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Thermal stabilization of digesters of biogas plants by means of optimization of the surface radiative properties of the gasometer domes

Matteo Bavutti[a], Luca Guidetti[a], Giulio Allesina[b], Antonio Libbra[b], Alberto Muscio[b]*, Simone Pedrazzi[b]

[a]*BioBoost Srl, via G. Capilupi 21, 41122 Modena, Italy*
[b]*BEELab, Dip. di Ingegneria "Enzo Ferrari", Univ. Modena & Reggio Emilia, via Vignolese 905/B, 41125 Modena, Italy*

Abstract

A new incentive scheme for power generation from biogas is favoring in Italy the construction of small plants. These ones, however, have poorer financial viability and biological stability than larger plants. In order to ensure adequate performance and a reasonable payback period it is therefore essential that every aspect of their operations is carefully designed. In this respect, summer overheating of anaerobic digesters due to solar gains must be prevented. A solution relies upon the implementation of a 'cool' gasometer dome with properly chosen solar reflectance, whose effectiveness was assessed through the use of a calculation code specifically built and validated by comparison with experimental data.

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Keywords: biogas, digester, dome, cool roof, solar gain

1. Introduction

Each EU country is being forced to increase its production of energy from renewable sources in an attempt to meet the requirements of the climate and energy package 20-20-20 [1-2]. Among renewable sources, one offering significant advantages relies upon the anaerobic digestion of biomass and the production of biogas, to be then

* Corresponding author. Tel.: +39-059-2056194; fax: +39-059-2056126.
E-mail address: alberto.muscio@unimore.it

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exploited for power generation or even CHP. Biogas plants are already common in countries like Germany and Austria. Recently, they began to spread also in Italy thanks to strong state incentives, which have made investments in this type of technology very profitable.

1.1. Advantages of biogas production

Biogas production through anaerobic fermentation of biomass offers many benefits to both farmers that host plants and the community. In particular, biogas production is appreciable because:

- the quality of livestock wastewater is improved by converting organic nitrogen into inorganic nitrogen, more bio-available to vegetation;
- more rigorous practices are introduced in the agriculture with regard to management of effluents;
- distributed energy generation is promoted, as well as emancipation from imported fossil fuels;
- a source of renewable energy is introduced that does not depend on external factors such as wind or sunlight as it can provide energy 24 hours a day, 365 days a year;
- renewable energy produced through anaerobic digestion is potentially storable without limits of time and power; the biogas, suitably refined, may even be introduced in the pipelines for natural gas distribution;
- farm incomes are promoted through involvement in activities useful to the community and not through grants;
- in the biogas districts, the industry related to biogas plants requires several types of high-level profession such as engineers, installers, maintenance personnel, biologists, etc.

1.2. Incentive scheme in Italy

The Ministerial Decree of July 6, 2012 [3], which entered into force in January 2013, regulates the new incentive scheme regarding renewable energy sources. The old incentive scheme, valid until the end of December 2012, provided for the grant of a feed-in tariff of 280 € per MWh_e fed to the power grid, for all types of biogas plant and guaranteed for 15 years. The new scheme provides incentives depending on the installed power and the type of biomass, favoring plants with electrical power smaller than 300 kW_e and/or fed with byproducts such as manure or waste of the agro-industry. For these plants, the incentive is € 236 per MWh_e fed to the grid and it is granted for 20 years. Plants with installed power smaller than 100 kW_e directly access to the incentives without having to go through the registration procedure required for larger plants [4].

In light of the information above, it is easy to understand why the biogas market is evolving towards the construction of small plants, primarily powered by manure. The transition from the era of large plants to that of small ones, however, is not painless. A small biogas plant presents a higher (about double) specific cost per kilowatt of electric power than large plants as built in the past years. A small plant is also affected by a greater sensitivity to biological issues due to the greater variability of its feeding diet. Therefore, in order to make safe and convenient the investment it is crucial to accurately evaluate each component and each phase of the biogas production process and thus minimize inefficiency losses or uncertainties of biological type, ensuring the continuity of biogas and electricity production. With this regard, a main problem that can adversely affect the profitability of biogas plants is summer overheating of anaerobic digesters. This problem is investigated in the present work.

1.3. Summer overheating of anaerobic digesters

The type of biogas plant most common in Italy essentially consists of a loading system (a pre-tank and/or a hopper), an anaerobic digester (typically a hot concrete pool insulated and heated, with a gasometer dome on top made of plastic material and a biomass stirring system inside), combined with a generation/CHP module for the production of electricity and, possibly, heat (usually an internal combustion engine coupled with an electricity generator). In the most common operating conditions, the anaerobic digester is maintained at a temperature close to 40°C by means of a heating system that recovers energy from the cooling system of the generation/CHP module. Constancy of temperature in the digestion bath is an essential requirement for correct operation as the methanogenic bacteria survive in a rather narrow temperature range, out of which the yield of the biogas plant may collapse.

Energy obtained from the cooling system of the generation/CHP module is usually sufficient to heat the digestion bath even in the colder months of the year. Only for small plants with digester characterized by a low volume/external surface ratio, the available heat may not be sufficient in the more rigid months. In this case, it is necessary to adopt additional components such as a condenser that allows heat recovery also from the flue gases of the generation/CHP module.

In summer, gains due to direct sunlight help to keep warm the digester, and this is useful as long as the ambient temperature allows the digester to dissipate this additional energy input in the external environment. If the dissipated energy is less than that absorbed from the sun, the digester can experience a temperature drift of the digestion bath that can endanger the stability of the biomethanization process in the biomass substrate. More specifically, overheating of the bath affects the growth rate of the bacterial species used for the production of methane (methane bacteria), which is extremely sensitive to temperature variations. It has been shown [5] that the optimum temperature for maximum bacterial growth and, therefore, maximum production of biogas is between 37°C and 40°C, a range that includes the majority of species of the methanobacteria family (Fig. 1).

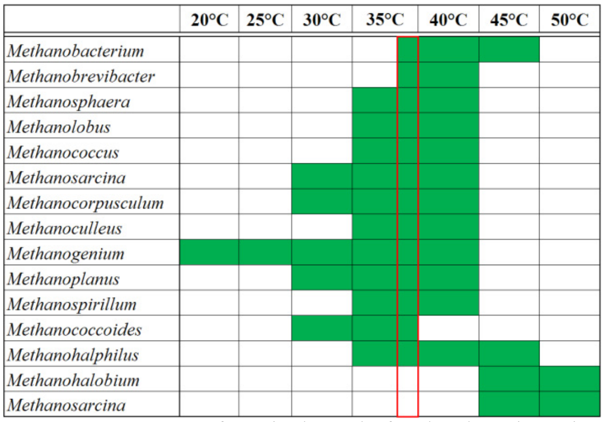


Figure 1. Temperature ranges for optimal growth of methanobacteria species [5].

Even in cases where thermal drifts of the entire digester do not occur, localized overheating of the gas contained below the gasometer dome creates overpressure that can be balanced only through the discharge of biogas directly in the atmosphere, with negative consequences from both the environmental point of view (due to the emission of a powerful greenhouse gas) or that of energy and economic performance.

2. Cool roof technologies to prevent summer overheating of buildings

Solar reflectance of a material quantifies the fraction of incident solar radiation that is directly reflected by a irradiated surface; its value ranges from 0, for a totally absorbing surface, up to 1 or 100%, for a perfectly reflecting one. Thermal emittance is defined as the ratio of the thermal radiation emitted from a surface and the theoretical maximum emission at the same temperature; its value ranges as well between 0 and 1. A surface with high solar reflectance absorbs only a small part of the incident solar radiation. Furthermore, if the surface is characterized by high thermal emittance, most of the solar energy is released to the external environment by thermal radiation in the infrared. ‘Cool roof’ is a technical term identifying a class of materials with high and certified values of solar reflectance and thermal emittance, both new and after weathering.

It has been proven that the use of cool roofs on opaque components of the building envelope has a highly positive effect, if not decisive, on issues such as summer overheating of buildings and the resulting physical discomfort experienced by people hosted in, as well as on energy consumption for air conditioning [6-13]. Cool roof materials can be either organic or inorganic, with different advantages and disadvantages: factory made inorganic tiles and coatings can reach very high levels of performance, while organic paints and membranes allow in situ coating of almost any type of surface. A few years ago, research and dissemination efforts on cool roofs and, more generally, on the development of innovative materials for control of solar gains were started also by the Energy Efficiency Laboratory (EELab) at Modena, Italy, targeted to the Italian context and carried out by either theoretical or experimental approaches [14-16]. The present work capitalizes on those efforts.

2.1. Cool roof coating of the digester dome

Conceptually, an anaerobic digester does not differ substantially from a residential or industrial building. In fact, it has an opaque insulated envelope with a roof on top (the gasometer dome) and it is maintained at a temperature different from the environment through the use of a heating system. It makes therefore sense to extend the countermeasures against summer overheating of buildings to anaerobic digesters. In this study, the potential in terms of control of either the temperature inside the digestion bath or the overpressure below the gasometer dome has been investigated and quantified, however without translating the temperature control into greater efficiency or profitability of the plant – this task will be presented in ongoing studies. It was instead possible to translate the overpressure control into a minor discharge of biogas and, consequently, greater incomes obtainable through the production of electricity.

3. Dynamic model of a biogas digester

In order to evaluate the effectiveness of cool roofs when applied to anaerobic digesters and, more generally, to investigate the thermal behavior of the digesters, a tool for calculation of the dynamic behavior of a whole biogas plant has been developed in the MatLab programming environment. In particular, the tool allows calculating the overall heat transfer balance between biomass contained in the digester and external environment. The tool is the evolution of the calculation model APE (Anaerobic Plant Emulator) developed at EELab [17]. In this work, the pre-existing model has been expanded to calculate heat loss through the structure of the anaerobic digester as the sum of the contributions of individual components:

- side walls;
- foundations;
- thermal bridges;
- gasometer domes.

In detail, calculation of the heat transfer between digestion bath and ground foundations or underground part of the side walls follows the procedure proposed by UNI 13370 [18]. Heat transfer through the part of the side walls above ground was evaluated according to UNI EN ISO 6946 [19]. The calculations also took into account the presence of thermal bridges at major discontinuities of the structure, which were evaluated following UNI EN ISO 14683 [20]. Heat transfer through the gasometer dome was calculated by a thermal model of a double diaphragm gasometer, using for the estimate of solar gains a calculation method proposed by ASHRAE [21].

3.1. Ambient temperature function

A main requirement for the developed model was to predict the temperature evolution of the digestion bath in function of the environmental conditions. Theoretically, an anaerobic digester should be kept throughout the year at the same temperature, to be imposed by an automatic regulation system. This is usually verified if the heating system does not malfunction and if, during the hot season, the digester is always able to dissipate the energy input due to solar gains. In fact, biogas plants are generally not equipped with cooling systems. In the developed model of actual biogas plants, a constant temperature of the digestion bath is consequently assumed during the months in which the balance of solar gains and energy dissipated by the digester is negative, while the temperature is left free to increase in the months when the balance is positive. This is equivalent to saying that, in the first case, sufficient heat is always supplied to the digester by means of the heating system, while heat is neither supplied nor extracted in the second case.

To determine in which one of the two conditions an anaerobic digester is, it is crucial to know the geographical location and the local climatic conditions. The calculation software has been built in such a way that one can access directly the libraries of real weather data [22], which provide for every day of the year the value of the daily maximum and minimum temperatures.

For calculation of the heat balance of an anaerobic digester it is a clear need to monitor continuously the ambient temperature during the year. On this purpose, a function able to return the time evolution pattern of the ambient temperatures was also implemented in the MatLab environment (Fig. 2), built from daily maximum and minimum values.

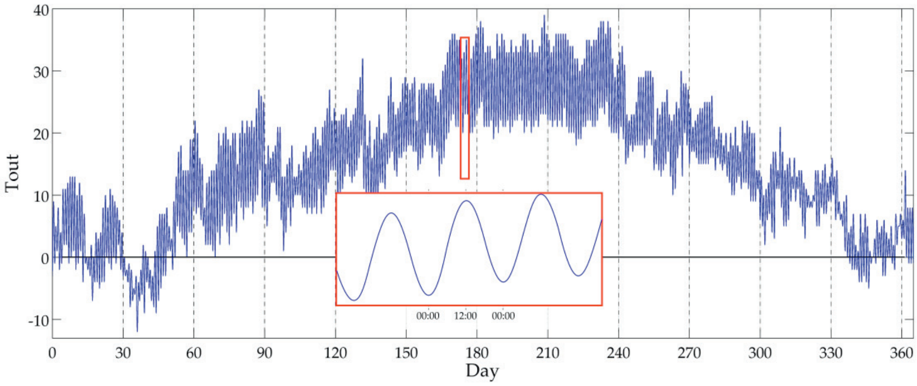


Figure 2. Ambient temperature in Modena, year 2012 (with exemplificative detail about June 23, 2012).

It was thus possible to perform the calculations and assessments related to the heat balance of the anaerobic digesters no longer on the basis of average parameters related to the locality of reference, but using values actually measured, thus avoiding underestimation of any exceptional events characteristic of a single year.

3.2. Digestion bath temperature

The heat balance evaluated for the anaerobic digester allowed quantifying the heat rate exchanged between external environment and digestion bath. Consequently, it was possible to determine the time evolution pattern of the temperature inside the digester and to predict summer overheating.

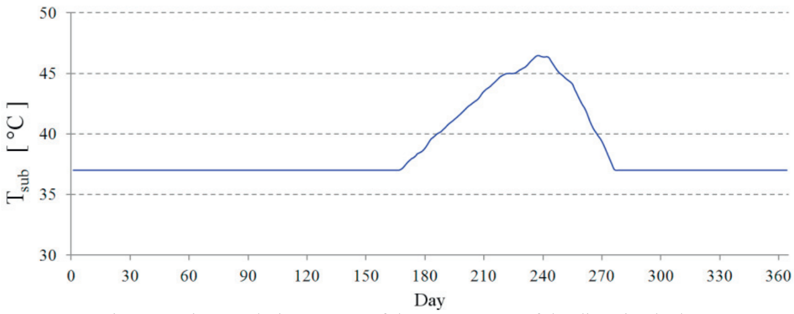


Figure 3. Time evolution pattern of the temperature of the digestion bath.

Recalling that the optimum temperature for the evolution of biological process in mesophilic conditions is between 37°C and 40°C, it is evident that during the winter time period it is necessary to have a heating system that ensures the maintenance of ideal conditions. Heating of the biomass has been taken into account in the calculation model by requiring the process temperature to be never below 37°C, but allowing it to increase above that value in days where the overall heat balance results in a net heat input to the digester. An example of the time evolution pattern over the whole year is given in Fig. 3.

4. Validation of the dynamic model

The development of the dynamic model was followed by a validation phase, carried out by comparison with data from three real biogas plants. These are characterized by different structural specifications and are located in geographical locations relatively distant from each other. By introducing the specifications of each plant in the dynamic model, it was possible to compare the theoretical results with those found experimentally in terms of time evolution of the digestion bath temperature. More specifically, a preliminary comparison allowed filling some gaps in the dynamic model about aspects that have a significant impact on the overall heat balance such as the temperature of the biomass substrate entering the digester. This is difficult to assess as it depends on the type of biomass and not only on the environmental conditions as one could suppose: in fact, the type of biomass that feeds a biogas plant can significantly affect the overall heat balance of the anaerobic digester because of either its state of aggregation (liquid or solid) or its temperature changes in more or less thermally insulated pre-storage tanks.

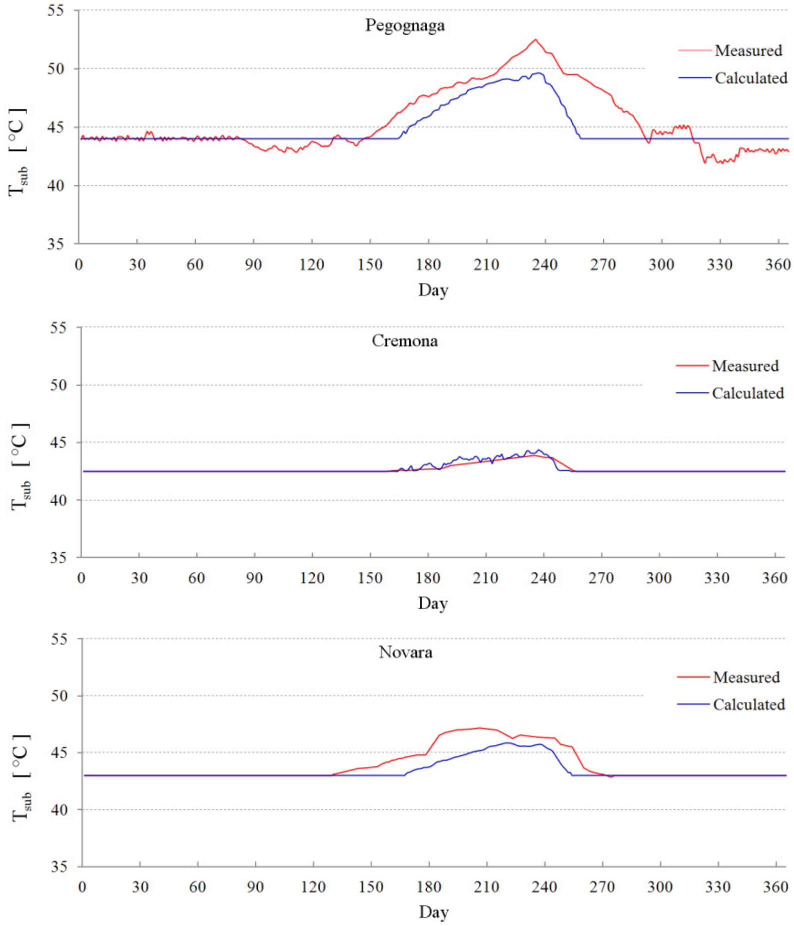


Figure 4. Theoretical and experimental time evolution pattern of the digestion bath temperature for three plants in Pegognaga, Cremona, and Novara (Italy).

Natural convection was assumed to be superposed to thermal radiation in the air volume enclosed by the two membranes of the gasometer dome. Finally, the external temperature with which the anaerobic digester exchanges heat was accurately estimated by building a curve of annual temperatures for each considered geographical area on the basis of daily climate data.

The implementation of the above presented improvements allowed obtaining a more than satisfactory agreement between results of the calculation code and what actually happened in the monitored digesters, as shown in Fig. 4.

4.1. Comparison with Design Builder/EnergyPlus

Parallel to the validation of the calculation model by comparison with experimental data, a comparison was also made with the output of a commercial software commonly used for dynamic simulations of buildings: the thermal behavior of the anaerobic digesters was modeled by Design Builder, a modeling environment in which one can create virtual buildings whose energy performance is simulated in the dynamic regime through the free software EnergyPlus. The model of the anaerobic digester was created in accurate representation of a real case, with foundations and concrete walls, insulation, exterior cladding and double membrane gasomerer dome (Fig. 5). By setting some parameters (geographical area, temperature of the digestion bath, etc.) it was possible to simulate the interaction between the digester and the external environment.

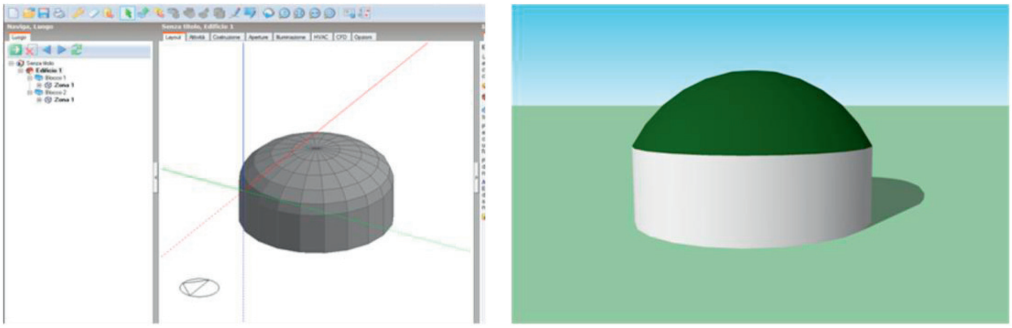


Figure 5. Sketch of the digester structure (Design Builder/EnergyPlus).

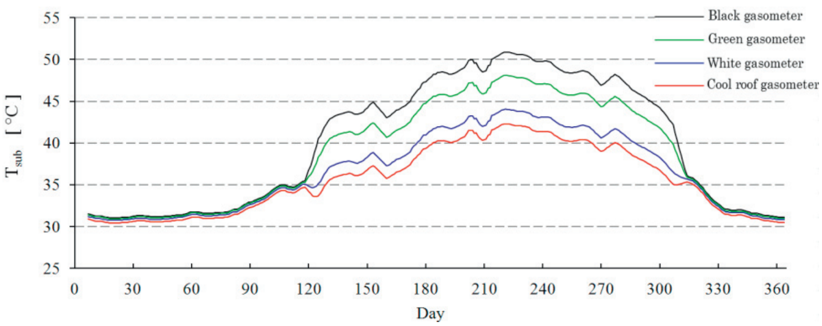


Figure 6. Temperature of the digestion bath for different domes colors (and solar reflectance value): black (5%), dark green (10%), white (78%), white cool roof (85%) (Design Builder/EnergyPlus).

The software does not allow setting a, initial temperature higher than 30°C within the modeled structure. One can offset such limitation by artificially shifting all structure and boundary condition temperatures under the hypothesis of linear dependences of heat transfer processes, however it is convenient to take into account the results of the carried out simulations in relative terms and not in their absolute value.

The calculation model developed with EnegyPlus was used as a predictive tool to verify how the change in solar reflectance of the gasometer dome may impact on the temperature of the digestion bath. The simulations permitted to adjust and refine the input parameters, ultimately attaining an evaluation of the thermal performance of the digester that reproduced in a satisfactory manner the real behavior. In a few words, simulations confirmed that summer overheating of the digester is a likely event if the digester dome presents unfavorable radiative properties.

The graph in Fig. 6 compares, in the course of a calendar year, the time evolution pattern of the temperature inside the structure modeled with Design Builder and shows how a cool roof surface ensures a considerable reduction of overheating of the biomass substrate contained in the digestion bath.

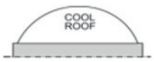
5. Analyses by the APE model

The developed mathematical model allowed evaluating the effectiveness of the proposed ‘cool’ coating solutions. Several simulations were carried out to compare the effects of changes in solar reflectance of the gasometer dome on the internal temperature of the digestion bath. A typical anaerobic digester of a plant with electric power 250kW$_e$ was taken as the reference case (see Tab. 1).

Table 1. Characteristics of the reference anaerobic digester.

Place	Modena	Internal diameter	[m]	20
Latitude	44°39'24" N	Digester height	[m]	6.0
Year	2012	Dome height	[m]	3.2
Dome material	PVC	Dome surface	[m^2]	370
Dome color	black	Net volume	[m^3]	1900

Table 2. Solar reflectance of the digester dome, maximum net heat rate input and digestion bath temperature.

	Dome color	Solar reflectance [%]	$Q_{in,hottest\ day}$ [kW]	$T_{sub,max}$ [°C]
	Black	4.8	75.4	46.2
	Dark green	10.3	70.4	44.1
	White	77.6	39.3	38.7
	Cool roof white	85	5.5	37.0

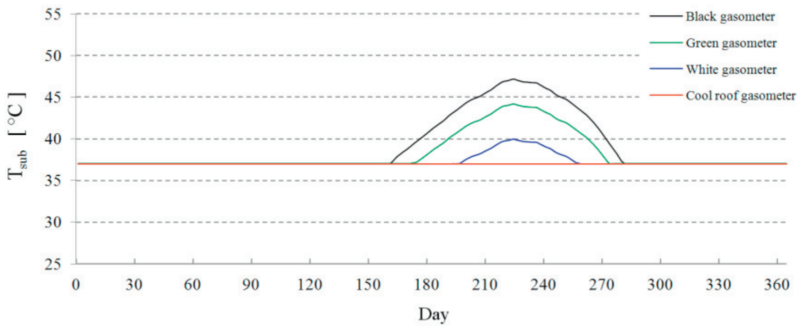


Figure 7. Temperature of the digestion bath for different domes colors (and solar reflectance value): black (5%), dark green (10%), white (78%), white cool roof (85%) (APE model).

Table 2 shows the values of solar reflectance, the maximum net heat rate input during the hottest day of the year, and the maximum temperature of the digestion bath in the calendar year. The positive effects of increasing the solar reflectance of the gasometer dome, also shown in Fig. 7, are clearly evident.

5.1. Influence of the feeding scheme on the summer temperature

The simulations have confirmed the original idea that solar reflectance of a digester dome, external ambient temperature and solar irradiance are the factors that mostly influence the temperature of the digestion bath. At the same time, the simulation highlighted other aspects that can be decisive, in particular:

- Temperature of the biomass input
- Bacterial activity
- Feeding scheme

In detail, the simulations have shown that anaerobic digesters mainly fed with vegetable biomass are more exposed to the problem of summer overheating, while digesters that are fed with livestock waste are exposed to a lesser extent. Indeed, the use of a vegetable biomass such as silage, because of its high energy content, results in a slower feed rate and a high substrate temperature in the digestion bath. The graph in Fig. 8 shows the volume of biogas vented by a plant with power 250 kW_e due to excessive pressure below a overheated gasometer dome: the area between the two curves represents the difference between the two considered feeding scheme (100% silage and 100% manure) in terms of biogas vented into the atmosphere. The yearly biogas and economical losses are given in Tab. 3.

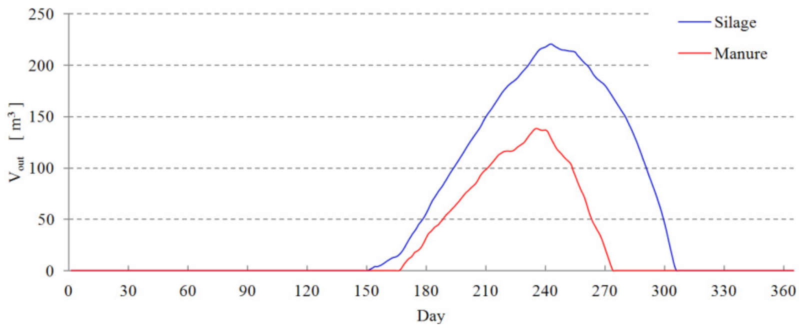


Figure 8. Volume of biogas dispersed for different feeding schemes.

Table 3. Comparison between feeding schemes in terms of dispersed biogas and economical impact.

	Mass flow rate [ton/day]	$V_{out,day,\ max}$ [m^3]	$V_{out,year}$ [m^3/year]	Economical loss [€/year]
Silage	13	220	19 355	9 200
Manure	55	138	8 418	4 000

6. Conclusion

The new regime of incentives for the production of electricity from biogas that entered into force in Italy in early 2013 encourages building of small plants. These ones, however, have lower specific profitability and biological stability than larger plants, which were generously encouraged until the end of 2012. For small plants it is therefore essential that every aspect of their operation is carefully designed to ensure adequate performance and the return on investment.

A main problem to carefully monitor in anaerobic digesters is summer overheating due to solar gains through the gasometer dome. This can undermine the profitability of biogas plants because of its deleterious effect on either the lives of methanogenic bacteria or the vent of biogas due to overpressure induced in the digesters by the overheating. A smart solution can be to finish the gasometer dome by cool roof materials with high solar reflectance.

The study presented here, mainly performed by means of a specifically built calculation code validated on the basis of experimental data, has allowed assessing the effectiveness of the proposed solution. It was shown that the adoption of a cool roof gasometer dome can greatly reduce (and even completely eliminate) summer overheating and vent of biogas, thus ensuring a saving in terms of biogas loss and, consequently, economical income up to 9200 €/year for a 205 kW_e plant. This compares with about 6000 € of estimated cost for the cool roof finishing if this is adopted since from design phase. Such result, however, is obtained when the gasometer dome is new and its solar reflectance is at its initial value. In order to limit the performance drop due to aging of the dome surface, true cool roof materials must be chosen having limited drop of performance after weathering.

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