted that the composition of this "waste" gas flow depends on the type of technology adopted: since no separation technology has a 100% effectiveness, this gas flow still contains a variable amount of methane. If it is allowed by law, this flow of gas can be released into the atmosphere otherwise it must be subjected to a further separation process.

The technologies on the market to carry out the *upgrading* are different and of different origin:

- Water scrubbing technology: is based on the ability of a high-pressure jet of water to clean the gas from impurities such as carbon dioxide and hydrogen sulfide. When brought to a low temperature and high pressure, pressurized water allows greater absorption of carbon dioxide than under normal conditions. This technique also reduces the levels of hydrogen sulfide and ammonia contained in biogas. The regeneration of water takes place through the application of a sharp reduction in temperature that allows the anhydride and other former gaseous components to return to gaseous form and separate from the water. To increase the effectiveness of biomethane extraction, the gaseous component obtained from regeneration is fed to the raw biogas entering the upgrading plant. To eliminate any trace of water vapor within the mixture rich in biomethane, the latter is subjected to a passage called *gas drying consisting* of a scrubbing process but using glycolic acid;

- Physics scrubbing with organic compounds: the difference between this technique and the one previously explained is to adopt, as a substitute for water, an organic solvent solution capable of increasing the solubility of CO_2. The choice of this type of system compared to the previous one is mainly due to characters related to the lower amount of liquid needed and the size of the system, which in this case is reduced than water scrubbing;
- Chemical scrubbing/washing: the refining of the gas is due to the absorbent action by some liquids such as glycols or aminos. This method is characterized, compared to the previous one, by the chemical regeneration of the scrubbing liquid. The high selectivity of the chemical reaction in question and the low solubility of the biomethane within the liquid solution used for scrubbing allow a massive and clean recovery of the biomethane left in the washing liquid. The solution adopted is composed of amines that during the regeneration phase of the liquid, although very effective with regard to the extraction of biomethane, requires a large amount of thermal energy to be able to purify the liquid from absorbed contaminants;
- Pressure Swing Adsorption (PSA): biogas is cleaned of contaminants thanks to the ability of some materials to attract and absorb contaminants through surfaces, such as molecular sieves and activated carbon. The material used to separate the components of biogas is mainly represented by activated carbon or molecular sieves. Inside pressurized tanks a stream of biogas is allowed to flow and these sieves physically and selectively absorb all the components different from the bio-methane. Once the bio-methane is cleaned, it is left out of the adsorber while the cleaning of the activated carbons takes place only at a later time through a gradual reduction of the pressure inside the tank, the expulsion of the waste components takes place due to further biogas input. This process reopens the *upgrading* process. A small part of bio-methane can be "captured" along with carbon dioxide and other secondary components. In order to minimize biomethane waste, this mixture obtained from the cleaning of

activated carbon is reintroduced into the *upgrading* cycle together with new bio-gas;

- cryogenic upgrading: exploits the different condensation conditions of biomethane and carbon dioxide contained in raw biogas. The CO_2 following a compression and cooling process get condensed before methane, which remains in the gaseous state allowing the separation of the two components respectively liquid and gaseous;
- membrane technology: the different permeation capacity of the gases is exploited, allowing to separate the biomethane (CH_4) and nitrogen (N) from oxygen (O_2), carbon dioxide (CO_2) and hydrogen (H_2) of the desulphurized gas through a hollow device filled with a material in the form of hollow fibers or straw placed parallel and endowed with a certain permeability. Inside the fibers is allowed to pass the biogas that, due to a pressure differential between the inside and outside of the straw, sees carbon dioxide, ammonia, water and other components leave the gaseous compound (biomethane has a low permeability, therefore, continues to flow undisturbed managing to exit the plant with a high concentration of CH_4. (24)

In general, it is possible to observe how, in recent times, membrane technology has become the most adopted option within plants. (51). The reasons are to be found in the intrinsic simplicity of this technology and in the economy of operation, with a expected service life close to 15 years.

The carbon dioxide separated during the upgrading process can be, depending on the case, released directly into the atmosphere or, thanks to greater awareness and new technologies, exploited through reuse. New plants (in Reggio Emilia, Italy one of the first European plant) are equipping themselves in order to reduce the amount of CO_2 emitted, for example by collecting it for medical purposes, for the food industry or for supply inside greenhouses.

5.5 Integration of the existing plant

To complete the case in question, it is assumed the integration of a refueling station for motor vehicles with compressed methane (CNG) fuel and which are well suited to be powered by biomethane. As this is a biofuel capable of reducing greenhouse gas emissions in vehicles to levels close to zero, the environmental benefit is easily identifiable: by using biomethane as a substitute or blended fuel, greenhouse gas emissions can be reduced by about 70% and nitrogen oxide emissions by 90%. (52).

The production of electricity and heat through cogeneration is not ceased and therefore the related plants are maintained: the production of biomethane through upgrading is actuated in parallel, ensuring, among other things, the possibility of exploiting the surplus biogas linked to the fluctuations in the production of digesters linked, for example, to the daily loading phases of the solid raw material.

Below, Figure 139, is an example diagram of the updated system:

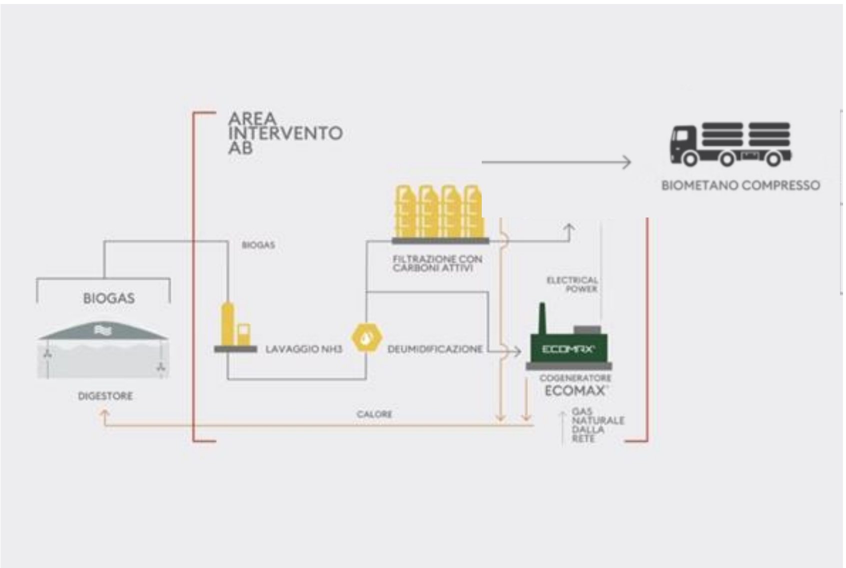


Figure 139: Cogeneration and biomethane refueling

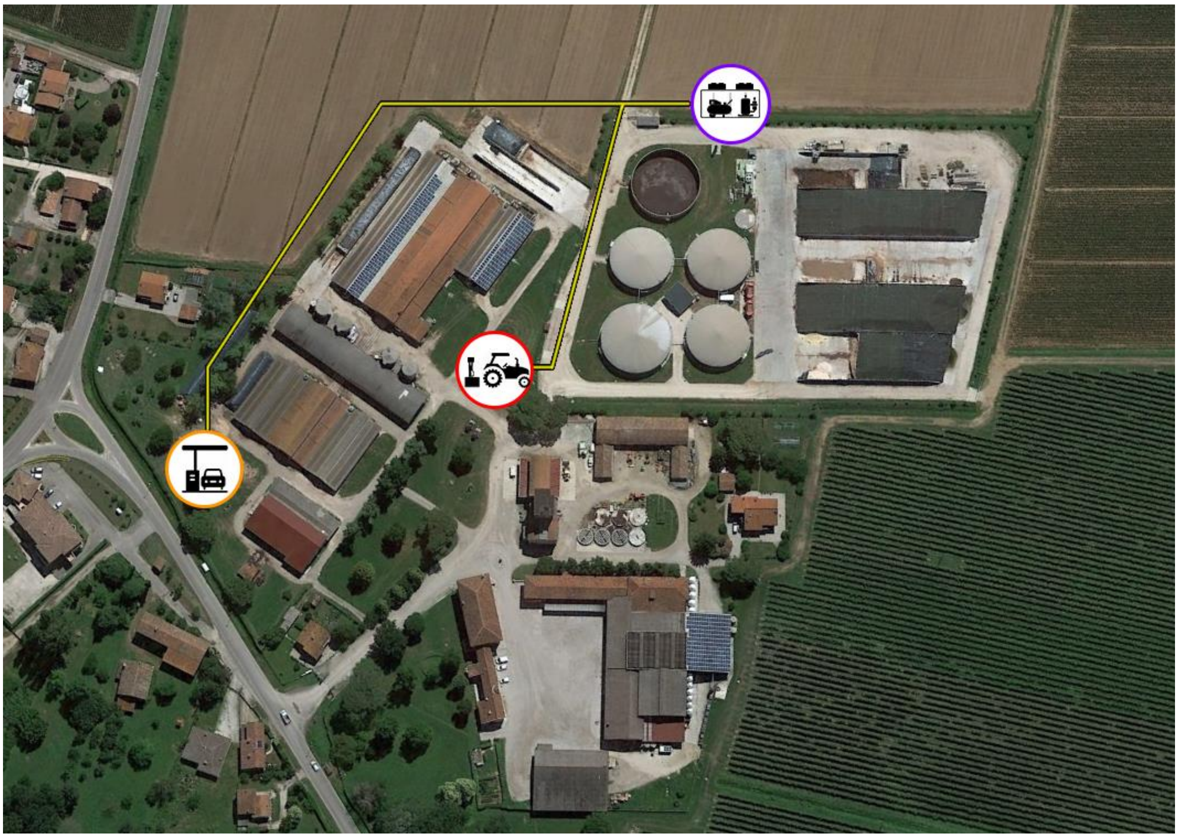


Figure 140: Bio-methane distribution map

5.5.1 Upgrading stations

The biogas from the digesters undergoes a preventive purification in order to eliminate as much NH_3 ammonia as possible inside the mixture and is subsequently sent to the heat exchanger served by the chiller for dehumidification. The mixture obtained, composed mainly of methane CH_4 and carbon dioxide CO_2, at this point of its process takes different paths depending on the final destination: the part destined for cogeneration is sent directly to the *CHP* group while the portion intended for compression is subjected to a further filtration cycle through layers of activated carbon, organized on skids, for the removal of pollutants. The quality of the biomethane produced by the plant is continuously controlled by gas chromatograph.

The successive operation is the actual upgrading process. Given the small size of this part of the system, in this case a modular system is installed inside a container, so as to contain the space necessary for the transportation and installations and at the same time have the different components under control. The system thus composed allows to manage a biogas flow of 150 Nm^3/h that after the process, considering a concentration of CH_4 equal to 55%, will correspond to 82.5 Nm^3/h of biomethane and 67.5 Nm^3/h of carbon dioxide.

The plant has been spatially subdivided, placing the upgrading station near the plant for the production of biogas, leaving to special compressors installed near the fuel stations the task of raising the CNG pressure to the values required for recharging the CNG storage cylinders. This configuration has a pressure of biomethane in transfer from upgrading to compressor in the order of ten bar (53), making possible the usage of pipes with reduced thickness compared to those that would be necessary for high pressure (about 250 bar in operation). Through this solution, substantial savings are therefore guaranteed from an economic point of view and at the same time the complications that high-pressure pipes (about 250 bar) would entail are avoided, including difficulties in creating and maintaining safety distances from underground lines. This plant layout also allows to maintain a centralized positioning of all the technological components of the system, thus facilitating their control and maintenance.

5.5.2 Public CNG refueling station

In a portion of the company's surface, located on the side of the perimeter public road, a public distributor is installed for the refueling of cars or vans powered by biomethane. As previously anticipated, the transfer of CNG from the production area to the tank will be carried out by means of a boost pump belonging to the purification plant.

Figure 141: Public CNG refueling station Source: Agriturismo Bosco Gerolo

The column, equipped with dispensing guns, is served by a modular group consisting of a container placed in the supply yard, containing storage cylinders and over pressurizing compressor, necessary to raise the pressure of biomethane from the ten bars present in the supply network to the 250 bars necessary for the supply of the CNG storage cylinders which will therefore be filled directly by the product coming from the purification.

Figure 142: CNG compression and storage module   Source: Cubogas

5.5.2.1 Reference legislation and requirements

The activity identified by the standard in Presidential Decree 01/08/2011 n. 151 as number 13 B.C - *FIXED INSTALLATIONS FOR THE DISTRIBUTION OF GASEOUS FUELS FOR TRANSPORT*.

The reference legislation for this type of installation is the Ministerial Decree of 24 May 2002, updated with the D.M. of 12 March 2019, containing the *Fire prevention standards for the design, construction and operation of natural gas distribution plants for transport*.

For the purpose of fire prevention and in order to ensure the safety requirements for the protection of persons and the protection of property against fire risks, the compressed natural gas (CNG) refueling plant for transport is built in such a way as to ensure the following objectives:

- to minimize the causes of accidental release of gases as well as fire and explosion;
- to limit, in the event of an incidental event, people injury;
- to limit, in the event of an incidental event, damage to buildings or premises adjacent to the installation;
- to enable rescuers to operate safely.

Following the dictates provided by the standards and as prescribed by current national and Community provisions, the equipment constituting the system must be specifically made for the planned installation. The maximum pressure of each part of the refueling system shall not exceed the maximum working pressure of each component and each constituent pipe.

These systems must be made with first-degree safety features and with fully shielded openings. With this request for safety it is meant that the construction characteristics of the artifacts are such as to guarantee, in the event of an explosion, the containment of materials both laterally and upwards.

5.5.2.1.1 General requirements and fencing

The requirements and construction methods of the distribution station are reported in point 2.1 of the aforementioned standard: in this section the constructive robustness of foundations, structures in elevation and roofs are required, as well as specifying the need for interconnection between the different parts.

It is not necessary that the area on which the plant stands is completely fenced, as it is home to a vending machine open to the public. It is recommended, however, that the side exposed towards the farm (south side) is delimited by a fence, not less than 1.8 m high, preferably made of masonry or prefabricated concrete walls.

5.5.2.1.2 Compressor room and storage vessels or cylinder

The modular unit containing the compressor system and the biomethane storage cylinders consists of an indivisible module and, given that the legislation ask that the room for the accommodation of the storage tanks has a 1st degree safety, this is extended to the entire metal box. This has anti-intrusion protection at the openings and responds to the different requests of point 2.5 of the legislation.

5.5.2.1.3 Gas plant

For regulatory purposes, the set of pipes, shut-off, exhaust and safety valves and the various equipment that make up the supply, compression, damping, accumulation, gas distribution and emergency system is considered a "gas system".

It is required that the design pressures of the system must be at least 10% higher than the maximum nominal working pressures and, in any case, not lower than the intervention pressures of the safety valves. The overpressure in the supply line of the distributor equipment shall not exceed 1% of the emission pressure, with pressure pulsations not exceeding 4%.

The pipes belonging to the distribution devices must be anchored to the base of the apparatus themselves and each equipped with an excess flow valve inserted adjacent to the anchor point. The valve itself must be suitable to prevent the escape of gas even in the event of accidental removal of the distribution device. Flexible pipes can only be used for compressor and cylinder wagon connections and must be internally resistant to natural gas and externally to abrasion and ageing. Their working pressure must not be lower than the one of the pipeline system into which they are inserted.

Pressure limitation devices and safety components must be designed in accordance with the provisions of point 2 of Annex I to Legislative Decree No 93 of 25 February 2000 - Implementation of Directive 97/23/EC on pressure equipment. Pressure limitation devices shall act before the actual pressure has exceeded the established maximum working pressure by no more than 1%.

Fueling points or stations for the supply of natural gas for transport must be provided with CE marking and related declaration of conformity to Legislative Decree 19 May 2016, n. 85. This CE marking must certify that the distributor is realized in a suitable manner in accordance with the risk analysis carried out by the manufacturer in accordance with all applicable Community directives. Distribution devices shall be fitted with a break-away coupling on the loading hose of the vehicle. The connection of the distribution apparatus to the gas supply line must be carried out via an non-return valve. Before the gas supply gun to the vehicle, a non-return valve shall be inserted. The exhaust system into the atmosphere must be able to withstand the mechanical stresses produced by the effluent gas at the working pressure. The releasing pipe that emits directly in atmosphere must be conveyed in a safe area and in any case the upper end of this duct must be located at a distance from the decking not less than 2,50 m and protected by a stainless flame cutting device.

The distributors must be electrically grounded in accordance with the provisions of point 2.9 of the same legislation and each distribution device must be used by an sht-off device placed at the base of the apparatus itself.

In order to prevent emission at a pressure of more than 220 bar, it is necessary that an automatic pressure control system interacting with the fuel flow meters or a system of equivalent effectiveness and not subject to tampering must be inserted on each emitting point of the distribution equipment.

Figure 143: Refuelling station   Source: Cubogas

5.5.2.1.4 Emergency safety system

The current legislation imposes to install a system controlled by safety buttons, with manual reset, located near the compressor room, the vehicle refueling area and the operator room, that are able to:

- completely isolate supply piping to distribution devices by means of remotely controlled shut-off valves, placed downstream of any storage or damping tank with a total capacity exceeding 50 Nm^3;
- completely isolate the low-pressure line from the compressor suction;
- shut-off the electrical circuit of the system, except for principal lines that supply safety systems.

5.5.2.1.5 Electrical, grounding and protection against atmospheric discharge plant

It is required that the natural gas distribution system for transport be equipped with electrical, of grounding and protection systems from atmospheric electrical discharges made in accordance with the D.Lgs. of 1 March 1968, n. 186.

The power supply of the different utilities, with the exception of fire-fighting water systems, must allow the shut-off measure, in addition to the electrical cabin, also by another control located in a protected position. Pipes and metal structures must be connected with the general grounding system. If from the probabilistic calculation of lightning, to be performed according to the provisions of the current standard, the critical parts of the system, (in this case the compressor and storage room) are not self-protected, the same must be protected with lightning rod systems, preferably of the cage type.

5.5.2.1.6 Fire protection

In the case scenario analyzed, the use of cylinder wagons is not expected and, in addition, the storage containers have a total capacity lower than 3000Nm^3. For this reason, the Regulations require only the presence of portable and/or wheeled fire extinguishers prescribed by the competent Provincial Command of the Fire Brigade in relation to the size of the system and the number of distribution devices.

5.5.2.1.7 Safety distance

All critical elements of the considered installation are equipped with 1st degree security. According to this requirement, internal and external safety distances are defined.

a) 1st grade safety elements:

Table 9: Safety distances for CNG public refueling station

Element	Horizontal distance [m]	Internal safety distance [m]	External safety distance [m]
Reduction and measurement cabin	2	--	10
Compressors room	5	--	20
Storage vassel room	5	--	20
Cylinder wagon box	5	--	20

b) Automatic refueling devices:

Table 10: Safety distances for automatic refueling stations

Element	Horizontal distance [m]	Internal safety distance [m]	External safety distance [m]
Refueling devices	10	8	20

In the considered case, care was taken to respect the before mentioned distances, also evaluating the requests relating to generic safety distances.

5.5.2.1.8 General emergency prescriptions

It is necessary that plant personnel must:

- be informed of the rules set out in this Annex, the internal safety rules and the contingency plan drawn up;
- act immediately in case of fire or danger by acting on the devices and emergency equipment supplied, as well as preventing, through signals, barriers and any other suitable means, that other vehicles or people access the system, and notify the rescue services.

5.5.2.1.9 Safety signaling

It is required that with regard to safety signs the provisions set out in Legislative Decree 9 April 2008, n. 81 are respected and it is specified that a suitable signage reproducing a flow scheme of the gas system and a plan of the distribution system also highlighting the emergency commands is exposed within the system and in a clearly visible position. The flow scheme, the floor plan of the system and the emergency controls must be visible even in the event of lack of natural lighting and the absence of ordinary lighting, by means of safety lighting systems.

Appropriate signs indicating the following rules must be displayed in the vicinity of distribution devices:

a) it is forbidden allow access to refueling for vehicles that do not meet the traffic requirements, including aspects relating to the approval of installed cylinders and the related periodic checks;
b) inside the area, within a radius of 6 meters from the perimeter of the distribution device, including inside the cockpit of the car, it is prohibited:
    - b.1. use equipment not adequately protected from the risk of ignition, including mobile phones;
    - b.2. smoke, also with electronic cigarette;
    - b.3. light or use open flames.

It is needed the presence of additional signage that shows the instructions concerning:

c) behaviour to have in case of emergency;
d) Position of safety devices;
e) the manoeuvres to be carried out to secure the installation, such as, for example, the operation of the emergency buttons and the operation of the fire controls;
f) the warning that the vehicle can be started only after the dispensing gun has been switched off.

(Paragraph thus replaced, lastly, by letter b) of subparagraph 1 of art. 1 of Italian Ministerial Decree 12/03/2019. Editor's note)

5.5.2.2 Identification of critical points

In order to be able to carry out a fluid dynamics simulation, the identification of the possible critical points of the system has been performed.

- compressor unit and storage vessels;
- automatic distribution devices for the refueling of motor vehicles.

As with the actual analysis, not all possible sources of biomethane emission are considered. Since the purpose of the work is to bring out scenarios that may occur as a result of a leak from the plant, the analysis will be focused on a single source that will then be considered representative for the others.

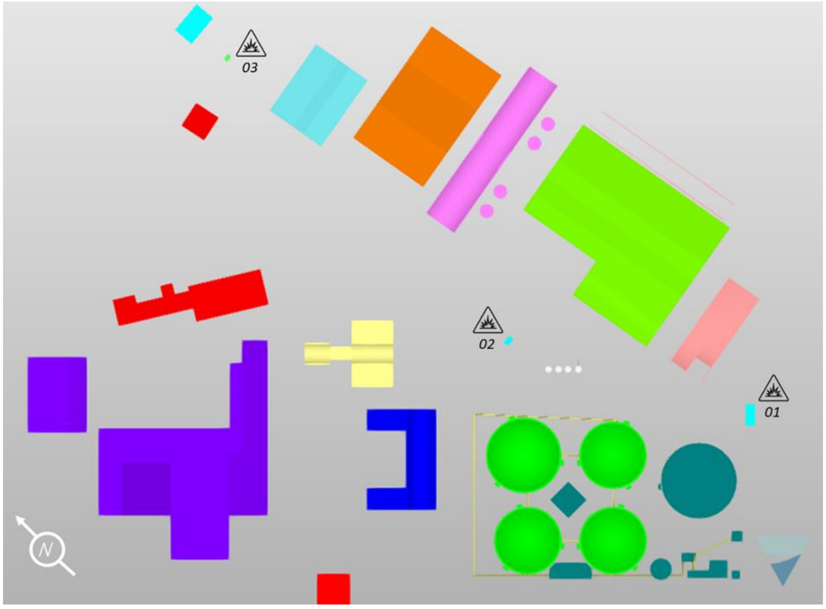


Figure 144: Identification of critical points

5.5.3 Corporate CNG refueling station

To exploit the potential benefits of feeding the operating machines through biomethane, it is planned to install a station for the exclusive supply of agricultural vehicles inside the company surface. A few months before the drafting of this work, the first natural gas and biomethane tractor was presented (54) supplied by the CNH group of Turin, equipped with a refueling system with a solution that also includes the refueling system with compressor. The system allows the refilling of the cylinders integrated in the operating machine, directly in the company, 24/7 and in complete autonomy, avoiding the need for refueling at the service station.

Figure 145: Bio-methane-fuelled innovative tractor

5.5.3.1 Reference legislation and requirements

During the period of creation of this work there is still no specific regulation for CNG filling stations for private and/or business use. To maintain the fire-fighting design in favor of safety, the rules relating to standard road distribution systems of natural gas for transport contained in the Ministerial Decree of 24 May 2002, updated with the Ministerial Decree of 12 March 2019, were also considered in this case. The plant in under investigation, although not open to public, is designed to be used by company employees for the fueling of agricultural machinery. In the same way, although the group for the compression and storage of CNG is small, it was preferred to follow a regulation as stringent as possible.

For the purpose of fire prevention and in order to ensure the safety requirements for the protection of persons and the protection of property against fire risks, the compressed natural gas (CNG) refuelling plant for transport will be built and operated in such a way as to ensure the following objectives:

- to minimize the causes of accidental release of gases as well as fire and explosion;
- to limit, in the event of an incidental event, people injury;
- to limit, in the event of an incidental event, damage to buildings or premises adjacent to the installation;
- to enable rescuers to operate safely.

Following the dictates provided by the standards and as prescribed by current national and Community provisions, the equipment constituting the system must be specifically made for the planned installation. The maximum pressure of each part of the refueling system shall not exceed the maximum working pressure of each component and each constituent pipe.

These systems must be made with first-degree safety features and with fully shielded openings. With this request for safety, it is meant that the construction characteristics of the artifacts are such as to guarantee, in the event of an explosion, the containment of materials both laterally and upwards.

5.5.3.1.1 General requirements and fencing

The requirements and construction methods of the distribution station are reported in point 2.1 of the aforementioned standard: in this section the constructive robustness of foundations, structures in elevation and roofs are required, as well as specifying the need for interconnection between the different parts.

It is not necessary that the area on which the plant stands is completely fenced, as it is home to a vending machine open to the public. It is recommended, however, that the side exposed towards the farm (south side) is delimited by a fence, not less than 1.8 m high, preferably made of masonry or prefabricated concrete walls.

5.5.3.1.2 Compressor room and storage vessels or cylinders

The modular unit containing the compressor system and the biomethane storage cylinders consists of an indivisible module and, given that the legislation ask that the room for the accommodation of the storage tanks has a 1st degree safety, this is extended to the entire metal box. This has anti-intrusion protection at the openings and responds to the different requests of point 2.5 of the legislation.

5.5.3.1.3 Gas plant

For regulatory purposes, the set of pipes, shut-off, exhaust and safety valves and the various equipment that make up the supply, compression, damping, accumulation, gas distribution and emergency system is considered a "gas system".

It is required that the design pressures of the system must be at least 10% higher than the maximum nominal working pressures and, in any case, not lower than the intervention pressures of the safety valves. The overpressure in the supply line of the distributor equipment shall not exceed 1% of the emission pressure, with pressure pulsations not exceeding 4%.

The pipes belonging to the distribution devices must be anchored to the base of the apparatus themselves and each equipped with an excess flow valve inserted adjacent to the anchor point. The valve itself must be suitable to prevent the escape of gas even in the event of accidental removal of the distribution device. Flexible pipes can only be used for compressor and cylinder wagon connections and must be internally resistant to natural gas and externally to abrasion and ageing. Their working pressure must not be lower than the one of the pipeline system into which they are inserted.

Pressure limitation devices and safety components must be designed in accordance with the provisions of point 2 of Annex I to Legislative Decree No 93 of 25 February 2000 - Implementation of Directive 97/23/EC on pressure equipment. Pressure limitation devices shall act before the actual pressure has exceeded the established maximum working pressure by no more than 1%.

Fueling points or stations for the supply of natural gas for transport must be provided with CE marking and related declaration of conformity to Legislative Decree 19 May 2016, n. 85. This CE marking must certify that the distributor is realized in a suitable manner in accordance with the risk analysis carried out by the manufacturer in accordance with all applicable Community directives. Distribution devices shall be fitted with a break-away coupling on the loading hose of the vehicle. The connection of the distribution apparatus to the gas supply line must be carried out via an non-return valve. Before the gas supply gun to the vehicle, a non-return valve shall be inserted. The exhaust system into the atmosphere must be able to withstand the mechanical stresses produced by the effluent gas at the working pressure. The reliesing pipe that emits directly in atmosphere must be conveyed in a safe area and in any case the upper end of this duct must be located at a distance from the decking not less than 2,50 m and protected by a stainless flame cutting device.

The distributors must be electrically grounded in accordance with the provisions of point 2.9 of the same legislation and each distribution device must be used by an sht-off device placed at the base of the apparatus itself.

In order to prevent emission at a pressure of more than 220 bar, it is necessary that an automatic pressure control system interacting with the fuel flow meters or a system of equivalent effectiveness and not subject to tampering must be inserted on each emitting point of the distribution equipment.

Figure 146: Refueling station   Source: Cubogas

5.5.3.1.4 Safety emergency system

The current legislation imposes to install a system controlled by safety buttons, with manual reset, located near the compressor room, the vehicle refueling area and the operator room, that are able to:

- completely isolate supply piping to distribution devices by means of remotely controlled shut-off valves, placed downstream of any storage or damping tank with a total capacity exceeding 50 Nm^3;
- completely isolate the low-pressure line from the compressor suction;
- shut-off the electrical circuit of the system, except for principal lines that supply safety systems.

5.5.3.1.5 Electrical, grounding and protection against atmospheric discharge plant

It is required that the natural gas distribution system for transport be equipped with electrical, of grounding and protection systems from atmospheric electrical discharges made in accordance with the D.Lgs. of 1 March 1968, n. 186.

The power supply of the different utilities, with the exception of fire-fighting water systems, must allow the shut-off measure, in addition to the electrical cabin, also by another control located in a protected position. Pipes and metal structures must be connected with the general grounding system. If from the probabilistic calculation of lightning, to be performed according to the provisions of the current standard, the critical parts of the system, (in this case the compressor and storage room) are not self-protected, the same must be protected with lightning rod systems, preferably of the cage type.

5.5.3.1.6 Fire protection

In the case scenario analyzed, the use of cylinder wagons is not expected and, in addition, the storage containers have a total capacity lower than 3000Nm^3. For this reason, the Regulations require only the presence of portable and/or wheeled fire extinguishers prescribed by the competent Provincial Command of the Fire Brigade in relation to the size of the system and the number of distribution devices.

5.5.3.1.7 Safety distances

All critical elements of the considered installation are equipped with 1st degree security. According to this requirement, internal and external safety distances are defined.

a) 1st grade safety elements:

Table 11: Safety distances for CNG public refueling station

Element	Horizontal distance [m]	Internal safety distance [m]	External safety distance [m]
Reduction and measurement cabin	2	--	10
Compressors room	5	--	20
Storage vassel room	5	--	20
Cylinder wagon box	5	--	20

b) Automatic refuelin station device:

Table 12: Safety distances for automatic refueling stations

Element	Horizontal distance [m]	Internal safety distance [m]	External safety distance [m]
Refueling devices	10	8	20

In the considered case, care was taken to respect the before mentioned distances, also evaluating the requests relating to generic safety distances.

5.5.3.1.8 General emergency prescriptions

It is necessary that plant personnel must:

- be informed of the rules set out in this Annex, the internal safety rules and the contingency plan drawn up;
- act immediately in case of fire or danger by acting on the devices and emergency equipment supplied, as well as preventing, through signals, barriers and any other suitable means, that other vehicles or people access the system, and notify the rescue services.
-

5.5.3.1.9 Safety signaling

It is required that with regard to safety signs the provisions set out in Legislative Decree 9 April 2008, n. 81 are respected and it is specified that a suitable signage reproducing a flow scheme of the gas system and a plan of the distribution system also highlighting the emergency commands is exposed within the system and in a clearly visible position. The flow scheme, the floor plan of the system and the emergency controls must be visible even in the event of lack of natural lighting and the absence of ordinary lighting, by means of safety lighting systems.

Appropriate signs indicating the following rules must be displayed in the vicinity of distribution devices:

a) it is forbidden allow access to refueling for vehicles that do not meet the traffic requirements, including aspects relating to the approval of installed cylinders and the related periodic checks;
b) inside the area, within a radius of 6 meters from the perimeter of the distribution device, including inside the cockpit of the car, it is prohibited:
    - b.1. use equipment not adequately protected from the risk of ignition, including mobile phones;
    - b.2. smoke, also with electronic cigarette;
    - b.3. light or use open flames.

It is needed the presence of additional signage that shows the instructions concerning:

c) behaviour to have in case of emergency;
d) Position of safety devices;
e) the manoeuvres to be carried out to secure the installation, such as, for example, the operation of the emergency buttons and the operation of the fire controls;
f) the warning that the vehicle can be started only after the dispensing gun has been switched off.

(Paragraph thus replaced, lastly, by letter b) of subparagraph 1 of art. 1 of Ministerial Decree 12/03/2019. Editor's note)

6 Analysis of fluid dynamic simulations

Authors have been moved by the will to deepen the characteristics of biomethane by evaluating the behaviour of this gas, even more volatile than biogas, in the case of a dispersion due to poor maintenance or accidents. This topic is made very topical by the vicissitudes in the Eurasia zone and the not too fast ecological transition taking place. The interest in this type of fuel is raised by the numerous subsidies at local and state level and by the continuous search for clean and above all cheap fuels. Compared to conventional fossil fuels, biogas and subsequently biomethane do not require major initial investments as they could deposits on and off-shore.

As reported in the first part of this paper, especially in Italy, there are numerous incentives for entrepreneurs who decide to invest in the production of biomethane and in particular for the *extraction* of biofuel for the supply of motor vehicles. Supported by this concrete attempt to diversify the sources of combustible materials, it was decided to simulate, on the basis of what was done previously, any incidental events concerning a distribution column for the supply of vehicles inside the company and concerning a small biomethane distributor open to the public and located along the Strada Provinciale 6 that runs along the plot of land on which the Cellars and the current Biogas plant are located. It is usefull to say that authors are conscious that the refueling station located at this point is not easily accessible to heavy vehicles in transit mainly on the Strada Regionale 251 (which crosses the SP6 a few meters); unfortunately for reasons of space and in anticipation of too small distances between the existing buildings and the distributor the current position has been adopted.

The plant designed will be used for the administration of compressed biomethane (*Bio-CNG*) and the analyzes see as subjects the joining flanges of the distribution network upstream of the Upgrading unit (point 01) – downstream of the service column for the refueling of the vehicles (point 02) – the compression unit of the public distributor (point 03). (Figure 147)

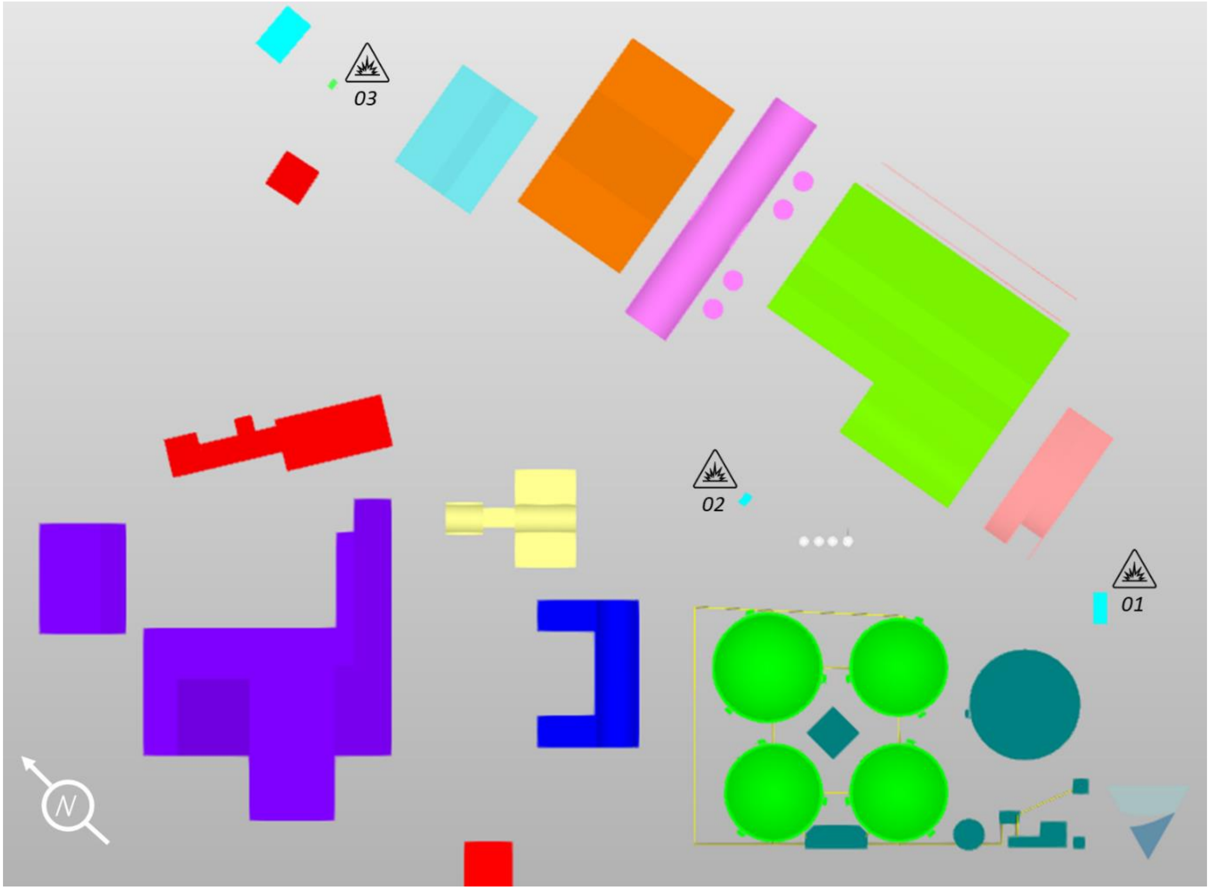


Figure 147: Biogas-upgrading critical points

It has been hypothesized that the possible source of the damage derives from a collision of a vehicle against these elements, during maneuvering operations. The possibility linked to the compression unit is not unlikely as on the market there are elements externally very similar to each other and with a casing supported only by small metal supports of reduced diameter.

The methods of execution of the simulations are the same shown in the part used for the presentation of the simulations with Biogas as a contaminant, what change are:

- Pressures of circulating gas (inside a biomethane transport pipeline placed between the upgrading unit and the gas compression box, biomethane runs at about 4 Bars). This implies a different and certainly higher emission rate (which will be calculated later);

- the molar mass of biomethane is 16.04 *kg/kmol* well below the biogas used previously. It is assumed that this strong difference in density leads to an upward migration of biomethane much more visible than biogas.

Operationally, the changes to VentoAEC model compared to the previous one concern:

- removal of refinement window not necessary for the calculation with a consequent lightening of the number of cells and with the following benefits in terms of calculation times;
- definition of new refinement windows in correspondence of the new critical points, characterized by an offset of 0.5m on all sides, normal equal to 0.2m and tangential equal to 10m and finally X_{ref}, Y_{ref}, Z_{ref} equal to 0.1 so as to ensure a minimum coverage to the emitting surfaces and the surrounding air volume;
- the other surfaces to which new refinement windows have been associated are those of the internal and external distributors, the biomethane compressor for delivery to the external distributor and the upgrading system placed near the digesters. For those surfaces, X,Y,Z of *refinement* equal to 0.8m were used;
- different emission sections from the ones used with biogas infrastructure; for this simulation the sections used for the release of the gas are all circular and of a section equal to about two inches, with normal vertical.

For what concern the climatic conditions adopted, the simulations were set in the climates that provided the most interesting results, for this reason the simulations performed are as follows:

Table 13: Biogas-upgrading scenarios configuration

Temperature	Air pressure	Wind speed	Wind direction	ID simulation
-9.3°C	99797 Pa	17 m/s	N	01_MET
		3 m/s	N-O	02_MET
			N	03_MET
			N-E	04_MET
		0 m/s	/	05_MET
32.6°C	99797 Pa	3 m/s	N-O	06_MET
			N	07_MET
			N-E	08_MET
		0 m/s	/	09_MET

The decision to proceed with simulations that do not include all cases with wind at a speed of 17 m/s derives from a preliminary study carried out to verify the usefulness of this simulation. This preliminary investigation derives from the considerations made for strong wind scenarios with biogas. The results obtained in that case were not relevant to the purpose of this work. As proof of what has just been said, below, the result obtained from the only simulation performed in strong wind conditions to demonstrate the absence of any character worthy of attention for the purposes of this work is reported.

The analysis methodology is the same as in previous analyses. Also in this case the software is asked to perform 1500 iterations. The parameters adopted are proposed below:

- Grid
  - dimension of *domain box* 5000m x 5000m x 500m;
  - surface refinement layer: *thin;*
  - grid density: *high*.
- Model of the fluid
  - fluid: air @ standard condition;
  - turbolences model: Spalart-Allmaras;
  - contaminant: methane CH_4;
  - *coupled* checked;
  - *buoyancy* checked;
  - Spalart-Allmaras variable $1x10^{-5}$ m/s;
- Flow conditions
  - adiabatic ground;
  - aerodynamic roughness of the ground: 0.1m;
  - reference height 10m;
  - Von Karman constant 0.41.

The very first of the value calculated and used for the realization of the model is the leaking speed of biomethane from the different critical points. For this purpose the formula used is the same as in chapter 6.2.1.3.4. The starting point is represented by Bernoulli's Theorem which relates the sliding speed, pressure and density of a fluid:

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

Where the terms:

- *p1* and *p2* represent the fluid pressures in section 1 and section 2, respectively;
- *ρ is the density of the fluid. For biomethane it corresponds to 0.657 kg/m³;*
- *v1* and *v2* represent the fluid velocities in section 1 and 2, respectively;
- *h1* and *h2* represent the altitudes of the two sections.

Imposing some initial hypotheses such as:

- $h1$ and $h2$ correspondents;
- *p1* equal to 4 bars + *p2;*
- *v2 equal to zero;*

the equation, if elaborated, leads to the numerical quantification of the gas emission velocity, in this case it is equal to 1000.2 m/s.

The temperature has been assumed to be equal to 50°C because of the upgrading process, while involving an increase in pressure and therefore an increase in temperature (increase in pressure with constant volume), sees a decrease in the same due to underground transport with poorly insulated pipes from the thermal point of view.

As far as the reading of the results is concerned, a *lower explosive limit* is set, also in this case, based on the formula proposed by the CEI EN 60079-10-1 standard and also used previously. It is reiterated that, as also suggested by 60079-10-1, the upper limit is not considered because it is subject to variations that can reduce the concentration until it enters within the explosive range.

For the conversion of the lower explosive limit expressed in ${m^3}/{m^3} \cdot 100$ in *LEL* expressed in ${kg}/{m^3}$:

$$LEL_m(\frac{kg}{m^3}) = \frac{LEL_V}{100} \cdot \rho_{0gas} \qquad [f.5.5.11\text{-}2]$$

Where the values:

- *LEL_m* corresponds to lower explosive limit expressed in ${m^3}/{m^3} \cdot 100$ and equal to 5%;
- *LEL_V* corresponds to lower explosive limit expressed in ${kg}/{m^3}$;
- *P_{0gas}* corresponds to the volumic mass of the gas and is obtained from the formula:

$$\rho_{0gas} = \frac{p_a \cdot M}{R \cdot T_0} \text{ espressa in } {kg}/{m^3} \qquad \text{[f.5.5.4-2]}$$

Dove:

- *P_a* corresponds to the atmospheric pressure of the site considered. It is equal to 99797 *Pa;*
- *M* is the molar mass of the flammable substance, for the biomethane it is eual to 16.04 *kg/kmol;*
- *R* is defined as the universal gas constant, corresponding to a 8314 *J/(kmol·K);*
- *T_0* corresponds to the atmospheric absolute temperature.

Assuming that the formula take is dependant from the air temperature, it raise necessary to compute two different *LEL_V:*

- *LEL_V* (-9.3°C) = 36.49 *g/m^3;*
- *LEL_V* (32.6°C) = 31.49 *g/m^3;*

The higher is the temperature the lower is the *lower explosive limit.*

According to the guidelines, the maximum explosiveness value is not considered for studies in open environments.

6.1 Analysis results

Below are reported, in the same way as biogas, the results of the different analyzes that have taken into account the infrastructure for the production, transport and distribution of biomethane. As already mentioned above, the analyzes are carried out focusing towards the points of discontinuity of the material (in this case the flanges of the pipes) and these points are located: upstream of the Upgrading unit, downstream of the service column for the refueling of the vehicles, at the compression unit of the public distributor.

Contrary to what was assumed when setting up simulations with biomethane *clouds* with concentration in the explosive range are very small, despite the great speed of fluid leakage. This result would derive from, in fact, the high rate of leakage of biomethane that would diffuse very quickly in a very large volume (a similar speech was made with biogas and wind at 17 m/s).

To provide further evidence to support this assumption, a view of the plant is presented with the three points visible at the same time and a range between 31.49 g/m 3 and 330 g/m^3 and the same view of the same simulation but with a range in which the minimum value has been reduced by 90% (3.15g/m^3 and 330 g/m^3). The representation belongs to simulation 07 (Figure 148 and Figure 149).

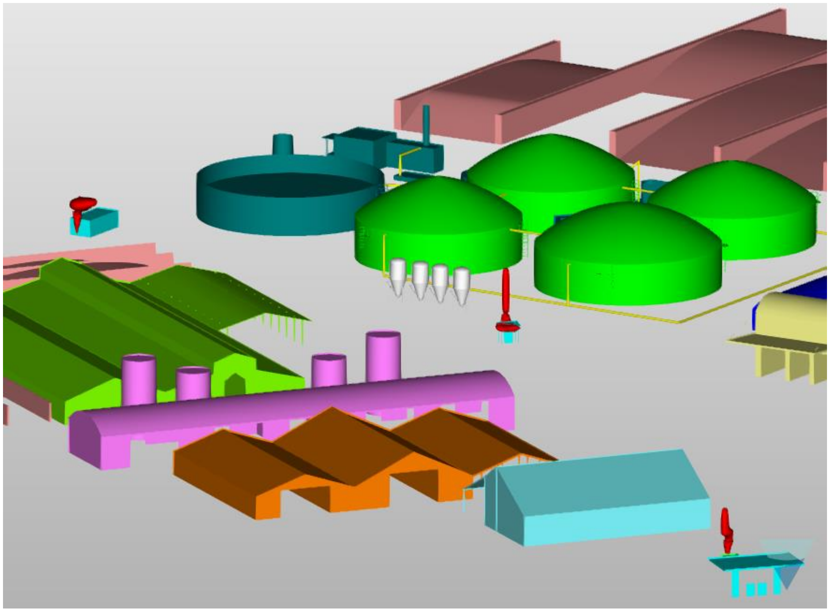


Figure 148: 3D view of the results Simulation-07 MET

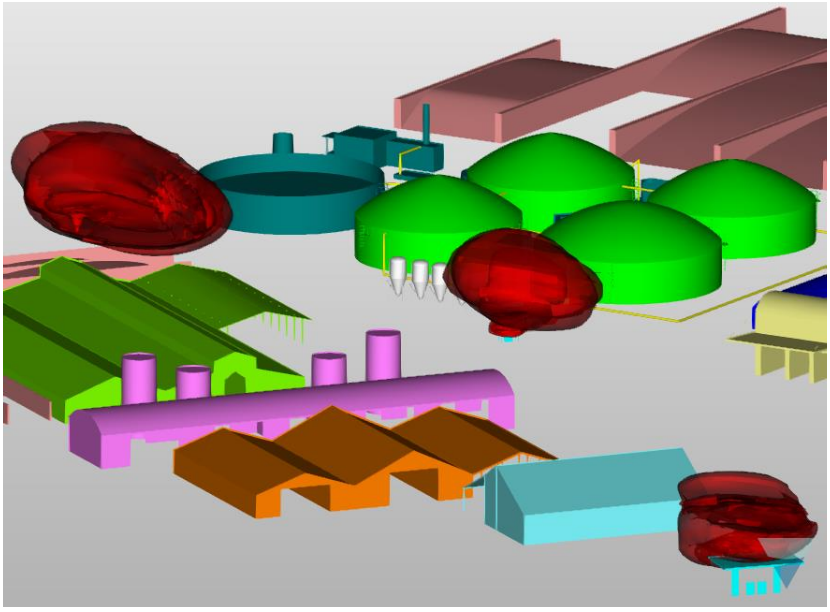


Figure 149: 3D view of the results with low conc Simulation-07 MET

In the first scenario, the layers of fluid with a flammable concentration are visible and they mainly develop upwards due to the exit thrust of the flange are visible. In the second image the clouds are larger (also in the X and Y directions). From this type of preliminary analysis the unexpected result is the small extension of the cloud with concentrations between the levels of explosiveness. Considering, moreover, that the comprehension of the results in plan would be very complex, in the following analyzes are proposed: a 3D view of framing for the single elements and 3D views of each individual cloud.

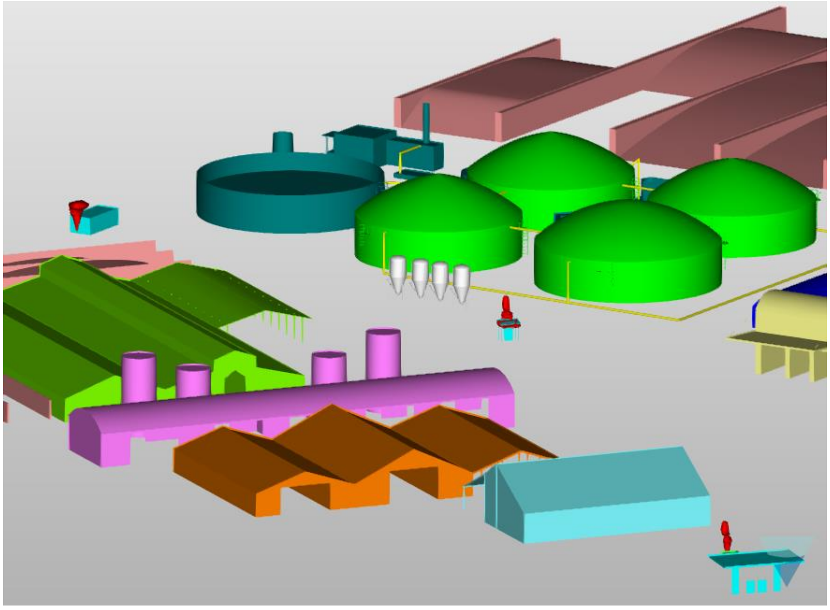
Below and for all subsequent analyses, the range is defined by the minimum value calculated also as a function of temperature and the maximum range set at 330g/m^3 because it is a value common to all configurations and closer to the various maximum extremes of the ranges.

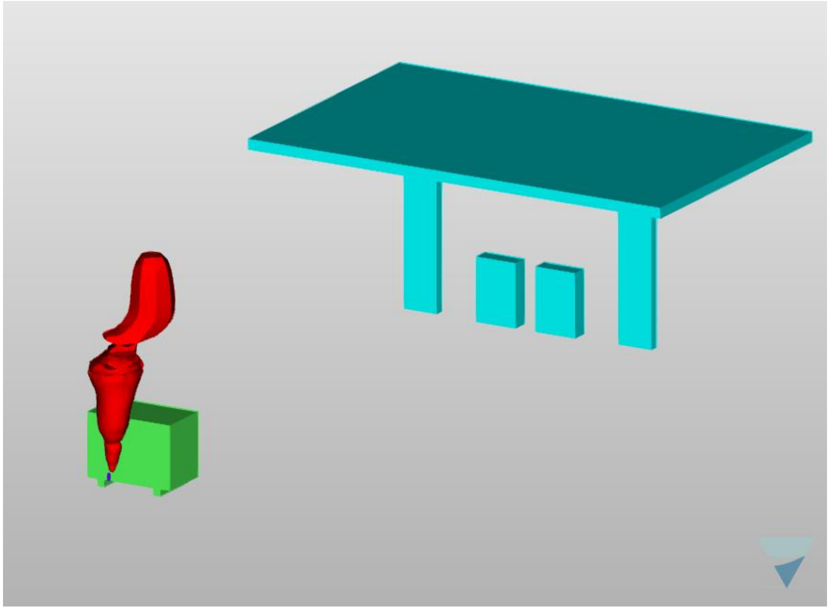
6.2 Simulation 01_MET

- Wind speed: 17 m/s;
- wind direction: North;
- atmospheric temperature: -9.3°C;

- *LEL*: 36.49 g/m^3;
- *UEL*: 330 g/m^3.

With this simulation a further verification was carried out to understand if analysis in this context, with very strong wind, can be useful for the purpose of this work. To return "impartial" results, the selected orientation is North. In the event that the results of this analysis lead to results evaluated as interesting, further analysis will be carried out in two further directions for all the chosen temperatures.





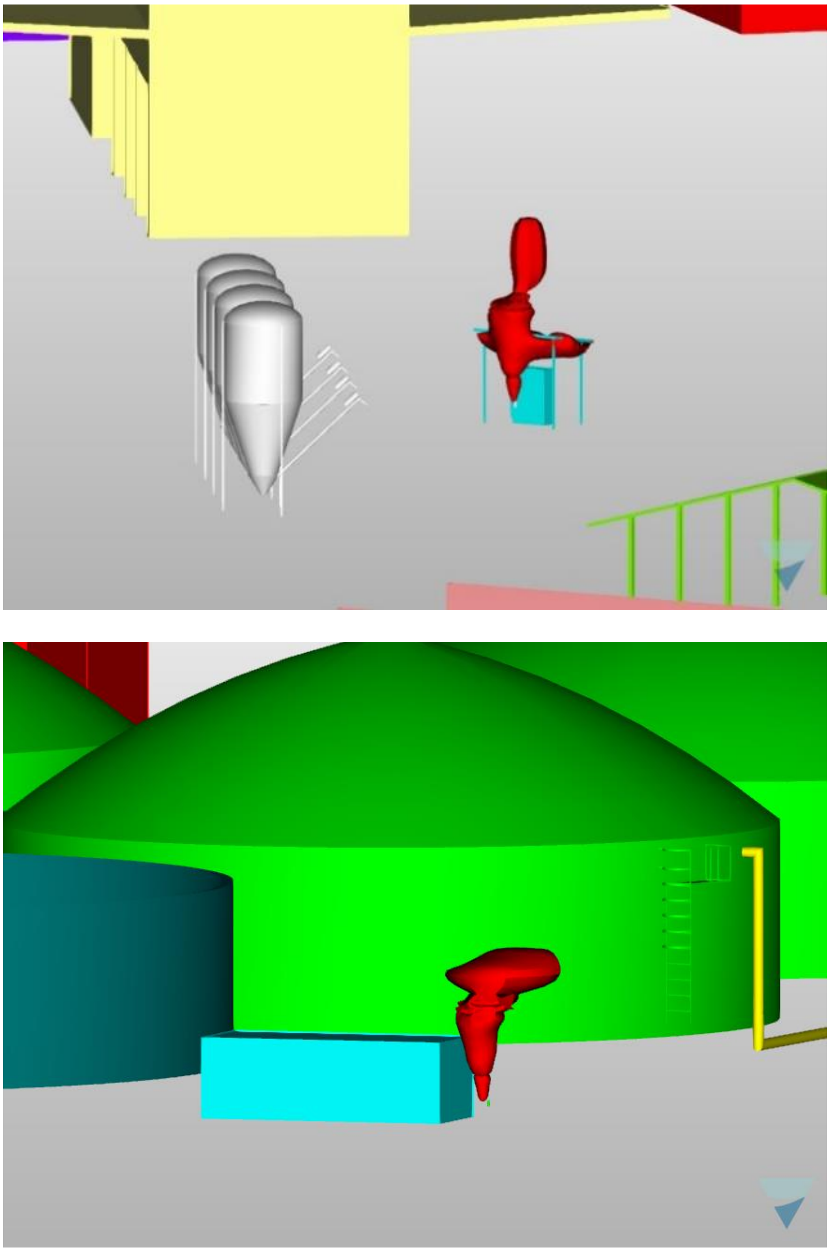


Figure 150: 3D views of the results Simulation-01 MET

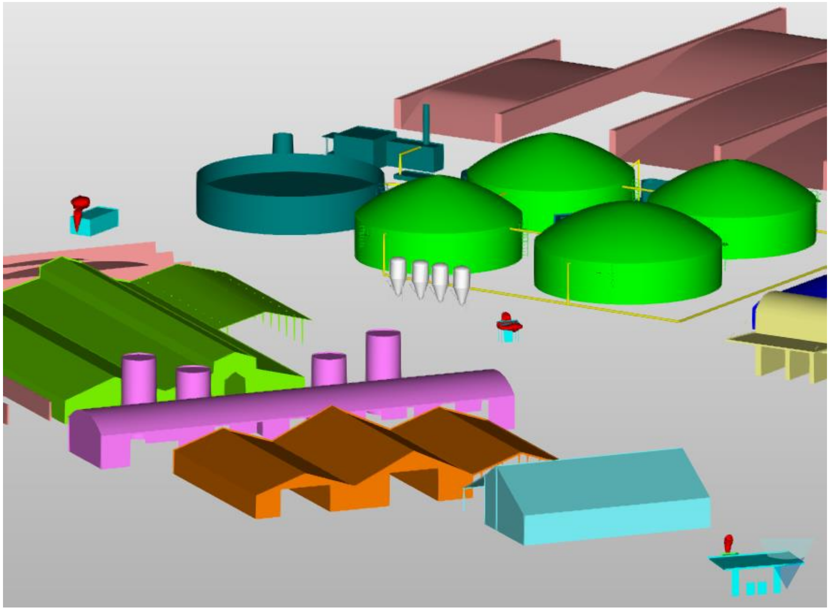
The effect of the strong wind does not lead to evident risks or to particular deviations of the path of the cloud that develops almost undisturbed upwards, thanks to the lower density of the air. As already reported above, the strong leaking speed of the gas, means that this cannot accumulate in a small volume but that it disperses only faster in the atmosphere leading to the production of a cloud very small that seems not to create any risky scenario, for all three critical points.

The only element worthy of consideration is represented by the inclined canopy of the internal distributor that seems to "collect" part of the cloud at a height of about 2.2 meters (Figure 150). At this altitude, however, the risk of contact with hot surfaces remains almost nil.

On the basis of this analysis, it was decided not to continue with the simulations concerning the wind at 17 m/s in any direction and temperature, the result would always be very similar and there would be no risk of explosion.

6.3 Simulation 02_MET

- Wind speed: 3 m/s;
- wind direction: North-West;
- atmospheric temperature: -9.3°C;
- *LEL*: 36.49 g/m^3;
- *UEL*: 330 g/m^3.



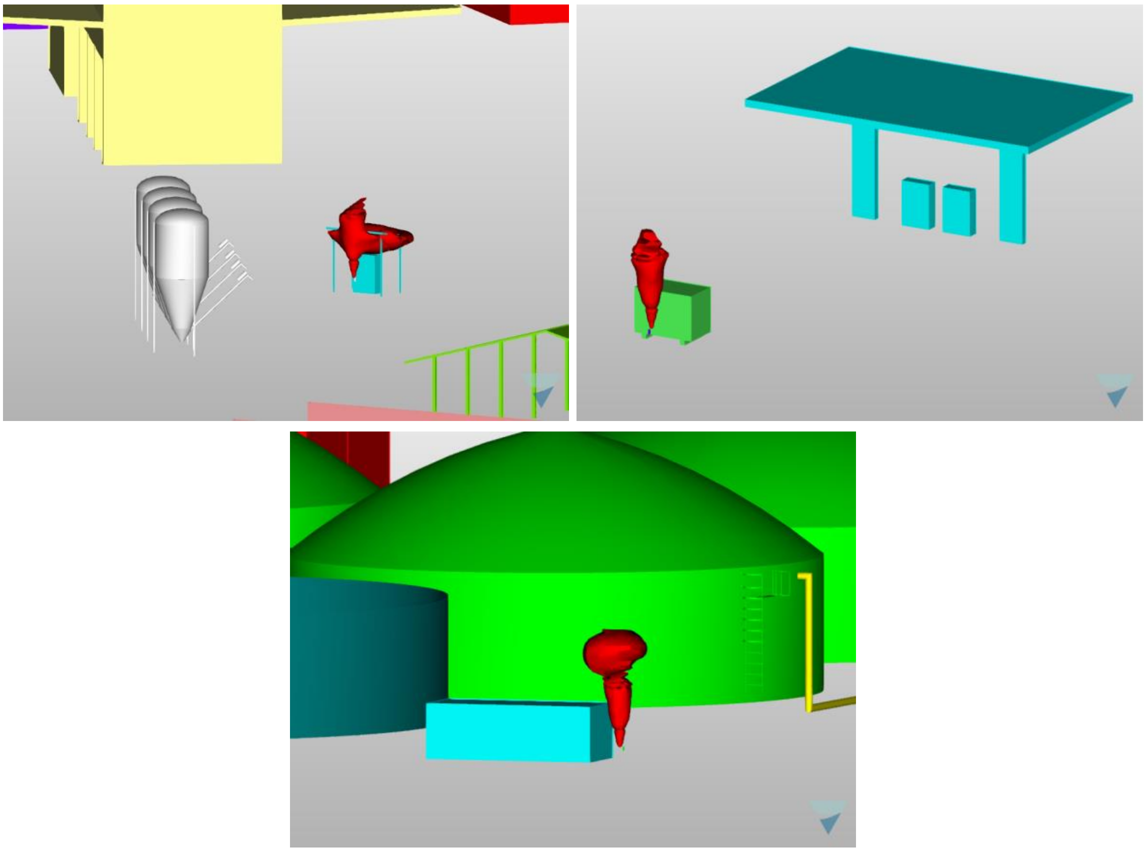


Figure 151: 3D views of the results Simulation-0s MET

Even in the case of this simulation with a much weaker wind, what determines the creation of a very small cloud more than those seen with biogas is the leakage speed. A possible risk of explosion or fire is very far to happen, in fact even the dangerous surfaces identified during the analysis with biogas, never come into contact with biomethane.

Although there are no obvious risks or dangers with such a wind, unlike in cases with wind at 17 m / s, it was decided to continue with the simulations by a lighter wind can certainly have visible effects on the development of a larger cloud.

6.4 Simulation 03_MET

- Wind speed: 3 m/s;
- wind direction: Nord;

- atmospheric temperature: -9.3°C;
- *LEL*: 36.49 g/m^3;
- *UEL*: 330 g/m^3.

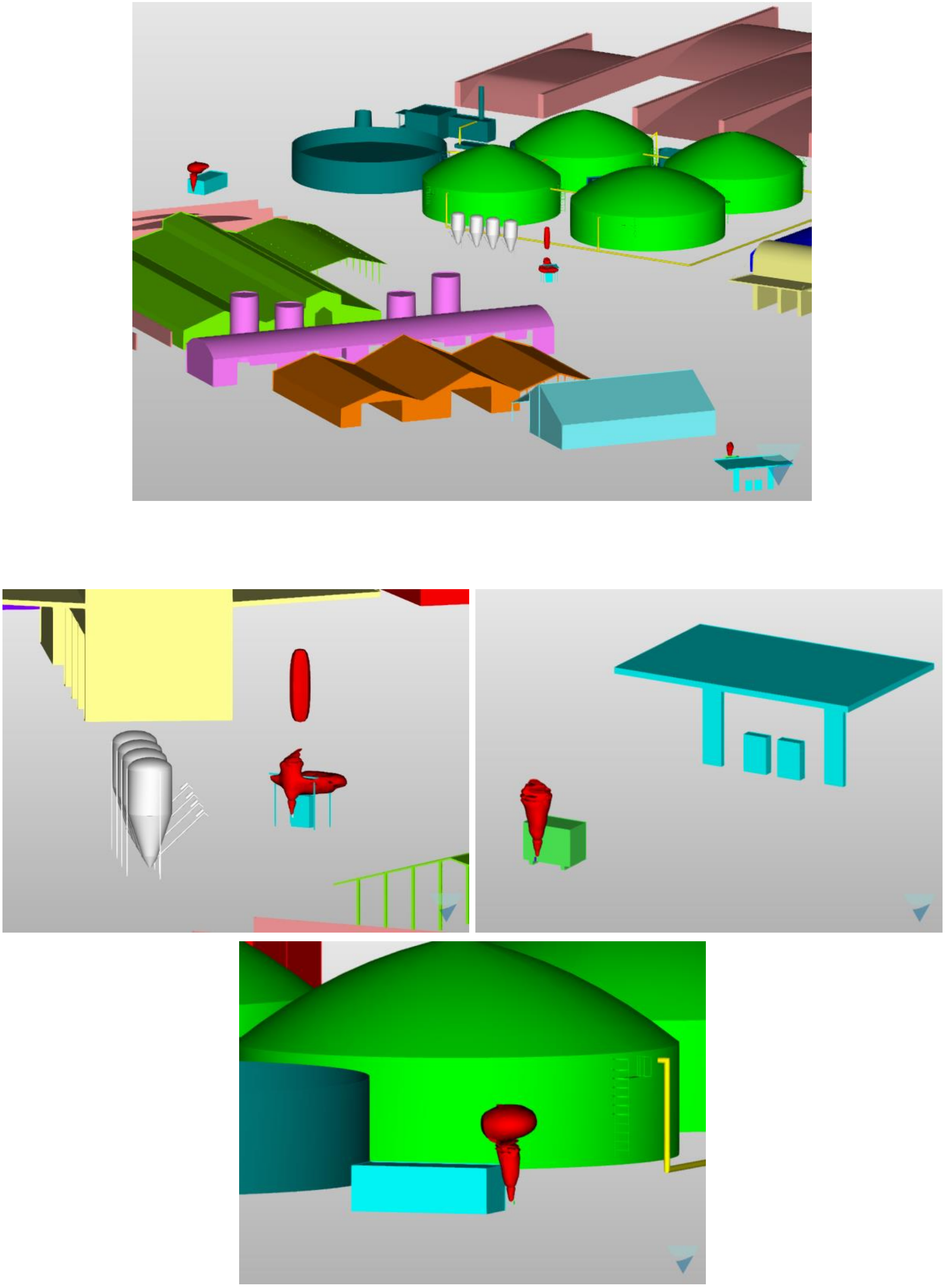
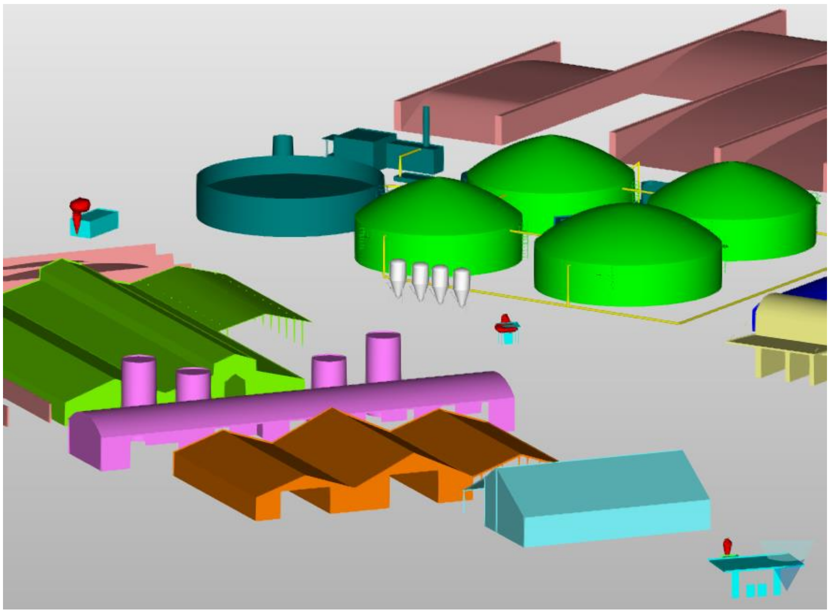


Figure 152: 3D views of the results Simulation-03 MET

Differently from the Figure 151 in this case the clouds, the one outgoing the private station overall, assumes a peculiar shape. The interruption of the gas cloud at the internal service distributor may be due to the wind which, due to deviations caused by the surrounding geometries, "crop" the cloud by reducing the concentration in the middle below the explosive levels. Again, there seems to be no reason for a dangerous scenario to arise during normal activities.

6.5 Simulation 04_MET

- Wind speed: 3 m/s;
- wind direction: North-East;
- atmospheric temperature: -9.3°C;
- *LEL*: 36.49 g/m^3;
- *UEL*: 330 g/m^3.



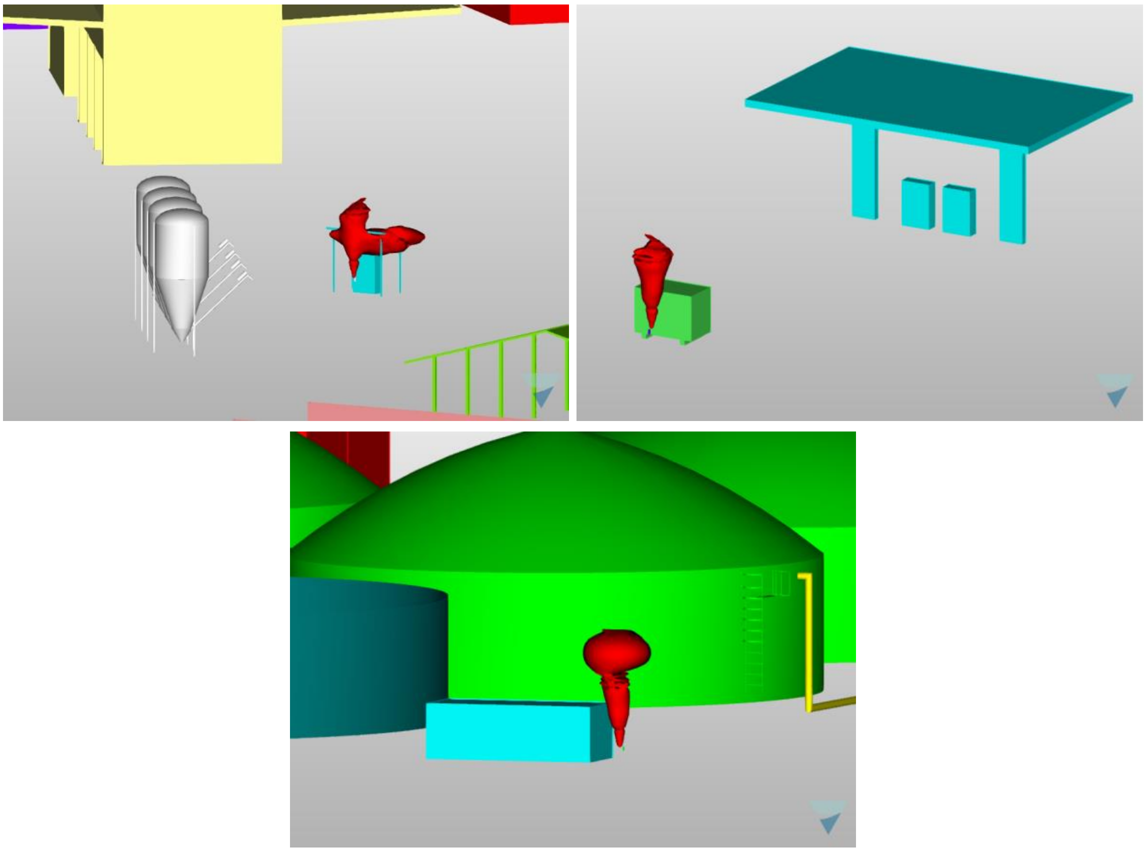


Figure 153: 3D views of the results Simulation-04 MET

Between the current simulation and the previous one, the most significant difference is represented by the loss of the internal distributor: in this case it is a smaller cloud that does not go beyond the perimeter of the coverage of the distribution column. No particular risk identified.

6.6 Simulation 05_MET

- Wind speed: 0.1 m/s;
- wind direction: North;
- atmospheric temperature: -9.3°C;
- *LEL*: 36.49 g/m^3;
- *UEL*: 330 g/m^3.

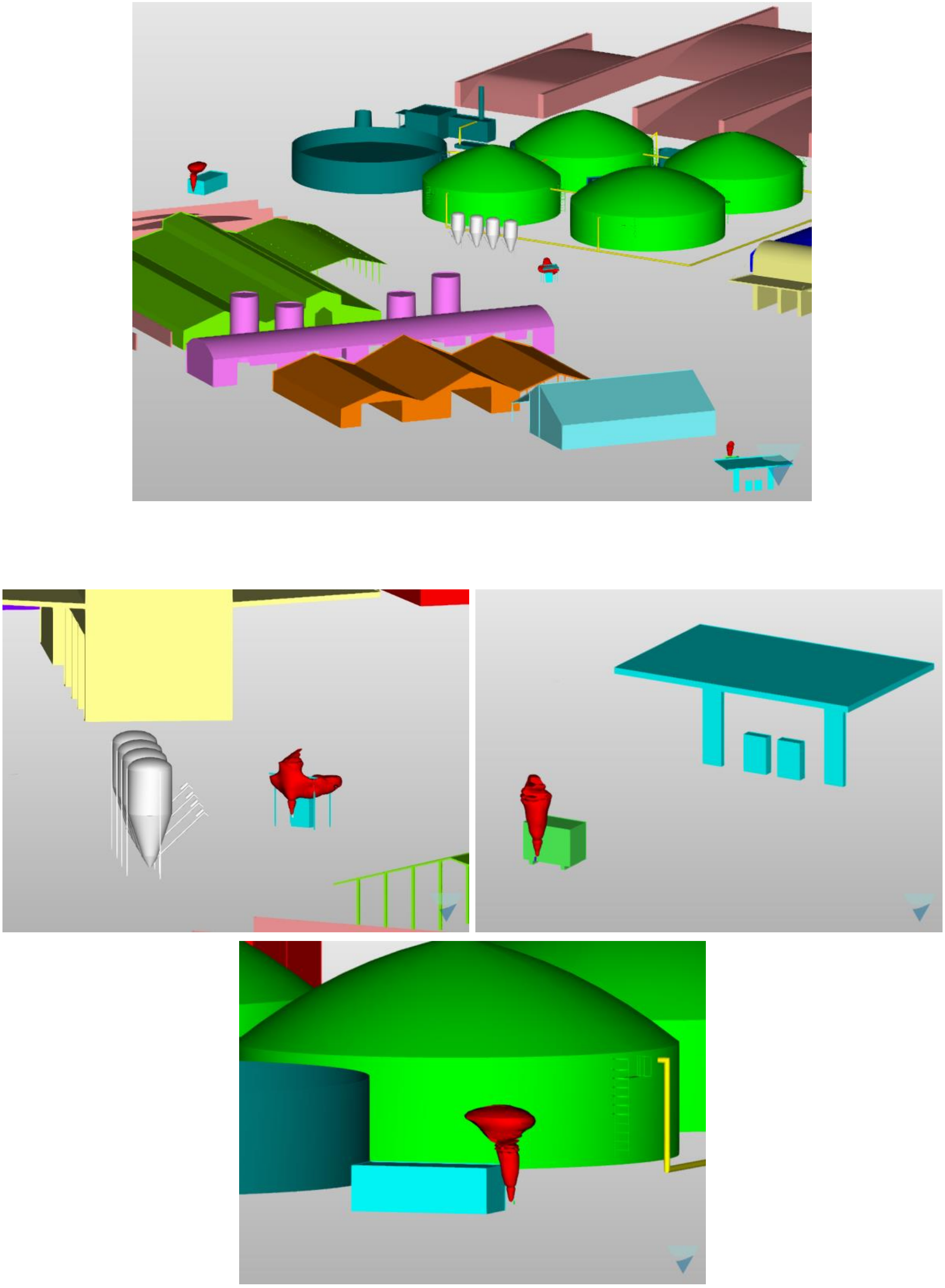


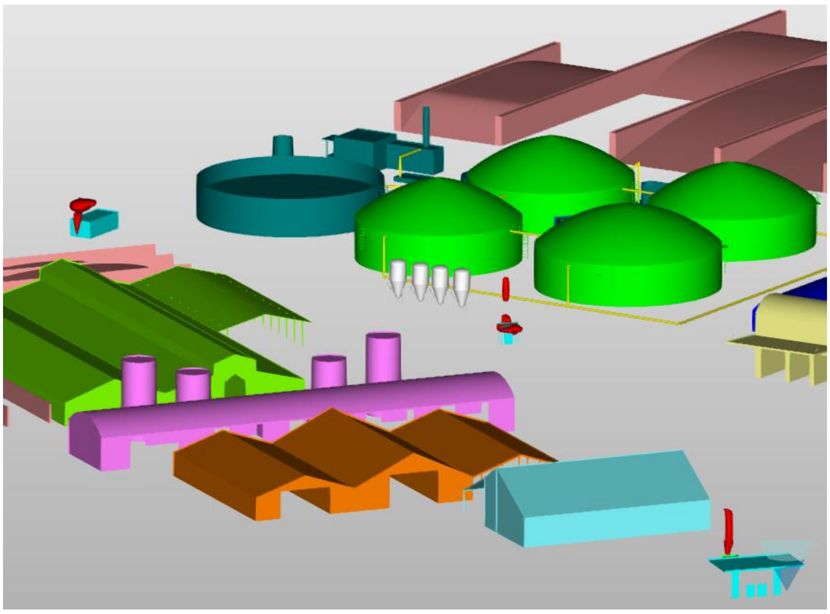
Figure 154: 3D views of the results Simulation-05 MET

Contrary to what was expected, even the null wind configuration does not lead to particularly critical results. The absence of wind does not "help" biomethane to accumulate as it happened for biogas. The responsibility for these results is given to the extremely high speed of biomethane leaving the surfaces. Surely with a more contained speeds, despite the great difference in density between biomethane and air, the volumes of gas in explosive concentrations would have been very different and extensive.

Since these results, a similar gas behavior is expected for subsequent analyses with different temperatures.

6.7 Simulation 06_MET

- Wind direction: 3 m/s;
- wind speed: North-West;
- atmospheric temperature: 32.6°C;
- *LEL*: 31.49 g/m^3;
- *UEL*: 330 g/m^3.



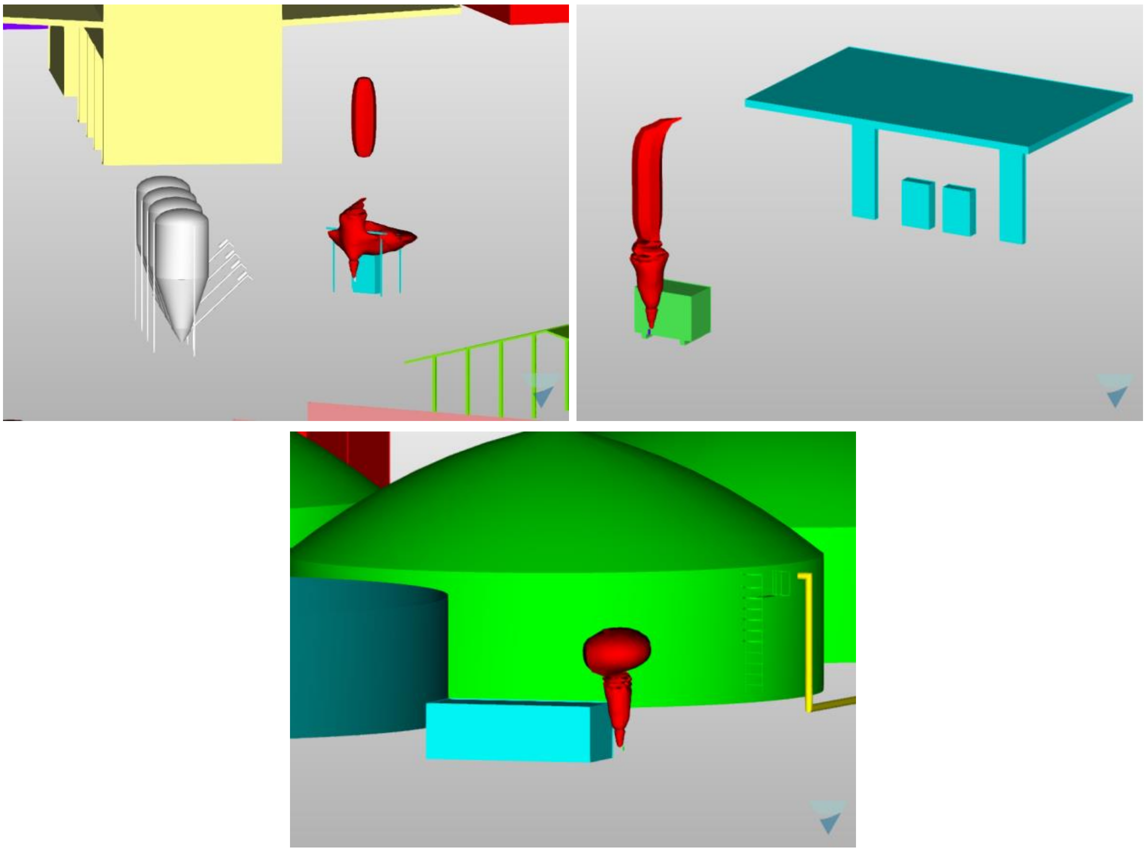


Figure 155: 3D views of the results Simulation-06 MET

Contrary to what was said at the end of the analysis of the results of the previous simulation, the temperature difference caused a very different dispersion of gas (as regards the internal station and the compression unit at the external station). When compared to the 6.3 (same conditions but with -9.3°C), the clouds are very different and more extensive. This can be due to the different volatility of biomethane but above all to the different lower level of *explosiveness* LEL_m which with this temperature is equal to 31.49 g / m^3 against 36.49 g / m^3 of the winter period.

6.8 Simulation 07_MET

- Wind speed: 3 m/s;
- wind direction: North;
- atmospheric temperature: 32.6°C;
- *LEL*: 31.49 g/m^3;

- *UEL*: 330 g/m^3.

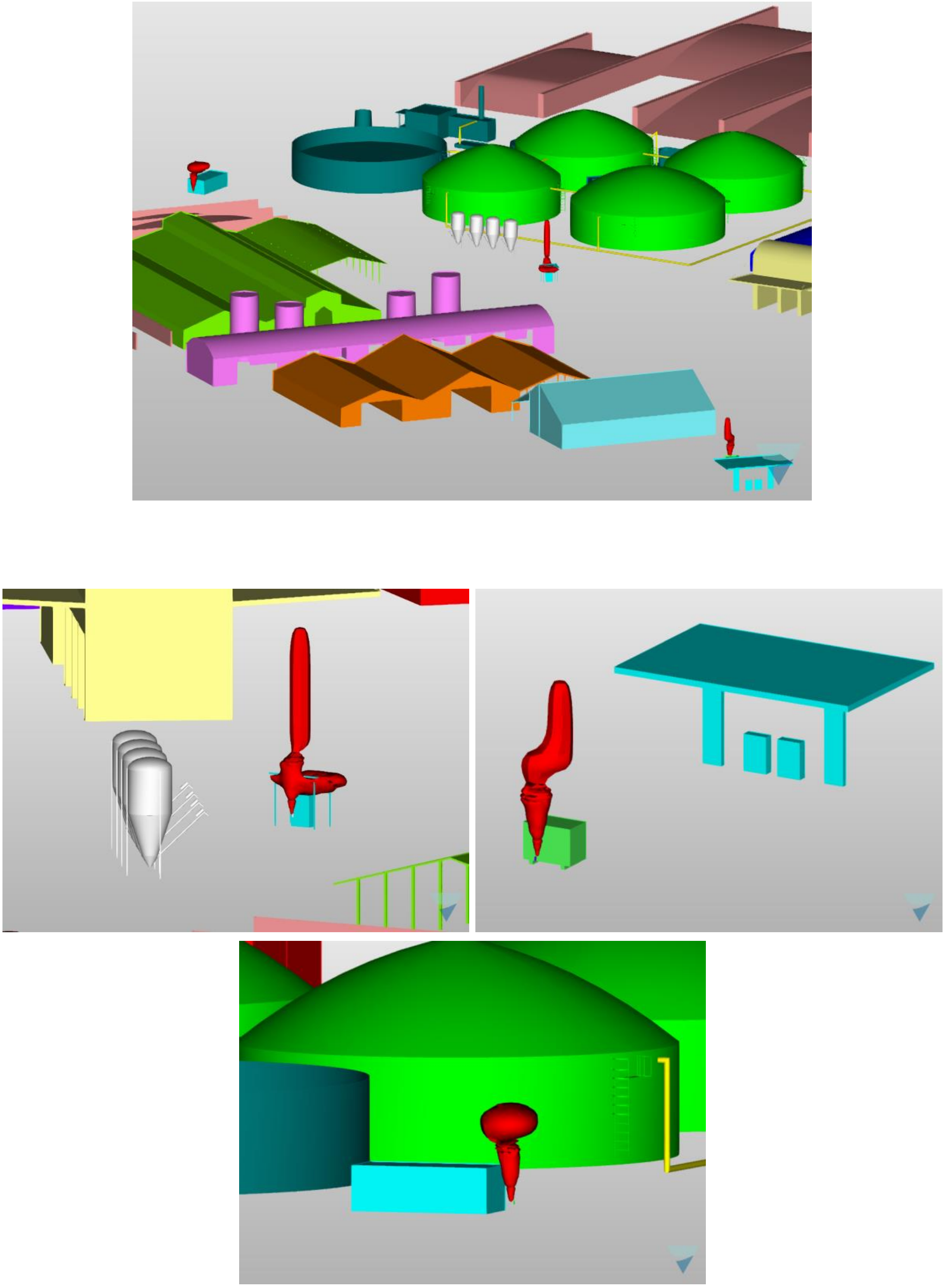
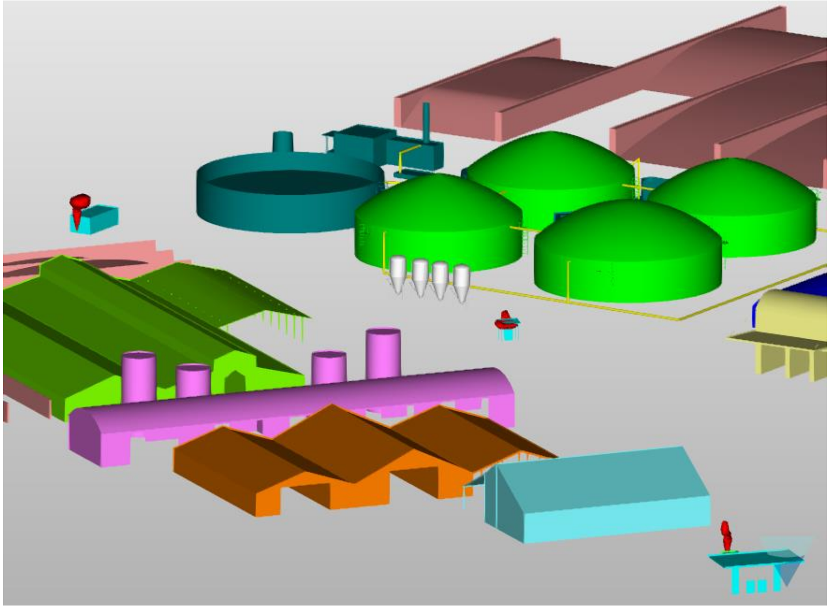


Figure 156: 3D views of the results Simulation-07 MET

Also with regard to this simulation, if compared to the corresponding winter simulation (6.4) a different developments of the clouds is visible, more extended upwards. The greater development of *red* volumes, only vertically, confirms that the lower density of biomethane and above all the speed and direction of output imposed during the setting phase are the determining factors or with greater influence on the final results.

6.9 Simulation 08_MET

- Wind speed: 3 m/s;
- wind direction: North-East;
- atmospheric temperature: 32.6°C;
- *LEL*: 31.49 g/m^3;
- *UEL*: 330 g/m^3.



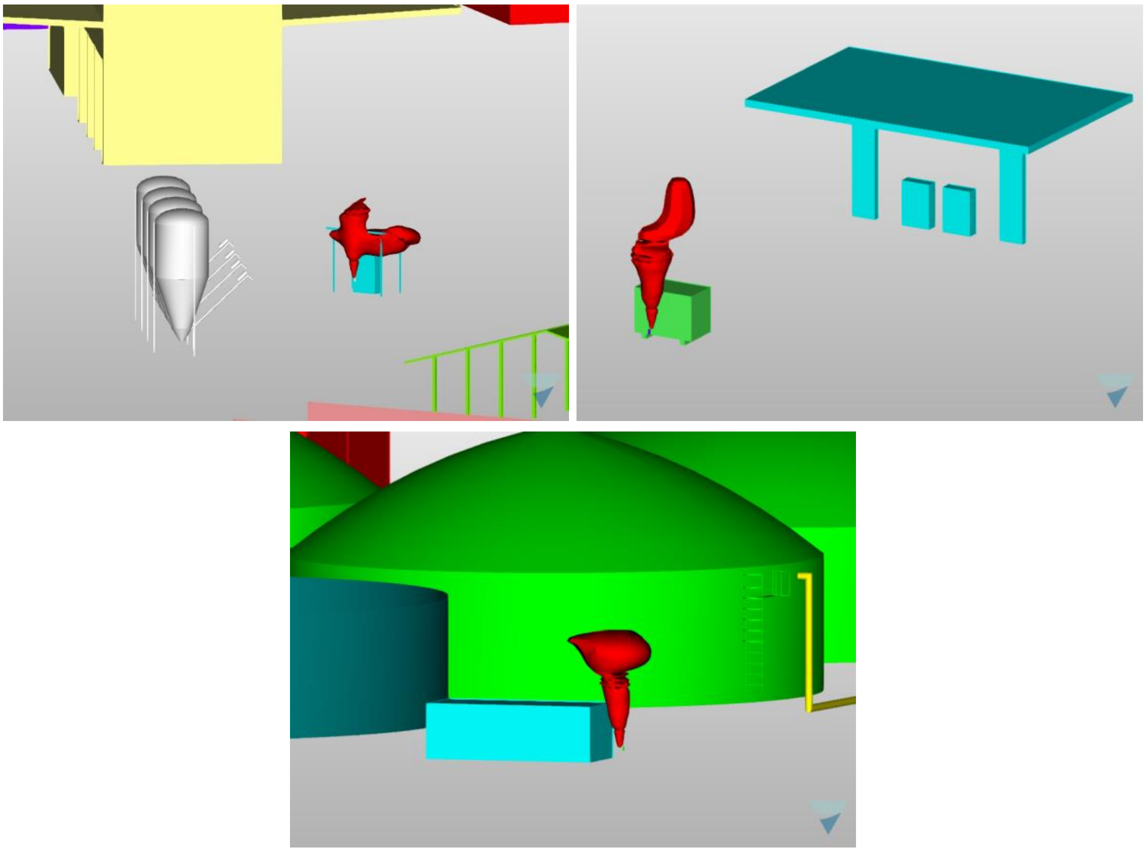


Figure 157: 3D views of the results Simulation-08 MET

The most visible difference between this and the 6.5 is visible at the compressor close to the public refueling station.

For greater completeness and clarity, below is attached a comparison of the bio-methane clouds extracted from the current simulation and from the simulation 04_MET where, just for representative purposes, the minimum explosive value equal to the summer case has been set, i.e. 31.49 g/m^3.

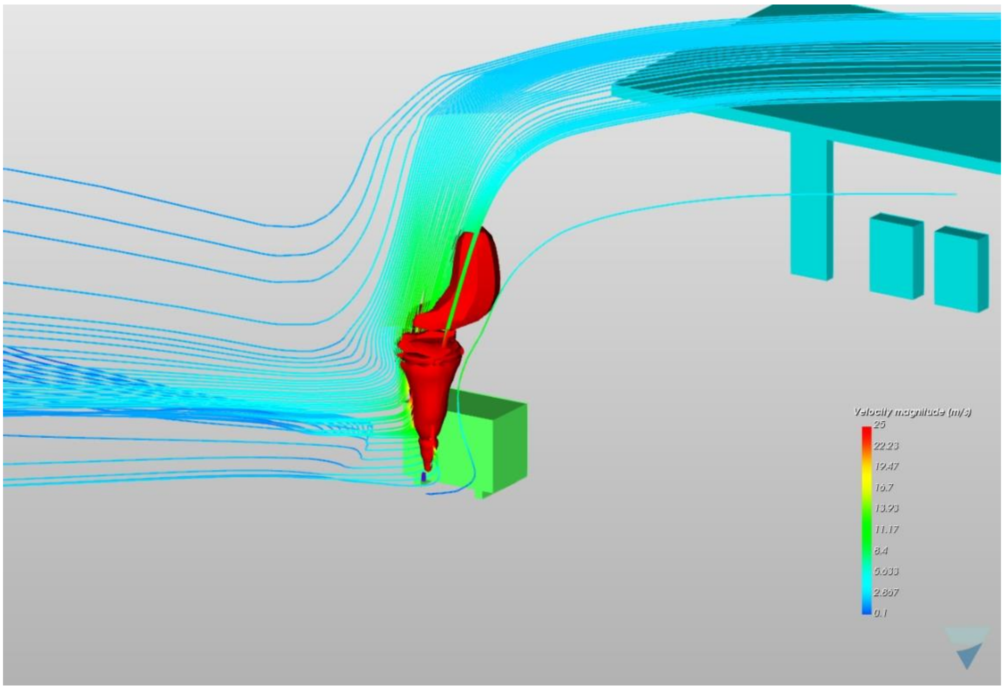


Figure 158: Streamline of the compression module Simulation-08 MET

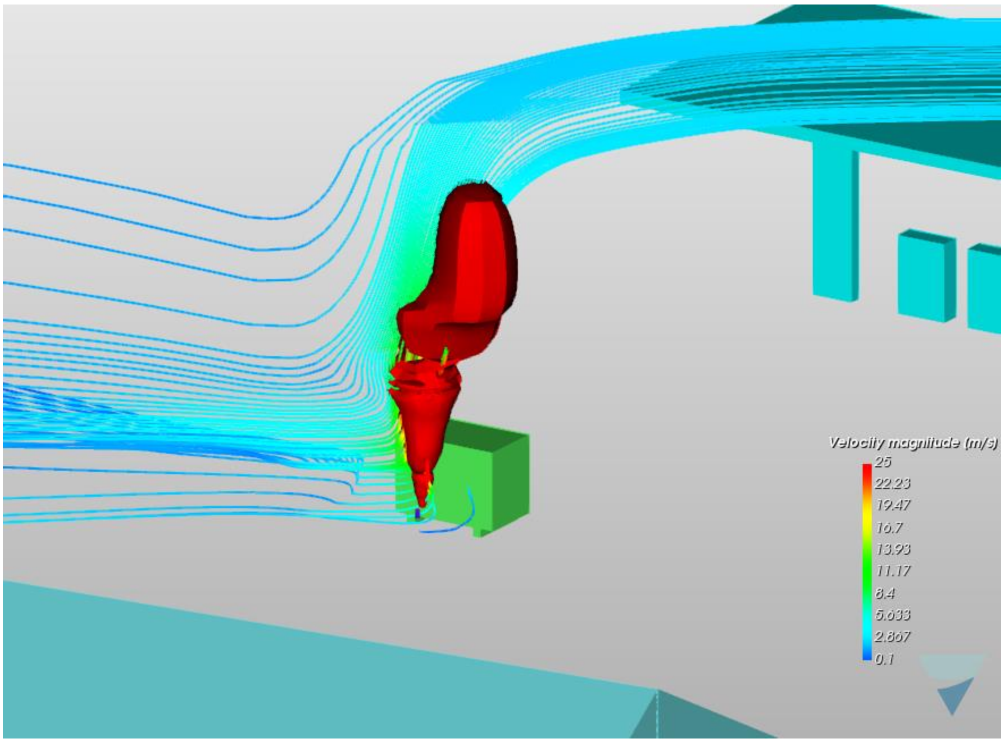


Figure 159: Streamline of the compression module Simulation-04 MET

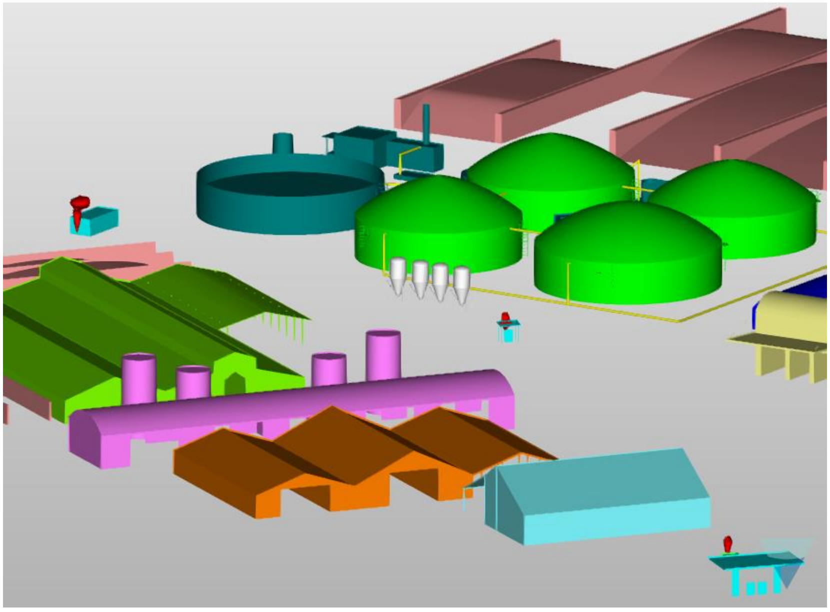
Carefully it is possible to notice how although the two clouds are very similar, they differ. This inequality is certainly attributable only to the atmospheric temperature that certainly affects the volatility of biomethane.

The flow lines represented are all passing through an imaginary segment passing through the exact point of gas emission and developing from 0m to 10m above the ground. As can be seen, the wind coming from South-West, once met the strong flow of outgoing biomethane is diverted upwards. In this case, unlike simulations with biogas, the wind is deviated from the gas flow and not vice versa.

Even with this configuration, however, possible critical scenarios are not recognized.

6.10 Simulation 09_MET

- Wind speed: 0.1 m/s;
- wind direction: North;
- atmospheric temperature: 32.6°C;
- *LEL*: 31.49 g/m^3;
- *UEL*: 330 g/m^3.



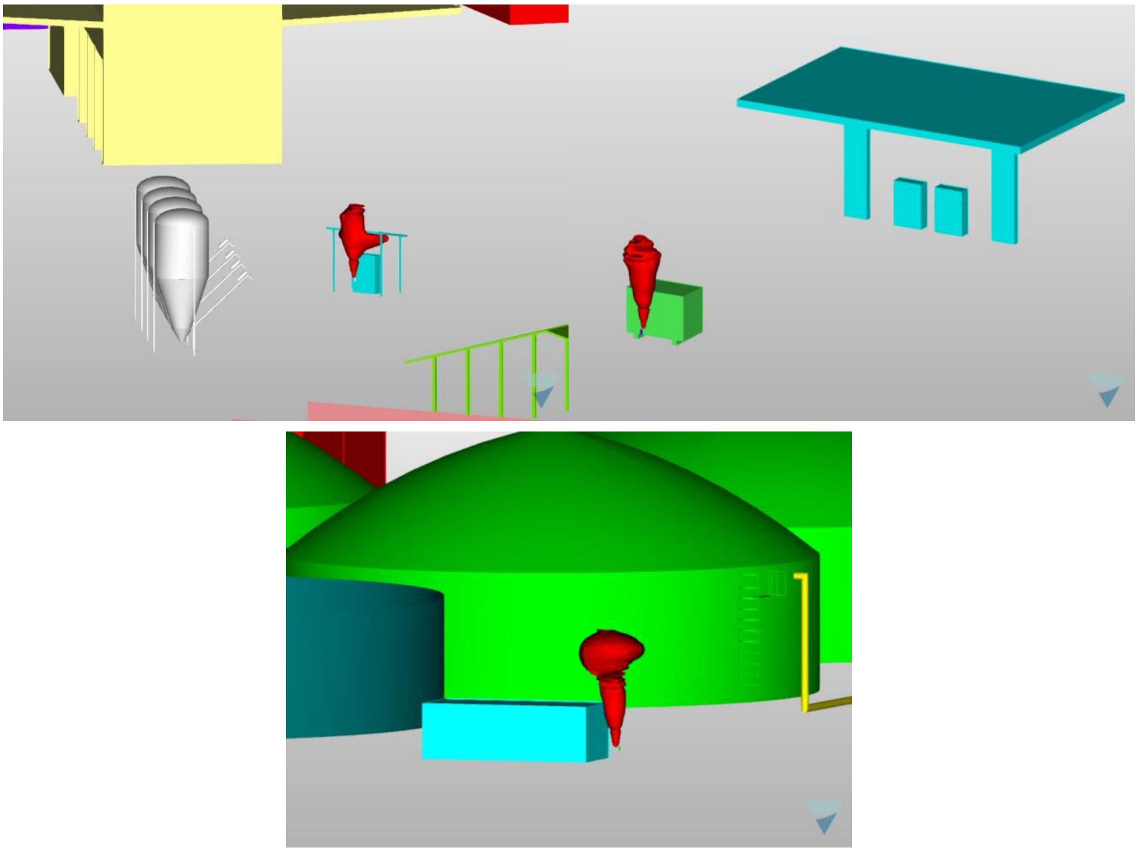


Figure 160: 3D views of the results Simulation-09 MET

To conclude, with this simulation there are no very visible differences with the winter and windless case. Also in this case no critical scenario has been recognized due to methane dispersion in hazardous areas or due to possible contacts with triggers such as moving vehicles or non-ATEX engines.

6.11 Conclusions

As far as biomethane is concerned, the factor that certainly influences the most of all is the rate of emission. At this speed any fluid moves along a lot of space undisturbed regardless of the wind and climatic conditions.

The 1000m/s emission also affects the concentrations of gas in a given area, as already mentioned in a previous simulation, an outgoing gas at this speed has the same effect as a very strong wind that distributes the gas to very large areas but causing an collection of gas (and therefore an increase in concentrations) in a certain very low volume, or in any case at levels not worrying for the risk of explosion. Certainly these analyzes have become very useful to define that despite being lighter than air, the methane expelled in these conditions would have no difficulty in moving upwards, in this the selected orientation of the emission surfaces with a normal vertical is also relevant. The choice of normal was made following the observation of some working systems and the most recurrent position of shutters used in these areas.

Comparing the "summer" and "winter" simulations, the visible differences, as demonstrated during the 08_MET simulation, are due to the different explosive values calculated in accordance with the CEI guidelines that take into account the external temperatures.

Regarding the possible risk of explosion, what has been derived from these simulations, which could be deepened with greater precision and greater configurations, is that is very low if under normal conditions.

7 General conclusions and suggestions

The two production systems, even if dealing with gases that have lower densities than air, would still require measures for the detection of methane (in biogas, the component to be kept under control to avoid fires or explosions is always methane) very different. This is because, based on what seen in the simulations, the behavior of biogas is very different from that of biomethane. In fact, due to the less "clean" composition and the outgoing pressures, biogas does not tend to rise directly into the atmosphere but its development is often influenced by the effect of the acting wind, while for what concerns pure methane (with lower density than air and biogas itself) because of the operating pressures it receives a boost towards the outside from the pipes such as to move for long paths undisturbed and parallel to the normal of exit.

It should be indicated that, as far as biomethane is concerned, the performance simulations are characterized by critical points having all normal output direct upwards. This did not allow any of the clouds (within the flammability ranges) to propagate horizontally or vertically towards the ground, which led to the obtaining of mean non alarming results. The discourse related to biogas is different, where both the vertical and horizontal emission sources have produced clouds such that some configurations are rather dangerous both for the potential contact with dangerous surfaces and in terms of extension of the cloud for areas characterized by an extended radius.

These two conclusions lead the authors to say that the two sub-plants, although often located in the same production plant (from raw material to cogeneration and from the extraction of biogas to the distribution of biomethane), certainly require two types of interventions and considerations for the application of preventive and protective measures.

The type of approach to the problem has effective results primarily on the safety of users and structures and in the background also has an influence on the expenses for the creation of a system of prevention and protection of this type of plant.

On the basis of these considerations, it is possible to define where it is necessary to reasonably invest money in favor of safety and where instead the presence of protective and preventive systems would be redundant and excessive.

From what has been said it can be deduced that, for example based on the experience gained as a result of the simulations performed, the plant dedicated to the production of biogas may require the installation, even massive, of sensors dedicated to the detection of methane positioned near the critical points as well as the application of further measures for the detection of malfunctions of the plant while, according to what has been observed with biomethane, the massive installation of sensors of this type would only be too much expense, beyond what is necessary. In fact, the areas where these devices could be useful are:

- internal station, placed under the canopy: for what has been observed a leakage like the simulated one would lead to the accumulation of a small, but still dangerous, amount of methane that could ignite if the distribution pump is used carelessly and without respecting all the appropriate indications;
- external station open to the public, located exactly above the refueling column: for the same reason as above or for risks due to the use of the system by users not properly informed careful to follow all the procedures of the case.

There are also measures that should be taken in common both for the biogas part and for that of biomethane. The training of operators, first of all, the construction of gates to control access to the facilities (excluding the external distributor open to the public) by unauthorized personnel, the presence of adequate devices for detecting and extinguishing the flames, etc.

The proposed method, therefore, is useful for the definition of spatial of all areas at risk of fire or explosion and which, therefore, would require the installation of all safety devices required by legislation, applied to any type of plant for the production of biogas and biomethane. Unlike the vertical approach to design, with a method of this kind we act almost punctually, reducing, in a justified way also numerically, measures and expenses for safety up to what is necessary. It is the task of the professional, in agreement with the owner and in any case the Fire Brigade, then to define up to what minimum level it is necessary to adopt all the protective and preventive measures.

8 Safety manual for biogas plants

Given their articulated pattern, biogas plants have different sources of risk either for health, environment and heritage, in this case divided into the different main categories:

1) Fire risk;
2) risk of explosion;
3) manure spill out and watercourse pollution;
4) injury during standard working activities;
5) injury during maintenance activities
6) confined spaces access;
7) various risks:
   i) toxic gases breathing (CO_2, H_2S, CH_4, etc.);
   ii) burn (surfaces with T > 70°C);
   iii) electro-shock (cogeneration unit, electrical transformer, engines, etc.);
   iv) noise and vibrations.

8.1 Fire risk

Figure 161: Fire event in a biogas plant Source: Google.com

As already faced in about Italian legislation, a unique standard or law doesn't exist, that can moreover be applied to the whole productive process. According to the different features and the different operative phases, different regulations must be followed.

Following the indications of the DM 03 February 2016, that's concerning the approval of the fire prevention technical regulation for the design, construction and operation of natural gas deposits with a density not exceeding 0.8 and biogas deposits, even if of a density greater than 0.8 , this plant is framed as belonging to type "d", or defined in the class "pressostatic accumulators: fixed containers, with variable volume used for the accumulation of gas produced by biological transformations (biogas) compliant with UNI 10458".

The working pressure allowed in this type of system, classified as gasometers, is equal to 0.5 bar (0.05 MPa) and therefore falls within low-pressure devices.

The storage capacity, measured in$^{m\ 3}$, is given by:

$$C = V \; x \; P/Po$$

Where:

- V is the geoemtric volume of the tank or pipe-tank, expressed in m^3;
- P is the maximum absolute pressure, in bar;
- P_0 is the barometric absolute pression, expressed in bar and assume to be convetionally equal to 1 bar.

Since these are digesters equipped with a gasometer, the maximum geometric volume is assumed as the geometric volume.

8.1.1 Classification of the deposits

In the case of the installation considered, digester with 25 meter in diameter has a volume of 1295 m^3 and equal to 1803 m^3 for the 28m digestors. The total volumetric capacity obtained estimated is equal to 5688 m^3, making the plant fall into the^{3rd} category.

8.1.2 Fencing:

The area of relevance is completely limited by a 1.80m fence and installed at 10m distant from the dangerous elements.

The fence is continuous type, sturdy and made with non-combustible material and it's liable to prevent access to the dangerous element by unauthorized people.

At least two gates have been built in the fence, with a width of more than 2.50 m, reasonably spaced and suitable to ensure, in case of need, the access of rescue vehicles and the exodus of the people present.

For gasometers and pressostatic accumulators, the maximum geometric volume is assumed.

Maximum absolute pressure is intended equal to the maximum working pressure as declared by the operator.

8.1.3 Hazardous elements:

Element inside the deposit are considered:

a) containers intended to storage gas (tank pipes, tanks, gasometers, pressostatic accumulators and digesters);
b) compression stations and the decompression ones;
c) any other element presenting a danger of explosion or fire under normal operating conditions, including the transfer point, fixed components and pipes with an operating pressure exceeding 5,0 bar (0,5 MPa).

For all the elements referred to in points b) and c), with operating pressures below 5,0 bar (0,5 MPa), the standards set out in the Ministerial Decree of 16 April 2008, containing the "Technical regulation for the design, construction, testing, operation and surveillance of works and distribution systems and direct lines of natural gas with a density not exceeding 0,8", must be complied with.

According to this prescription, gasometer linking pipe, storage unit piping to the remaining component of the plant must comply with such standards.

8.1.4 Safety distances:

Around each storage tank or group of tanks, an area must be left unobstructed from vegetation and whatever can rise fire danger. The width of this area of this area cannot be less than the protection distance.

Safety distances related to the deposits constituted by the gasometers and digestors (low pression), are reported in the Table 14:

Table 14: Safety distances in function of storage volumes

Single storage tank capacity	Close buildings [m]	Protection [m]	Internal safety [m]	External safety [m]			
				1st cat.	2nd cat.	3rd cat.	4th cat.
X ≤500m³	6	4	5	30	25	20	15
500m³ ≤ X ≤ 5000m³	10	4	5	30	25	20	15
5000m³ ≤ X ≤ 50000m³	15	6	8	35	30	25	-
50000m³ ≤ X	20	8	10	40	35	-	-

8.1.5 Constitutive elements characteristics:

Gasometers, accumulators and digesters must be designed, manufactured in accordance with regulations and protected from corrosion. Each gasometer must be design in order to ensure , if needed, a complete isolation of itself from the rest of the plant: the interception devices must therefore be easily accessible in every moment, visually identifiable and must ensure high reliability to ensure their safe operation.

In each connecting pipe must also be inserted, in the immediate vicinity of the gasometer, a closure to ensure the exclusion of the gasometer from the rest of the system if necessary.

Each gasometer must be equipped with:

- correct devices to control the volume of gas contained and the internal pressure;
- devices designed to signal the achievement of limit values, superior and inferior, the permissible content of the gasometer in operation, and, where appropriate, to prevent these values from being exceeded.

The pipes connecting the gasometers, accumulators and digesters to the rest of the plant must comply with the rules wrote for natural gas plants with a pressure of less than 5 bar referred to in 1st Section of the Ministerial Decree of 16 April 2008.

Static accumulators must be coherent with what is imposed by the UNI 10458 standard.

The pressostatic accumulators and their digesters, have a storage capacity of more than 500 m^3, for this reason they must be equipped with two automatic and independent safety systems: one for the detection of gas leaks and one for the detection of the loss of tightness of the pressostatic cover. They must also be equipped with a fast-emptying system that can be actuated from a protected area for flare combustion.

8.1.6 Obligations of users:

Users, with the exception of changes that may be necessary for emergency situations, are required to observe the limitations imposed on the contour of the installation area of the depot and not to alter its safety conditions for fire prevention purposes.

8.1.7 Electrical and protection systems against atmospheric discharges:

Electrical systems and protection against atmospheric discharges must be made to perfection in accordance with current legislation. The power supply of the various users must be interceptable, as well as from any electrical cabin, also from a control located in a protected position and certainly accessible even in case of fire. Any electrical supplies to fire-fighting water systems must be equipped with a separate emergency control, provided with special signs highlighting their specific function.

8.1.8 Fire extinguishing equipment and systems:

The generic storage rooms and rooms intended for the hazardous elements of the system must be equipped with portable fire extinguishers, of an approved type, in compliance with current legislation. The number and extinguishing capacity of portable fire extinguishers must be established in relation to the fire risk assessment, in accordance with the applicable criteria provided for by current legislation. The extinguishing capacity may not be less than 34A 144B C.

The fixed deposit must be ensured against fire by a hydraulic plant designed , installed, tested and managed to perfection and according to the standards decree of the Ministry of the Interior 20 December 2012, in order to allow the intervention on any dangerous element of the deposit, even with fractional flow. To comply with UNI 10779, the performance and power supply characteristics corresponding to a hazard level 2 (3rd category) and for above-ground tanks of 4th category of geometric capacity exceeding 100 m^3 must be guaranteed.

8.1.9 Safety signalling:

Appropriate fixed safety signs must be affixed, in particular in order to: - warn of the dangers arising from flammable substances; - signal the prohibition of approaching the deposit by strangers and that of smoking and using open flames; - indicate the rules of conduct and telephone numbers of the Fire Brigade and the technician of the company responsible for the pipeline or plant to be fed, in order to allow timely reports of anomalous or emergency situations also by third parties; - report the areas in which explosive atmospheres may form in such quantities as to endanger the safety and health of persons, identified in accordance with Annex XLIX of Legislative Decree no. 81 of 9 April 2008. Safety signs must comply with the requirements set out in Annex

XXV of Legislative Decree no. 81 of 9 April 2008 (Ordinary Supplement to the Official Gazette no. 101 of 30 April 2008). The gas pipes in sight must be marked with the yellow color in accordance with current legislation, with the exception of the pipes used during emergency supplies.

8.1.10 Obligations of the plant owner:

The owners are required to observe the limitations imposed on the contour of the installation area of the depot and not to alter its safety conditions for fire safety purposes.

8.2 Explosion risk

Figure 162: Explosion of a biogas plant   Source: Santafocadelfiuli.it

As seen in the previous chapters, the main danger with biogas is the flammability of the methane contained in it and the explosive property of the methane-air mixture. The explosion range is between 5 and 17% by volume of methane in the air.

All equipment, instrumentation and sensors installed in areas classified EX (EXplosive), must be certified for use in areas with possible formation of potentially explosive atmospheres in accordance with the ATEX Directive 2014/34 / EU. The following categories of apparatus must be used in the different zones:

- zona 0: category of equipment 1G;
- zona 1: at least category of equipment 2G;
- zona 2: category of equipment 3G.

A part for what has already been wrote and considered in the chapter ………, reporting the ATEX evaluation, some additional considerations must be made.

In the moment of the introduction of oxygen (through atmospheric air), necessary for the biological oxidation of hydrogen sulfide by aerobic microorganisms (these are able to produce elemental sulfur and sulfuric acid, promoting the subsequent formation of sulfates) during this segment, particular attention must be paid to the amount of oxygen introduced inside the gasometric dome. This must be carefully dosed in order to avoid the formation of a potentially explosive mixture inside the gasometric dome than under normal conditions is considered to be a non-explosive atmosphere. For safety's sake, it is recommended that the oxygen content be measured continuously in order to avoid the risk of fire and explosion.

In order to avoid that as a result of any overpressure, the hydraulic guard loses its sealing capacity, it is suggested to arrange the following precautions:

- installation of several (even if redundant) sensors for continuous monitoring of the pressure of the biogas contained within the gasometric domes;
- installation of an automatic liquid refill system inside the hydraulic guard safety valve, so as to guarantee the presence of the correct liquid level inside the valve body.

In general, based on what has been observed by the simulations of accident scenarios in typical weather conditions for the site, it is necessary to carefully evaluate, on a case-by-case basis, the placement of non-ATEX certified devices and in general the possibility of performing dangerous operations in the immediate vicinity of the fence located around the production site. This measure is essential to minimize accidents defined as "*secondary*", in which spot-fire phenomena can occur and cause secondary fires.

8.3 Manure spill-out

Figure 163: Sewage spill from a biogas plant Source: Ruralpini.it

Production and storage of wastewater in the form of sewage is a potential cause of significant pollution due to the production of dangerous agents both for the protection of health and the environment (especially aquifers).

A critical compound of the sewage of this typology is represented by Nitrogen (N), whose combination with hydrogen H leads to the production of ammonia (NH_3) which is not only harmful to the atmosphere because it is highly volatile, it is also harmful to the water reserves because it leads to soil acidification and contributed to water eutrophication (55). Within the biological masses subjected to digestion process, the levels of ammonia contained reach values close to 60/70% of the total nitrogen present.

Inside the digestate produced by the fermentation of biomass, there is often also a modest amount of H_2S which, in addition to being highly dangerous for human and animal health, can be harmful for the tightness of the tanks. These if long exposed to H_2S rich atmospheres, risk losing the protective layers, putting it in a position to be attacked by corrosive substances that weakening the structure and losing in tightness that would cause, then, the uncontrolled dispersion of the sewage in the ground.

In addition to the different technologies for the abatement of pollutants available in commercial, the farmers can contribute to the reduction of the environmental impact acting simple precaution measures such as localized spreading of the wastewater that avoids the spraying of the jet or through the immediate burial of the same previously distributed on the soil.

A useful measure to avoid this scenario is represented by the addition of additives (chemical or natural) that help to keep the pH of the sewage around 6, thus obstructing the emission of ammonia. Around these acidity values, ammoniacal nitrogen slightly changes its composition losing the characteristic volatility. Among the most used additives is sulfuric acid (H_2SO_4) (56).

8.4 Injury during standard working activities

Figure 164: Accident in a biogas plant   Source: Repubblica.it

The high automatization level of these plant asks for a limited human presence, to whom is demanded a high level of specialization.

The general preventive measures consist, in fact, in the automatization of the process and the plants, reducing as much as possible operations to visual controls from the office control room, both via dedicated software for continuous diagnostics and via computer, and closed-circuit camera system.

Manual intervention from operators should be limited where it is not possible to rely on devices and machines.

Of these phases, the critical issues are analyzed below.

8.4.1 Solid biomass loading phase

Figure 165: Loading of solid fraction Source: MX-benne.eu

a) Crushing: the biomass is stored in deposits contained between walls called "trenches". The handling necessarily takes place through mechanical wheel loaders managed by the operator. The risks may concern the use of machinery and the management of machinery, the phase of ascent/descent from the vehicles. Same risk derives from crushing from the machinery itself driven by other operators or in case of failure to activate the locking devices. The system must be fenced and provided with a gate, in order to avoid the access of non-authorized people and vehicles, since not being able to have the certainty that people or vehicles;

b) Fall from a height: during the operations of progressive removal of the corn silage covering sheet, the operator is subject to the risk of falling from the perimeters of the trenches (height 4m) and from the processing front. To reduce the first occurrence, there are mobile containment lines on the market, which can be folded down if necessary and can be raised quickly in conditions of need (57); for the second case, as well as to avoid avalanches of silage, which can bury the operator, it is necessary to implement certain precautions (58):
   - when moving and loading high front masses, it should be present a second operator close to the trench;
   - pay attention to landslides in silage, especially when operator notice a dry layer between two wetter layers;
   - when the operator is at the top of the trench, he must stay at least 5 meters away from the front and avoid approaching if its integrity is doubtful;
   - be extremely careful when removing the top of the silage. Consider using a fall arrest harness connected to a pole at a distance from the front;
   - in the case of very high fronts, take representative fodder samples on the mixer wagon and avoid taking is on the silage front;
   - do not stand on the front buckets of the telehandlers to obtain samples from higher heights;
   - be aware of slippery wet conditions when walking around trenches or heaps that release leachate.

8.4.2 Control and / or loading of the liquid phase

During the normal operations of control and handling of the liquid phases present in the plant, the operator may be subject to risks of different kinds. The two main ones are explained below:

8.4.2.1 Risk of falling into the sewage pit

Figure 166: Liquid phase pumping Source: Veneroni-srl.it

If not equipped with appropriate perimetric protections around the pit, this can represent a strong danger to the safety of workers during its opening and loading operations. The presence of hydrogen sulfide H_2S inside the tanks exposes, in case of fall of the operator, to strong dangers of fainting and blocking of breathing in a few seconds. In order to avoid this danger, it is necessary to define safety procedures (59):

- avoid access inside a closed gate when the sewage is enlivened;
- make sure that the ventilation in the working area is maximum;
- avoid any type of flammable source near to the plant;
- make sure that there are no people near the plant when the wastewater is pumped to the outer tanks;
- use an H_2S meter to evaluate the concentration before and after pumping (it must be placed outside the shed or on the poolside, using an extension probe);
- before starting to pump the wastewater, check the pH by placing a strip of measuring paper on a pole immersed in the slurry for at least 50 cm. In case of acidity (pH ≤4), the risk of high concentrations of H_2S being released with agitation increases:

- avoid entering the tanks without an adequate protective device and a harness system that allows recovery in case of need. In the case of entry, the presence of a properly trained person must remain outside the tank**;**
- make sure that the grating covering the tanks is well placed and safety fixed;
- the tank must be equipped with a fence with a minimum height of 1.80 m, not climbable and equipped with a dense mesh anti-intrusion net;
- it is necessary to draw up a protocol that considers this information and make sure that all staff know it and put it into practice.

8.4.2.2 Risk of falling from raised parts

Figure 167: Raised passages in a biogas plant   Source: L'Arena.it

The lack of special parapets or the inadequacy of these, if they are not of adequate and sufficient height with regard to the passable surfaces, may constitute a source of risk for the fall of the operator. Following the indications of Legislative Decree 9 April 2008, n.81 – "Implementation of Article 1 of Law 3 August 2007, n.123, on the protection of health and safety in the workplace", it is necessary that the parapets have a height of not less than 1 m and must have a footrest of minimum height 150 mm. A further recommendation is about the slope of the parapet, that should not be higher than 15°.

For the prevention against falls, the main technical regulatory reference that can be applied, is the technical standard UNI EN ISO 14122-3: 2010. This standard contains the different measures to follow for the construction of stairs (fixed and portable), landings and handrails, providing the useful characteristics to reduce the risk of slipping, falling and breaking and structural failure (60).

These measures, combined with the total prohibition of leaning out of the parapets, can help reduce the number of injuries and the extent.

These measures, combined with the total prohibition of leaning out of the parapets, can surely help reduce the number of injuries and the extent.

8.5 Risk of injury during maintenance activities

Figure 168: Injury in a biogas plant   Source: LavocediMantova.it

Maintenance activities are often carried out, compatibly with the extent of processing and by internal resources of the plant. Given the extremely varied type of machinery present and the presence of atmospheres at risk of fire and/or explosion, particular attention must be paid during maintenance operations. Sometimes, these are not described in detail by the standards and it is therefore the task of the operator and the owner to identify the appropriate maintenance operations and the relative frequency, depending on the type of system and the needs of users. Routine maintenance work can be entrusted to internal staff of the company, only after proven that they are adequately trained and competent. Extraordinary maintenance, on the other hand, must be entrusted only to competent and qualified companies pursuant to art. 3 of Ministerial Decree 37/2008 (Art. 8, Ministerial Decree 37/2008), which are required to issue the declaration of conformity of the interventions carried out, pursuant to art. 7 of Ministerial Decree 37/2008 (61).

In general it is necessary that the plant is implemented by:

- compliance and user manuals records;
- emergency lock-out systems of machines;
- installation of smoke detectors at critical points or confined spaces where it may be necessary to enter;
- safety signs appropriate to the dangers present and to the general fire prevention rules;
- protective devices for rotating or moving parts.

The activities on the different systems present for the suction, treatment and compression of biogas represent an important source of fire and explosion risk: in order to reduce them, it is necessary to adopt measures to prevent the formation of explosive atmospheres and their ignition: it is necessary first of all that the electrical systems are explosion-proof and the use of anti-spark tools is required (e.g. copper-beryllium tools).

Recently built machinery must be CE marked (declaration of conformity, use and maintenance manual and equipped with controls arranged in such a way as to avoid accidental start-up, identifiable with clear and easily understandable indications. Directive 2006/42/EC of the European Parliament and of the Council of the European Union of 17 May 2006 on machinery and amending Directive 95/16/EC defines that, in the case of machinery marketed before 1996, it must be CE marked only if modified in terms of purpose of use.

Maintenance interventions can be carried out according to different criteria. It is possible to group them into two macro categories:

- *predictive* (Threshold and second condition): maintenance is carried out according to the time of use and the estimated duration of the useful life of components, fluids, accessory parts, without waiting for the occurrence of the fault and the consequent unpredictable machine downtime. Often at this juncture are also carried out interventions defined as "by opportunity", that is, periodic interventions are taken advantage of to carry out restoration operations on unscheduled parts.
- *corrective* (failure): maintenance is carried out to resolve faults that have occurred because of accidents or failures due to deterioration. This kind of maintenance is the most delicate because it does not allow programming and is often carried out in an emergency, so with limited time and resources.

In order to ensure an adequate level of safety in the workplace, maintenance should be scheduled as much as possible in order to maintain a high level of efficiency of plants and equipment and, at the same time, to avoid interruptions in work due to unforeseen interventions that could request fast intervention performed without the suitable safety measures.

In all cases, maintenance interventions must be carried out by trained and experienced personnel, who operate according to well-defined, clear, widespread and shared schemes and prescriptions at all levels. All operations must be reported in special registers, indicating the date of execution of the intervention, the nature, the outcome and the operator.

Before the operational execution of the maintenance, it is necessary to verify that the machinery is disactivated, adopting the necessary impediments to avoid that these can be inadvertently reactivated. If operations cannot take place when machinery is stationary, extraordinary safety measures must be put in place, especially if coordination between different companies is necessary. Restoration of power supply should be possible only in the absence of danger to the workers concerned.

General safety precautions for interventions on machines and plants are (62):

- shut down of the electric driving force;
- shut down of gases/service fluids;
- deviations or closures of water flows;

- internal/external Fire Brigade detachment alert;
- alert external installations and communication to local civil authorities;
- reclamation with inert gases of pipelines, vessels, equipment, rooms in which vapors, gases or dusts susceptible to fire or to form explosive atmospheres may be present. During each maintenance operation, the absence of gas in the section of the pipelines under verification must be ascertained, also considering the place where it is located (inside a building, outdoors or underground).

8.6 Working in confined spaces

Figure 169: Confined spaces operation   Source: Italiarespirazioni.it

Access to confined spaces with saturated air with polluting and/or harmful gases is a risk factor common to many industrial and agricultural activities. In the case of a plant of this type, the dangerous space is represented by the digester volume that is rich in atmosphere charged with agents such as hydrogen sulfide or methane that is part of the biogas. Access to an buildings of this type is mandatory during some maintenance activities that require the direct intervention of an operator inside the tank emptied of sewage, in order to perform maintenance works on some components inside the digester that for malfunctions or scheduled maintenance must be removed from their housing for example.

More generally, within confined spaces, the risks for operators are manifold: chemical, physical, structural or even injury risk.

The chemical risk is associated with all those possible scenarios that see the onset of a fire or an explosion or even the asphyxiation of the operator. The physical risk derives from all the stresses to which the operator is subjected during activities such as vibrations, noises, particular and stressful climatic conditions. The structural risk is present whenever the conformation of the spaces of the elements inside the area is such as to be an obstacle during the performance of the activities, leading to difficulties in moving or accessing that could cause falls or other more or less serious injuries. Finally, the risk of accidents is linked to falls of material, falls from a height, crushing, etc. (62)

Often this type of intervention is carried out by employees of third-party companies specialized in this type of activity, which take care of the education and training of the operator, the planning of activities, risk analysis and emergency management as well as the supply of material suitable for carrying out this activity such as personal protective equipment and work equipment.

Access in such environments should be only the last available option if the operations cannot be carried out from the outside.

In a such hostile environment such as the digester, the presence of corrosive and irritating gases such as ammonia and hydrogen sulfide forces operators to enter it equipped with a respirator and any device capable of protecting the respiratory tract, clothing that covers the whole body and that does not allow the passage of any gas or any liquid mass, as well as the necessary devices that allow it to operate safely and in the shortest possible time such as lights, glasses or visors or all-covering masks connected to the supply of breathing air, protective helmet and in general space-saving instrumentation.

The legislation that defines the basic rules of work within spaces of this type is D.Lgs. 81/2008 which identifies a series of obligations, prohibitions and preventive measures in order to reduce the likelihood of an accident during the activities.

8.7 Various risks

As far as a biogas and cogeneration plant is concerned, the risks present in the activity range from injuries to asphyxiation. Given that the maintenance activities inside the digesters are carried out stationary and open-air system, if this were not possible it would be carried out by qualified personnel who know the risks of this type of environment and know how to deal with any emergency scenarios and above all is equipped with the appropriate equipment to operate safely.

It should be emphasized that plants of this type are managed by a few people, who well know the plant and what is around it. Despite this, the possible risks present in this type of environment concern:

- Inhalation of toxic gases that can lead to asphyxiation;
- fall from above inside the sewage tank;
- fall from above;
- sliding;
- fall of materials;
- explosions and fires;
- contact with very hot surfaces;
- contact with non-insulated electrical equipment;
- handling heavy machinery;
- harmful vibrations and noises that in the long run can cause permanent damage;
- lifting and transporting excessive loads;
- accidental ingestion of dangerous substances;
- possible interference due to several people present around and inside the plant.

Personnel working around and throughout the plant are obliged to follow the training and training regarding all possible risks detected during the analysis. All these risks must be identified and evaluated during the project phase, and all the necessary measures to reduce the risk to acceptable levels must be evaluated. If this is not possible, as a last step, it is necessary to provide the personal protective equipment useful to the operator, who is forced to use them whenever necessary.

8.7.1 Inhalation of toxic gases (CO_2, H_2S, CH_4, ecc.)

Figure 170: Toxic gases breathing Sources: Italiarespirazioni.it

The presence of hydrogen sulfide among the products constituting the gaseous mixture makes the process of desulphurization of biogas necessary, as it is corrosive for engines using gaseous biofuel and is a poisonous gas for humans: it is lethal only at high concentrations, but at low concentrations it accumulates in tissues, creating even long-term damage, with symptomatology characterized by dizziness, depression, malaise, reduced motor coordination, headache, effects on the fetus, irritation to the eyes and throat, cough.

Being a flammable gas heavier than air, it tends to accumulate in dangerous concentrations in burrows, pits, trenches, wells and other depressions or cavities.

8.7.2 Risk of burns (surfaces with T > 70°C)

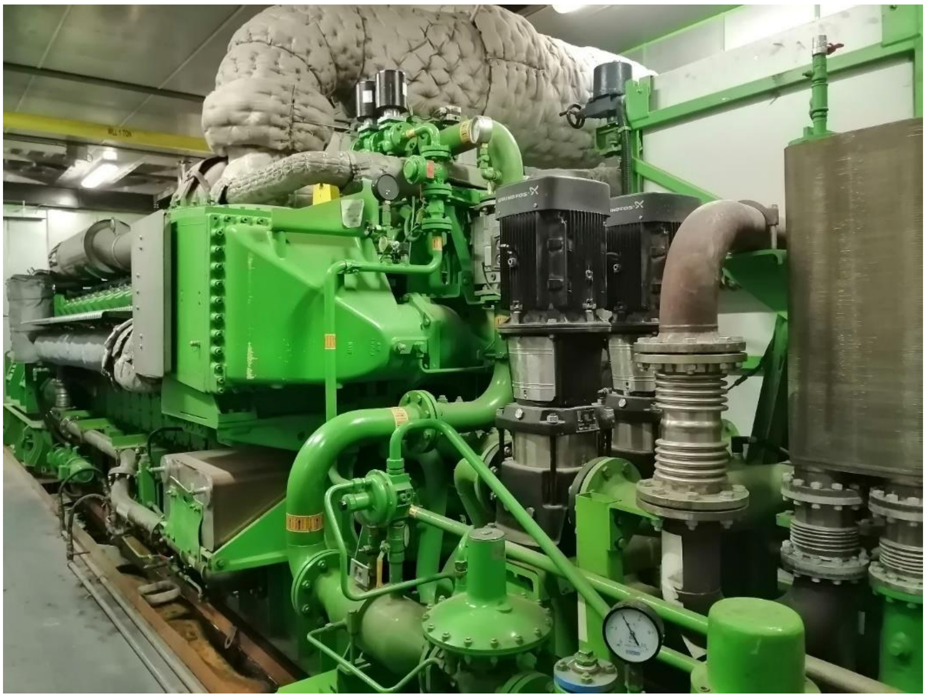


Figure 171: Cogenerator hot surfaces   Source: Exapro.com

It is necessary consider the burning risk coming from the non-shielded contact with cooling or heating system for the biogas plant components (for example the hot surfaces of the cogenerator) or just surfaces exposed to the flare activated.

8.7.3 Risk of electric shock

In this kind of plants there are various electric instruments and equipment, distributed in a large area (cogeneration unit, transformer, motors, etc.). These devices, many of which are equipped with electric motors, such as pumps, mixers and in general devices operating at high voltage can, in case of improper use or due to defects in the cogeneration unit, cause deadly electrical shocks.

Figure 172: Plant electrical power cabinet   Source: Tecnoeffesrl.com

In this regard, the creation of a grounding network for the protection of operators from indirect contacts is essential. This consists of a series of dispersers (copper or galvanized iron), fixed vertically in the ground and connected to each other by a series of electrical conductors. The presence of a single grounding network has several advantages over the installation of insulated dispersers. The creation of an equipotential plate ensures that the contact voltages are greatly reduced, as long as the electrical conductivity of the soil is considered. In general, a moist soil with a high presence of mineral salts, has a low electrical resistivity while a dry, rocky or gravelly soil is characterized by a higher resistivity, making it necessary to install a greater number of ground dispersers.

8.7.4 Noise and vibrations

In order to avoid damage to the hearing of the operators involved in the production processes, it is necessary to proceed with the measurement of personal levels of exposure to noise in compliance with the provisions of Title VIII of Legislative Decree 81/08 (Consolidated Safety Act).

Figure 173: Ear protector   Source: Materialeantinfortunistica.it

The obligations borne by the Employer are summarized in carrying out the necessary surveys and processing of the technical report, in addition to the supply of special personal protective equipment such as noise-cancelling headphones and / or earplugs. An area characterized by high level of noise is the one surrounding the cogeneration unit.

8.8 Security and emergency management

The owner of the plant must take into account the aspects related to the management of safety and emergencies, putting in place all the measures envisaged to ensure the operation of the systems, safety devices, fire protection systems.

Operators must have continuous access to the user manual for the operation of the plant, to the biogas flow schemes and to a plan with the indication of any areas protected by fire-fighting systems (and their positioning) as well as that of classification of areas with potential risk of formation of explosive atmospheres. It is good habit to affix the latter in different clearly visible points of the plant.

If the production unit is subject to the obligation to draw up the emergency plan, the employer should include in that document all the procedures for the management of the shutdown and safety of the plant and to ensure the safety of workers (63).

8.9 Safety documentation

According to the decree of the Lombardy Region, DDS 4 July 2014, n. 6463 - Guidelines for the safe management of plants for the production of electricity from renewable sources, through anaerobic digestion of organic matrix substrates, commonly called "biogas", it is necessary that the following documentation is present and that this is made available for consultation at all times:

Manual of use and maintenance of machine: (provided by the manufacturer)

The use and maintenance manual of the "machine", drawn up in compliance with the principles set out in Legislative Decree 17/2010, Annex 1st point 1.7.4, must provide, among other things:

- Definition of the normal operating states, anomaly, failure, emergency, for the various sections of the machine; explanation of their meanings;
- analysis of confined places and related risks; indication of the minimum conditions and requirements required to allow permit access into confined places;
- description of ordinary scenarios and typical and recurrent failures, with indications of the procedures to be implemented in the various cases (reference to maintenance procedures);
- description of the safety systems and devices present on the plant, operating logic, their degree of reliability and independence from the programmable logic unit of plant management;
- definition of any "remote" management, with description of the effect and prevention of possible "conflicts". Indication of the procedure for the "manual" management of emergency conditions
- the manual must provide for the maintenance and replacement program of the various components subject to wear. For each type of maintenance, it must

indicate the level of competence required, and whether or not that competence is available in situ, the number of operators required and the safety measures to be activated, including the equipment of PPE and any necessary detection tools (e.g. gas concentration detectors) both fixed and personal.

Prevention programming document:

(by the Employer - Client)

a) description of the safety organization of the user company, with possible definition of the roles and residual tasks in case of outsourcing of the management of the plant;
b) PPE - also of 3rd category - which must be present on the plant; management and training procedures;
c) Fixed and personal detection systems supplied (maintenance in efficiency, procedures of use).

Fire Prevention Certificate:

(by the Customer/Manager)

The activities subject to visits and fire prevention controls related to the types of plant in question, with reference to Annex 1 of Presidential Decree 151/2011, are:

- n. 1 - Establishments and plants where flammable and/or oxidizing gases are produced and/or used with overall quantities in a cycle exceeding 25 Nm^3/h;
- n. 49 - Groups for the production of subsidiary electricity with endothermic engines and cogeneration plants with a total power of more than 25 kW.

The presence of other subject activities must be evaluated and declared by the Customer.

Identification and delimitation of zones with danger of explosion "ATEX":

(by the Customer/Manager)

A special table must represent the areas in which explosive atmospheres may form, their classification and their extension. Verification of the adequacy of the components (electrical and non-electrical) present in these areas (Title XI of Legislative Decree 81/08) must be carried out and, in the case of areas classified 0 and 1 in which there are electrical systems, these must be approved and subjected to periodic verification according to the procedures established by Presidential Decree 462/2001. Operating instructions must be provided and indicated to avoid producing triggers (e.g. use of anti-spark and anti-static equipment and tools).

Training and staff training plan:

(by the Employer - Client)

It is necessary to introduce a education and training process for personnel (at the start of activity and subsequently). This section also includes emergency workers, firefighting and first aid. The documentation related to the training must be made available even after the end of the course.

Internal emergency plan:

(by the Customer)

Phase: ORDINARY AND EXTRAORDINARY MAINTENANCE: This section lists cognitive elements and information that must be consulted by the control committee in the exercise of the inspection activity.

1. Analysis of transients, malfunctions, foreseeable failures, repairs, emergency situations and maintenance (by the Manager):
   a. description of the maintenance conditions of the plant and table of the timing of the checks, ordinary maintenance;
   b. analysis of the risks of malfunction, operations and procedures applied to bring the plant back to its ordinary operation phase, including a description of the safety measures to carry out repairs and to put the plant in a safe condition.
2. Modes of access to Confined Places (by the Customer and contractors) according to what is indicated by the Manufacturer in the use and maintenance manual it is good to define the "general framework" of the system in order to identify in the best possible way any risks present. In particular, those connected with access to "confined places". Compliance with Presidential Decree 177/2011 on the suitability of companies called to operate in these places and the illustrative manual approved by the Permanent Advisory Commission of 18.4.2012 is recommended.

3. Maintenance register - Operating diary (by the Manager to be kept at the plant): Document, provided for by Legislative Decree 81/08 art. 71 paragraph 9, in which all maintenance and control interventions carried out on the basis of the provisions of paragraphs 4 and 8 of the same art. 71. In the same register it is advisable that all the operations carried out on the plant and the significant events that have occurred, even if not maintenance-aimed, are also noted, in order to always have an updated description of the status of the entire plant.

9 Conclusions

The analysis of fire safety in plants of this kind is undoubtedly interesting and articulated. By proposing an innovative method, accident scenarios resulting from the leakage of flammable and explosive masses of biogas within a truly existing and functioning plant were treated. The fluid dynamic simulations of the same scenario but in different climatic conditions, allowed to evaluate through direct comparison, the effect of the individual variables.

The approach defined in this work, considering the influence of the environmental factors typical of the areas of construction of the plant on the dynamics of potential accidents, can undoubtedly be useful to improve fire design. Allowing to predict with good approximation the accident scenarios, it is possible to operate a more conscious plant integration, in particular that relating to safety: the distance and position of installation of methane detectors and the more realistic definition of the safety perimeters are some of the possible advantages. The proposed methodology allows a wide elasticity in the customization of the different variables involved, also arriving at the parameterization of biogas, whose mixture is strongly influenced by the power supply of the plant and therefore never standard as could happen for common gases such as methane.

Being a dynamic method, this lends itself very well to implementations aimed at improving its accuracy and forecasting spectrum according to the characteristics of the plant. The evaluation of a biogas mixture having a particular composition and the climatic analyses related to the exact installation site would undoubtedly lead to a refining of the results, as well as implementation of the number and extent of accident scenarios. Although it is impossible to predict all scenarios, such an implementation increases the possibility that the real scenario will fall within the range of possibilities envisaged.

In addition to the potentiality of being an aid for the professional fire-safety engineer, the basis of the proposed method could favor the collaboration between the manufacturers of the different components of the system, allowing to identify more effectively the critical issues due to interference during all production phases, thus increasing the degree of safety characteristic of a plant.

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