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Risk Assessment of a Biogas Production and Upgrading Plant

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In the present work, the risk assessment of a biogas production and upgrading plant, representative of most of the biogas sites widespread throughout Europe, was carried out. The biogas is produced by anaerobic digestion for heat and power generation. An upgrading section (based on membrane technology) was also considered, for the production of biomethane to be injected in the national gas grid. A set of possible loss of containments for each equipment unit was defined and the potential dangerous phenomena were identified by means of an event-tree analysis. The impact of such phenomena was assessed in terms of damage distances.

1. Introduction

The global demand for bioenergy is strongly increasing in recent years and will rise even more until 2035, driven by strategies to reduce air pollution that lead to government support policies. In this scenario, the supply of all types of biomass is growing substantially, including biogas and municipal waste (International Energy Agency, 2013). (Florin et al. 2014; German and Schoneveld, 2012; Koçar and Civaş, 2013; Soland et al. 2013).

The actual volume of biogas produced in the world is not known (REN21, 2014). Still some numbers for this sector can be given: by the end of 2012, in Europe more than 13800 biogas power plants were running, with an installed capacity of 7.5 GW. In this panorama, Germany dominates the market (Eurostat 2014). In EU, the production of biogas is expanding also because of the policy changes (European Parliament, 2009): Italy alone saw its number of biogas plants to grow of 250 % in 2013 because of the economic support for small-scale plants. In the U.S., the number of the operating plants is 2200 (REN21, 2014).

In this emerging industrial sector, the development of the involved technologies and the optimization of the processes have been widely studied (Keck et al. 2014; Miltner et al. 2009; Niesner et al. 2013). There are some studies regarding occupational safety (e.g. Pietrangeli et al. 2013), however, a systematic and comprehensive approach is still lacking from the process safety point of view (Heezen et al. 2013).

The risk associated with a biogas plants are fire and explosion (typically related to methane), and toxic release (due to the presence of hydrogen sulfide). These are the scenarios that were analysed in the present work.

The considered case study is the production of biogas from the anaerobic digestion of livestock slurry. This process and related facility is quite representative of most of the biogas sites widespread throughout Europe. An upgrading system by means of membrane technology was also considered, in order to evaluate the effect of producing biomethane to be injected in the national gas grid. This use of biogas is well known in some European countries and is expected to grow fast in Italy in the next years thanks to the incentives recently introduced (Ministero dello Sviluppo Economico, 2013). A safety assessment was performed and results, in terms of damage distances, are presented and discussed.

2. Methodology

The risks associated with biogas production and upgrading to biomethane were investigated. First of all, two generic schemes for production and upgrading were created on the basis of the technical information gathered

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during some visits to different Italian biogas facilities. This data were integrated with those found in literature (FNR, 2010). The description of the schemes obtained is presented in the next section.
A safety assessment of the reference plants was carried on applying the methodology suggested by Tugnoli et al. (2007), which is based on the guidelines traced by the “Purple Book” (Uijt de Haag and Ale, 1999). A schematic representation of the steps to follow is presented in Figure 1.
The first step of the methodology is the identification of the equipment present in the process and the related operative conditions such as pressure, temperature, substance involved and hold-up.
After that, a set of credible critical events, referred to as Losses Of Containment (LOCs), is assigned to each Process Unit (PU). The possible LOCs suggested by the methodology for the equipment involved in this analysis are (Uijt de Haag and Ale, 1999):

- LOC1: small leak, continuous release from a 10 mm equivalent diameter hole;
- LOC2: catastrophic rupture, release of the entire inventory in 600 s;
- LOC3: catastrophic rupture, instantaneous release of the entire inventory;
- LOC4: pipe leak, continuous release from a hole having 10 % of pipe diameter;
- LOC5: pipe rupture, continuous release from the full-bore pipe.

For each of them, a simplified bow-tie diagram has to be built in order to define both the direct causes leading to the critical event (left side of the bow-tie) and the resulting dangerous phenomena (right side of the bow-tie). These diagrams can be obtained using several methodologies. In this study the Methodology for the Identification of Major Accident Hazards (MIMAH) proposed by the ARAMIS project was used (Delvosalle et al. 2004). The dangerous phenomena identified by means of the bow tie-analysis (flash-fire, jet-fire, Vapor Cloud Explosion (VCE), toxic cloud) result in different types of physical effects (thermal radiation, overpressure or toxic concentration). An example of simplified bow-tie diagram for the catastrophic rupture is shown in Figure 2.

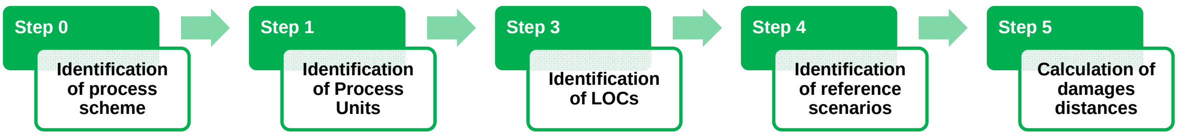

Figure 1: Schematic representation of the steps of the methodology used for the risk assessment.

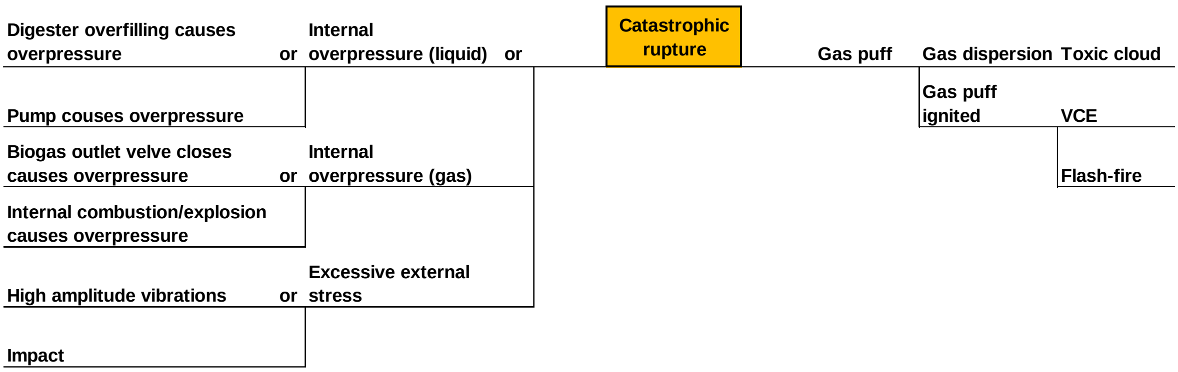

Figure 2: Bow-tie diagram for the catastrophic rupture (LOC3) of the primary digester represented in Figure 3.

In order to compare these events, the damage distances corresponding to a given physical effect is calculated. The effects on humans (i.e. 1 % mortality level for a human being exposed to the effect of the dangerous phenomenon considered) were taken into consideration to define threshold values for each physical effect, as indicated by Tugnoli et al. (2007) and reported in Table 1. The calculation of the damage distances was carried out using conventional models found in literature (Lees, 1996).

Table 1: Threshold values assumed for damage distance evaluation (Tugnoli et al. 2007).

Dangerous Phenomena	Threshold value
Flash-fire	½ of Lower Flammability Limit (LEL)
Fireball	7 kW/m^2
Jet-fire	7 kW/m^2
Pool-fire	7 kW/m^2
Vapour Cloud Explosion (VCE)	14 kPa
Physical/mechanical explosion	14 kPa
BLEVE	14 kPa
Toxic exposure	Immediately Dangerous to Life and Health (IDLH) concentration

*LFL: Lower Flammability Limit;
**IDLH: Toxic Concentration Immediately Dangerous to Life and Health

3. Description of the case study

The case study considered in this work is the production of biogas from livestock slurry (the corresponding reference scheme is reported in Figure 3). The core of the plant consists of two digesters with a volume of 2700 m^3 each. Both of them are equipped with 900 m^3 membrane gasometers for the storage of the biogas produced. In the primary digester (E01 in Figure 3), the temperature is maintained constant at 47 °C in order to establish a favourable environment for the bacteria involved in the degradation of the raw material. In the secondary digester (E02), the temperature drops to 42 °C, creating a better condition for methanogenic bacteria and ensuring a higher methane yield. The biogas produced (300 Nm^3/h), saturated in water, contains methane and carbon dioxide in a ratio of 60/40 on a volume basis. A small quantity of hydrogen sulphide (100 ÷ 200 ppm) is also present together with nitrogen, oxygen and trace gases. The low concentration of hydrogen sulphide is obtained by injecting small amount of air directly in the digesters in order to provide the oxygen required by specific aerobic bacteria, which convert this pollutant into elemental sulphur. The raw biogas coming from the secondary digester (E02) goes into the primary one (E01), from which is sent to a chiller (E03), where it is cooled to 15 °C and the condensed water is removed. Then, the dried biogas is delivered by a blower (E04) to the Combined Heat & Power (CHP) unit (E05), where it is used as fuel in a gas spark ignition engine for both power (600 kW_{el}) and heat generation (600 kW_t).
Besides the CHP generation unit, an upgrading system based on membrane technology (represented in Figure 4) was also analysed. In order to inject biogas into the natural gas grid, methane content needs to be raised up to 97 %, while H_2S and other pollutants have to be removed.

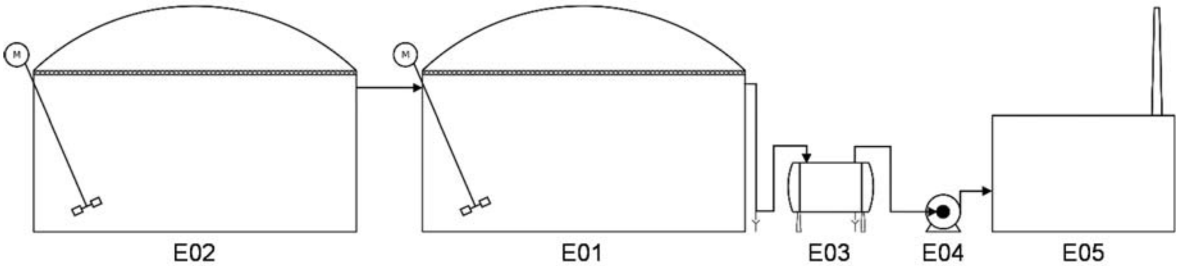

Figure 3: Reference scheme for biogas production from livestock slurry.

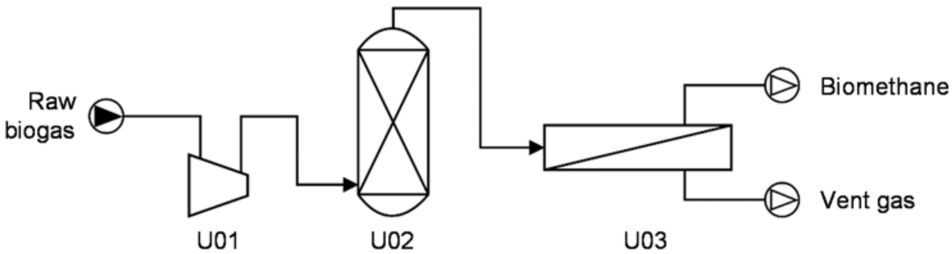

Figure 4: Reference scheme for biogas upgrading by membrane technology.

Biogas upgrading is the operation in which the methane content of raw biogas coming from the production phase (desulfurized and dried) is raised to meet the quality requirements for final utilization (FNR, 2010). In the present work, membrane separation was considered. This process is based on the selectivity of a membrane with respect to the diffusions of methane and carbon dioxide. This entails that one component (in this case carbon dioxide) is transported through the membrane at a higher rate than the other (in this case methane). The higher is the selectivity, the higher will be the purity and the recovery of methane. The driving force for the transportation of each component is the difference in partial pressure over the membrane. For this reason, the membrane module operates at a pressure of 20 bar. The diameter of the pipelines from the compressor (U01 in Fig 4) to the membrane module (U03) is 150 mm. The presence of hydrogen sulphide is detrimental for the integrity of the membrane. Therefore, a desulfurization unit (U02) is required before the biogas stream enters the membrane module.

4. Results

In Table 2 and Table 3, the results of the safety assessment are shown for production and upgrading of biogas respectively. Scenarios for which the damage distance resulted to be less than 2 m were considered negligible due to the scarce accuracy of the software in modelling near field release.

Regarding the production section (Table 2.), the scenarios that resulted in the greatest damage distances were given by the catastrophic rupture with instantaneous release of the entire inventory (LOC3) for both the digesters. This is mainly due to the amount of flammable substances stored in the membrane gasometer which, when released instantaneously, has the potential of provoking a VCE with a damage distance of about 100 m.

The damage distances associated to the CHP were negligible since the substance handled by this PU is mainly exhausted gas.

The low concentration of H_2S resulted in a low damage distance when the toxic effect of the releases is considered. Furthermore, this scenario (toxic cloud) is relevant only for the two digesters. In this case, however, the affected area (an ellipse with the major axe equal to the damage distance reported in the table) resulted confined within the wall of the digester itself. Therefore this specific scenario can be considered as having a very low impact. It is worth noticing, however, that there exist situations in which the desulfurization process is carried out in a unit different from the digester, for instance, a scrubbing column. In these cases, the concentration of H_2S within the digester can reach 1500 – 2000 ppm_{vol} raising the toxic hazard related to the release scenarios.

Table 2: Results related to biogas production and CHP generation equipment.

Process Units	Operating conditions		LOCs	Dangerous phenomena	Damage distances [m]
Secondary digester (E02)	T [°C]:	42	LOC 2	Flash-fire	20
	P [barg]:	0.01		Jet-fire	21
	V [m^3]:	900	LOC 3	Flash-fire	25
	CH_4/CO_2:	62/38		VCE	101
	H_2S [ppm_{vol}]:	150		Toxic cloud	8
Primary digester (E01)	T [°C]:	47	LOC 2	Flash-fire	19
	P [barg]:	0.01		Jet-fire	21
	V [m^3]:	900	LOC 3	Flash-fire	24
	CH_4/CO_2:	60/40		VCE	100
	H_2S [ppm_{vol}]:	150		Toxic cloud	8
Dryer (E03)	T [°C]:	15	LOC 5	Flash-fire	14.5
	P [bar]:	0.01		Jet-fire	16
	CH_4/CO_2:	60/40			
	H_2S [ppm_{vol}]:	80			
Blower (E04)	T [°C]:	15	LOC 5	Flash-fire	9.5
	P [barg]:	0.02		Jet-fire	15
	CH_4/CO_2:	60/40			
	H_2S [ppm_{vol}]:	80			

Table 3: Results related to biogas upgrading equipment.

	Operating conditions		LOCs	Dangerous phenomena	Damage distances [m]
Compressor (U01)	T [°C]:	50	LOC 5	Flash-fire	3.5
	P [barg]:	19		Jet-fire	11
	CH_4/CO_2:	60/40			
	H_2S [ppm_{vol}]:	80			
Desulfuriser (U02)	T [°C]:	50	LOC 5	Flash-fire	3.5
	P [barg]:	19		Jet-fire	11
	CH_4/CO_2:	60/40			
	H_2S [ppm_{vol}]:	0			
Membrane (U03)	T [°C]:	50	LOC 4	Flash-fire	4.5
	P [barg]:	19		Jet-fire	3.5
	CH_4/CO_2:	100/0			
	H_2S [ppm_{vol}]:	0			

LOC1: small leak, continuous release from a 10 mm equivalent diameter hole
LOC2: catastrophic rupture, release of the entire inventory in 600 s
LOC3: catastrophic rupture, instantaneous release of the entire inventory
LOC4: pipe leak, continuous release from a hole having 10% of pipe diameter
LOC5: pipe rupture, continuous release from the full-bore pipe

For what concerns the upgrading section (Table 3) the damage distances obtained from the analysis are comparable with those calculated for the biogas production if the VCE is disregarded.
Figure 5 puts in comparison the maximum damage distance obtained for each process unit involved in the two sections (biogas production and upgrading).

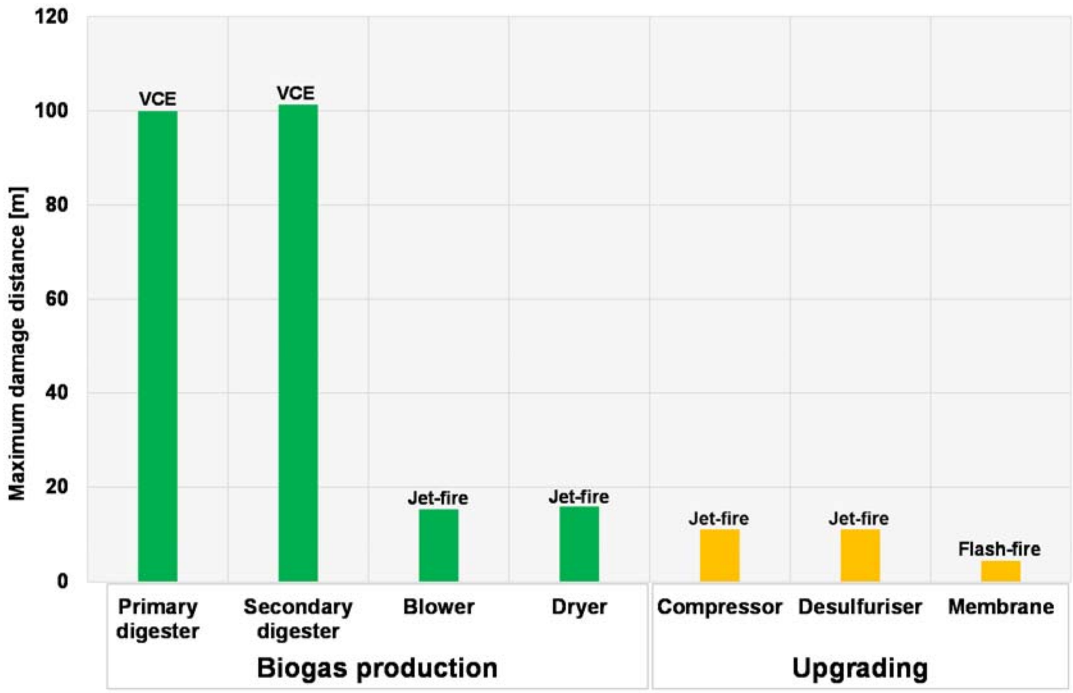

Figure 5: Comparison of the maximum damage distances obtained for the process unit of both sections of biogas production and upgrading.

5. Conclusions

The analysis identified the scenarios which have the highest impacts (damage distances) for a typical plant where biogas is produced from livestock slurry and upgraded to biomethane by means of membrane modules. Among the process units identified, the two digesters stand out as the ones having the highest damage distances. These correspond to the VCE scenarios.

An interesting result appears clearly from the comparison of the damage distances between the production and upgrading sections: adding the upgrading process does not introduce any scenario and the resulting damage distances are not greater than those obtained for the unit involved in the biogas production units.

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