Production of green energy from Co-digestion: Perspectives for the Province of Cuneo, Energetic Balance and Environmental Sustainability

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Abstract - **In Italy and many European countries energy production from biomass is encouraged by strong economic subsidies so that biomass energy plants are getting large diffusion. Nevertheless, it is necessary to define the environmental compatibility taking into account global parameters as well as environmental impacts at regional and local scale coming from new polluting emissions. The environmental balances regarding new energy plants are of primary importance within very polluted areas such as Northern Italy where air quality limits are systematically exceeded, in particular for PM_{10}, NO_2 and ozone. The paper analyses the renewable energy scenario relating to manure anaerobic digestion and biogas production for the Province of Cuneo, N-W Italy, and the environmental sustainability of the possible choices. The study is focused on energy producibility, heat and power, nitrogen oxides and ammonia emissions, GHG balances dealing also with indirect releases of CH_4 and N_2O, as well as emissions due to energy crops production. The most important conclusion that can be drawn is that the production of renewable energy from anaerobic digestion could cover up to 13% of the Province electricity consumption but sustainability in terms of CO_2 emissions can be reached only through an overriding use of agricultural waste products (manure and by-products instead of energy crops) and cogeneration of thermal energy at disposal; the application of best available techniques to waste gas cleaning, energy recovery and digestate chemical-physical treatments allows positive emissive balances.**

***Keywords-** anaerobic digestion; NOx; ammonia; environmental balances, energy efficiency; biomass*

I. INTRODUCTION

Renewable energy plants (based on biogas produced by anaerobic digestion of manure and energy crops, vegetable oil, wood and solid biomass) are getting large diffusion in Northern Italy because of the benefits deriving from the production of energy on one's own, the reduction of odour nuisance from manure and the increase of its biological stability and, most of all, the economic return (pay-back times can be as short as 4-5 years in Italy) based on electricity production. The new energy scenario has to be considered within the environmental background of the area where it is introduced, involving air quality limits compliance, the use of best available techniques, energetic efficiency (also thermal), emissive balances, global warming issues, biomass origins, aspects dealing with the use of water and fertilizers for energy crops, nitrates leaching towards groundwater. This is the focus of the present study.

II. STATE OF THE ART

In literature there are many references about bioenergy production and related environmental sustainability, in particular the individuation and utilization of indicators or methodologies corresponding to LCA have been studied; the evaluated aspects concern both the original definition of the evaluation scheme and subsequently the description of many practically interesting applicative situation have been obtained. As far as biogas production and utilization is concerned, in [1], the energy efficiency of different biogas systems was evaluated and specific energy balances were defined; the study provides bases for assessment of environmental compatibility, including management of spent digestate. It has been observed [2] that biogas systems lead to environmental improvements, arising from changed land use and handling of organic waste products, which often exceed the direct benefits from fossil fuel replacement; from the other side an impact factor, of different numerical value, can be originated, arising from the utilized raw material, the energy service that is provided, the replaced reference system. The use of LCA has been suggested by Colin et al. [3] to evaluate the contribution to climate change of biomethane production by monofermentation of cultivated crops, and it resulted adsolutely lower than the contribution of natural gas importation; also the effects on ecosystem quality and human health damages were evaluated. In order to define the required information concerning energetic aspects, experiences of co-digestion of energy crops and cow or pig manures have been conducted on different scales [4][5], in order to define the influence of operating parameters on methane yield and post-methanation potential. From a

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methodological point of view, a standard methodology has been outlined [6], to compare the greenhouse gas balances of bioenergy systems with those of fossil energy systems: a careful definition of system boundaries, and many operating issues have been dealt with in detail, with the final aim of an optimization from the greenhouse gas emissions point of view. In order to establish a reliable approach to the impact assessment of biomass cultivation phase, different LCA models were developed [7], and data from experimental fields were used for testing. The aspect of GHG balances of bioenergy systems producing electricity, heat and transportation biofuels has been examined in comparison with fossil reference systems in Cherubini [8] from standard LCA. In literature there are a lot of studies relating to this field. From the indicated references it is possible to establish that the environmental balances for energy crops exploitation are well defined and may examples are at disposal for useful comparisons; in any case a specific definition of the local context and the existing operating conditions must be carefully examined, in order to arrive to valid conclusions for a proposed application.

III. ENVIRONMENTAL CONDITIONS OF NORTHERN ITALY

Air quality of Northern Italy is one of the most polluted of the world, maybe the worst in Europe, due to the strong human activities and the orography of its territory. PM_{10}, NO_2 and ozone concentrations measured at the ground level diffusely and permanently go beyond the quality standards. In particular, PM_{10} concentration is only partly due to particulate primary emissions because the chemical analysis of PM measured in Northern Italy confirm that secondary particles (deriving from NOx, SOx, NH_3 and VOC) account for 60-70 % of total PM concentration [9]. Moreover, some European studies report [10] the following aerosol formation factors, to be considered by weight, starting from gaseous pollutants: NOx 0,88; SOx 0,54; NH_3 0,64. As it is clear from the reported figures, in order to control and improve air quality in Northern Italy, the emissions of gaseous compounds such as NOx and ammonia (mostly emitted by agriculture) should be mainly reduced. Another strong environmental critical issue of Northern Italy is nitrate contamination of surface and ground-water resources mainly due to the use of fertilizers and the land-spreading of animal manures.

IV. ENVIRONMENTAL COMPATIBILITY FOR ANAEROBIC DIGESTION PLANTS

The main environmental concerns referring to animal manure management are odours due to uncontrolled fermentation, ammonia emissions from the storage and the land-spreading and greenhouse gases (GHG) release (CH_4 and N_2O). Anaerobic digestion (AD) can be an answer to odour nuisance but it is totally ineffective on nitrogen content of digested materials; moreover, as we will see later on, also CH_4 and N_2O could be enhanced with respect to the *ante operam* conditions.

Due to obvious economic drivers, manure is rarely digested alone; on the contrary, energy crops such as maize, triticale and sorghum and, sometimes, agro-residues are fed to digesters in order to increase the volatile solid (VS) content and then biogas production (higher methane yields). AD plants formally proposed in Northern Italy in the last months are several and they are all characterised by high crop/manure ratios within the mixture to be digested, (crops sometimes represent more than 50% of the feedstock).

As previously mentioned, within anaerobic digesters, nitrogen contained in the primary mixture is not removed and almost the same amount can be found in the digested material, under different forms: as a matter of fact, a large part of nitrogen contained in proteins is hydrolyzed to ammonium ion (NH_4^+) and dissolved ammonia (NH_3) that can be volatilized; an increase in pH, NH_3 concentration and temperature, 3 conditions that do occur after anaerobic digestion, enhance ammonia emissions during storage and after field application. Moreover, nitrogen content of the mixture to be digested is strongly increased by the use of energy crops (for example, maize silage contain 4.3 kg N/ton of FM)

This way, the nitrogen amount to be managed along with digested materials can be strongly larger than that in primary manure and it is surely more suitable for volatilization.

Based on reliable emission factors and international studies (CORINAIR, IPCC and IPPC BAT reference documents, Italian experimental results and so on) it is possible to assess that 34 ±11% of nitrogen contained in the storage is emitted as NH_3-N from the storage and land-spreading (almost 15% from the land-spreading) of fresh animal manure. This amount could be strongly enhanced by chemical-physical conditions induced by digestion; as a matter of fact, according to different crop/manure ratios, ammonia emissions can be much larger than those from fresh manure, up to three times when manure represents just one third of the mixture to be digested.

As far as energetic scenarios at the regional scale are concerned, in the case we decide to send 10% of manure produced in the Piedmont region (1300 kt/y) to AD together with the same amount of energy crop (maize), 531 GWh_{el} could be produced but ammonia emissions would show an increase around 2300 t/y and more than 700 t NOx/y would be emitted from the engine, that corresponds to a huge neo-formation potential of more then 2000 t/y of PM_{10} (or, more correctly, $PM_{2.5}$). These data can be also seen as a specific emission of secondary particulates around 4 g/kWh_{el} due to energy production from AD, whereas the average secondary PM emission factor for the Italian national power system (SO_2: 0,67 g/kWh_{el}; NOx: 0,523 g/kWh_{el}; PM: 0,024 g/kWh_{el}) is 0,85 g/kWh_{el}. As obvious, the reported figures refer to plants without any ammonia abatement devices, that are not generally planned for new installations. The large amount of ammonia release could be strongly reduced by employing stripping-absorbing towers for digested materials

(H_2SO_4 solutions are usually applied as absorbents in order to obtain a fertilising by-product that could be sold); alternatively, the storage tank could be covered (a solid cover should be implemented because straw covers or natural crusts could be less effective in reducing NH_3 emissions and have the potential to increase GHG emissions [11]) and Best Available Techniques to the land spreading of digestates (immediate incorporation, use of deep injectors) should be applied. On the other hand, NOx emissions could be largely reduced by Selective Catalytic Reduction (up to 90%), but the technical feasibility of this solution depends on the poisoning potential of waste gas and the purification possibilities.

As far as greenhouse gases balances are concerned, 0,0032±0,0012 kg N_2O-N/kg excreted N are expected to be emitted from the storage of fresh manure; moreover, an indirect N_2O should be considered, dealing with volatilised nitrogen: the proposed emission factor is 0.01 kg N_2O-N/(kg NH_3-N + NOx-N volatilised).

Another environmental aspect that should be analysed when dealing with anaerobic digestion is the post-methanation potential, that is the uncontrolled emission of methane from the storage of digested materials. As a matter of fact, the post-methanation somehow depends on the volatile solid content of the slurry and it is well known that the VS removal efficiency of AD is never 100%; on the contrary VS conversion to biogas is for the most part a function of the biodegradability of the primary mixture to be digested and the dimension of the digester through the hydraulic retention time (HRT). Based on several experimental data, the VS removal efficiency is often lower than 50%.

This way, taking into account the VS content in the digested material that sometimes can be remarkable (more than 50% of the original quantity) on the one hand, given the temperature of digested materials, the presence of specialized anaerobic biomass coming from the digesters and the long time at disposal for the storage (even more than 100 days) on the other hand, the post-methanation could represent a considerable emission.

Some authors [12] report that "typically 5-15% of the total biogas produced can be obtained from post-methanation of residues" while the CROPGEN project [13] inform that up to 12-31% of total methane production can be recovered from post-methanation of digestates. The post-methanation potentials measured within the CROPGEN project for digestates incubated for 100 days at 5, 20 and 35°C were 1-9, 73-120, 133-197 l CH_4/kg VS respectively. As far as the mentioned project is concerned, the post-methanation potential doesn't change during feeding regimes with 30-40% of crops in the feedstock. Other studies [14] report post-methanation potentials of 160-210 at 35-55°C, 53-87 at 15-20 °C and 26 l CH_4/kg VS at 10°C for a storage of 250 days.

In order to develop proper GHG balances around the technical choice of anaerobically digesting manure and crops, a post-methanation potential of 50 l CH_4/kg VS and a VS removal efficiency of 50% can be used to calculate the indirect GHG emissions from the storage of digested materials. As far as GHG emissions from untreated manure are concerned, the emission factors proposed by IPCC can be considered a good reference: for a mixture of swine and dairy cattle manure and a climate between cool and temperate, an emission around 4 kg CH_4/t of manure can be expected.

As pointed out by Figure 1, co-digestion of manure and energy crops (when energy crops represent from 30 to 70% of feedstock), causes indirect GHG emissions that nullify the "energy bonus" due to CO_2 avoided emissions [15]: based on our assumption the indirect emissions of GHG can be quantified as 400 ± 67 g CO_2eq/kWh$_{el}$, mainly due to CH_4 releases from the storage of digestate, that is comparable to the Italian average CO_2 emission factor for energy production (496 g CO_2/kWh$_{el}$): the reported figure represent the average value for three different post-methanation models. Furthermore, it should be said that the proposed balances neglect the emissions of CH_4 and N_2O from the biogas engine, as well as CO_2eq emissions relating to cultivation and transport of energy crops; these contributions would even worsen the reported GHG balances. This way, in the case energy bonus, that is strongly economically propelled, is cancelled by uncontrolled GHG released, the renewable energy mission of AD would be betrayed.

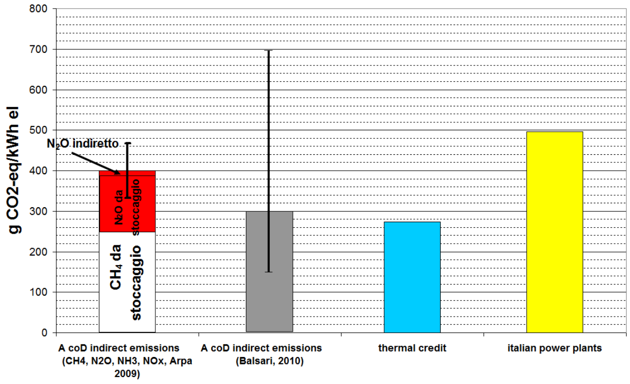

Figure 1. Indirect GHG emissions for Anaerobic coDigestion and thermal credit due to cogeneration

The negative impacts of indirect emissions from co-digestion of manure and energy crop are confirmed by some recent studies [16] and [17]; the first presentation points out a range from 150 to 700 g CO_2eq/kWh$_{el}$ for AD (the higher value corresponds to co-digestion of manure and energy crops and it is mainly due to production and transport of biomass), while the second author reports (personal communication) that "in extreme cases (open storage of digestate and low HRT) the CO_2eq balance can reach levels of 600–700 g CO_2eq/kWh$_{el}$, that means: biogas production causes the same GHG emissions as German conventional electricity production".

As one can easily observe from the mentioned data, energy production from AD could have a negative meaning as far as sustainability aspects are concerned. As obvious, the solution can be technological as higher HRT, thermophilic digestion regimes, gas-tight storage of digestates (and combustion of released methane in the biogas engine) and thermal oxidation of waste gas from the engine can strongly reduce methane indirect emissions. Moreover, cogeneration of thermal energy can save up to 300 g CO_2eq/kWh$_{th}$, as showed by Figure 1, improving GHG overall balance.

V. ENERGY-CROPS AND MANURE AVAILABILITY FOR THE PROVINCE OF CUNEO, ENERGY PRODUCTION SCENARIOS

The Province of Cuneo is characterized by intensive livestock farming, more than 428.000 cattles and 824.000 swines, producing a huge amount of manure, around 8 millions tons per year. In the same area, 50.000 ha are destined to maize cultivation (173.000 in the Piedmont Region) and 30.000 ha (130.000 in the Region) to other cereals (wheat, sorghum, triticum). Based on the average producibility, the last regional planning on renewable energies (DGR 28/09/2009 n. 30-12221 "Relazione Programmatica dell'Energia della Regione Piemonte") stated that up to 5% of cultivated fields could be used to produce energy crops, that is more or less 478.000 t/y of maize and 198.000 t/y of other cereals, still remaining within an environmentally and socio-economic sustainable context. That is to say that 200.000 t/y of energy crops could be produced in the province of Cuneo in order to improve biogas and energy production by means of anaerobic codigestion. In the following Table 1, data on manure and energy crops yearly production, dry matter and volatile solids content of materials, biogas producibility and power are reported. It is important to observe that AD of all manure produced by the province could generate 80 MW$_e$, that is 12% of electricity consumption of the province would be provided.

Table 1. Potential energy production from anaerobic co-digestion of all manure produced in the Province of Cuneo and energy crops from 5% of cultivated fields

	Manure/Crops (t/y)	dm (w/w)	VS/dm	Biogas (Nm^3/tVS)	MW th IN	MW el OUT	MW th OUT
Cattle: 428.088	5.295.449	18%	75%	350	150,70	60,28	47,47
Swine: 824.663	2.944.047	10%	80%	350	49,65	19,86	15,64
maize	150.000	34%	96%	700	20,64	8,26	6,50
cereals	50.000	30%	96%	650	5,64	2,25	1,78
						90,65	**71,39**

At the same time 60 MW$_{th}$ (the thermal consumption of fermentation process, 30 % of available heat, has been already subtracted) could be produced and destined to the substitution of existing heating plants or some industrial use (drying of digestate, wood, cereals). In the case the choice is anaerobic co-digestion of all manure and energy crops according to the regional sustainability criteria, the produced electricity would be 91 MW (13,5% of total consumption) and 71 MW of extra thermal power.

As a matter of fact, on 31th December 2010, 28 biogas plants are regularly authorized in the Province of Cuneo; on the whole, the feedstock is formed by 150.000 t/y of cattle manure, 68.000 t/y of swine manure, 114.000 t/y of maize and 43.000 t/y of other cereals, as reported by Table 2. That is to say that energy crops represents 42% of the feedstock, and they are very close to the maximum quantities admitted by regional sustainability criteria. The electricity production corresponds to 1,5% of the total consumption of the Province; unfortunately, the thermal energy at disposal, almost 9 MW (73,8 GWh/y), is dispersed for the main part, just 20-30% being use for small district heating or drying plants.

Table 2. Authorized energy production from anaerobic co-digestion of manure and energy crops

	Manure/Crops (t/y)	dm (w/w)	VS/dm	Biogas (Nm^3/tVS)	MW th IN	MW el OUT	MW th OUT
solid cattle manure	98.531,00	0,22	0,75	350	3,66	1,46	1,15
liquid cattle manure	51.003,33	0,10	0,75	350	0,86	0,34	0,27
swine manure	68.367,92	0,07	0,8	350	0,86	0,34	0,27
maize	107.988,67	0,34	0,96	700	15,86	6,34	5,00
triticum	25.972,50	0,3	0,95	650	3,09	1,24	0,97
sorghum	15.020,83	0,26	0,96	650	1,57	0,63	0,49
ryegrass	1.750,00	0,26	0,96	650	0,18	0,07	0,06
pigswill	5.925,00	0,72	0,96	700	1,83	0,73	0,58
maize grains	341,67	0,72	0,96	700	0,11	0,04	0,03
						11,21	**8,83**

VI. GREENHOUSE GASES BALANCE

In order to estimate the possible CO_2 benefits arising from renewable energy plants it must be considered that, on the basis of the emission inventory for the Province of Cuneo (year 2006), agriculture and livestock farming represents 18% of total CO_2eq emissions of the Province.

In the case all manure of the Province is digested together with 200.000 t/y of energy crops (scenario in Table 1), assuming that all available thermal energy is used to displace existing heating plants (fuelled by natural gas for 70% and gasoil for 30%), that is optimal CHP, the benefit in terms of avoided CO2 eq is quantified by Table 4. the results lies on the following assumptions:

1. electricity production: 496 g CO_2/kWh$_e$;
2. replaced heating plants: 55 kg CO_2/GJ for natural gas, 74 kg CO_2/GJ for gasoil;
3. 10314 t CH_4/y from traditional manure management are avoided;

4. post-methanation potential from the storage of digested materials: 5% of produced biogas (192 g CO_2 eq/kWhe);
5. GWP: 25 for methane, 298 for N_2O;
6. enhancement of ammonia volatilisation due to AD is neglected.

The reported figures comprehend the indirect N_2O emissions due to nitrogen oxides and ammonia emissions (calculated in the next chapter): if we use the overall factor suggested by Balsari [18] for AD without energy crops (250 g CO_2 eq/kWh$_e$), the results would be very similar (total avoided: -621.017 t CO_2 eq/y). The reported data outline that the described energy scenario would save 50% of the whole GHG emissions from agriculture, 10% of all CO_2 eq emissions of the Province. This would be an extraordinary result as far as CO_2 saving targets at 2020 are concerned (17% of final energy consumption has to be provided by renewables). The calculated CO_2 benefit could be even better (up to – 818.328 t CO_2 eq/y) in the case post-methane is recovered by means of gas-tight storage tanks.

Table 3. Avoided GHG emissions for Table 1 scenario

	t CO_2 eq/y
avoided emission from electricity production	-393.877
avoided emission from CHP	-170.817
avoided emission from traditional manure management	-257.850
Indirect emission from anaerobic digestion	+185.299
Avoided CO_2 eq (TOTAL)	**-637.245**

On the contrary, the actual biogas plant authorized configuration (Table 2) would give the results showed by Table 4. In this case, the further assumptions are:

1. replaced heating plants: only 25% of the available thermal energy is used to replace natural gas and gasoil boilers (70 and 30 % respectively);
2. 258 t CH_4/y from traditional manure management are avoided;
3. indirect emissions for anaerobic co-digestion: 600 g CO_2 eq/kWhe [18];
4. enhancement of ammonia volatilisation due to AD is neglected.

In the actual conditions, biogas plant are not able to give any environmental advantage at the global scale (the balance is very close to break even) because the energy bonus due to the production of renewable energy is compensated by strong indirect GHG emissions and cogenerated thermal energy is not used in an effective way. The calculated results are confirmed by [19] that reported an indirect GHG emissions of 542 g CO_2 eq/kWh$_e$ for a feedstock 50:50 manure/energy crops.

Table 4. Avoided GHG emissions for authorized scenario

	t CO_2 eq/y
avoided emission from electricity production	-45.584
avoided emission from CHP	-4.942
avoided emission from traditional manure management	-6.460
Indirect emission from anaerobic digestion	+55.142
Avoided CO_2 eq (TOTAL)	**-1.844**

VII. ENVIRONMENTAL COMPATIBILITY AT THE LOCAL SCALE

The environmental balance carried out in the previous chapter for GHG at the global scale should be enlarged to comprehend also criteria pollutants that are very important at the local and regional extent. The following Tables 5 and 6 reports the total emissions dealing with the described energy scenarios for NO_X, PM_{10}, NH_3 and SO_X.

Table 5. Criteria pollutants balance for Table 1 scenario

	t NO_X/y	t SO_X/y	t PM_{10}/y	t NH_3/y	t N_2O/y
avoided emission from electricity production	-415	-532	-19	0	0
avoided emission from CHP	-155	-107	-7	0	0
avoided emission from traditional manure management	0	0	0	-12.659	-354
Indirect emission from anaerobic digestion	+953	0	0	+12.990	+362
Avoided emission (TOTAL)	**+382**	**-639**	**-26**	**+330**	**+8**

As one can easily observe, the emissive balance is not positive for both the analysed scenarios. In the case of the "sustainable configuration" (Table 1), NO_x emissions at the local scale (+ 953 t/y) are not totally compensated by avoided emissions due to electricity production and cogeneration and the increase of ammonia releases is around 330 t/y: the overall balance in terms of secondary particles (based on aerosol formation factors reported in the previous chapter) outlines an increase of 177 t PM_{10}/y. As far as the authorized plant configuration is concerned, the balance is even worse, + 196 t PM_{10}/y, mainly relating to additional ammonia emissions (+ 275 t/y) due to the use of large quantities of energy crops. Moreover, it should be remembered that in the latter configuration, a strong increase of nitrogen content (880 t N/y →1.546 t N/y) has to be faced when managing digested materials, according to the limits of land spreading (170-340 kg N/ha) while in the sustainable scenario, where manure represents 98% of the feedstock, the increase of nitrogen to be managed along with digestate would be negligible (30.663 t N/y → 31.463 t N/y).

Table 6. Criteria pollutants balance for authorized scenario

	t NO_X/y	t SO_X/y	t PM_{10}/y	t NH_3/y
avoided emission from electricity production	-48	-62	-2	0

avoided emission from CHP	-4	-3	0	0
avoided emission from traditional manure management	0	0	0	-363
Indirect emission from anaerobic digestion	+118	0	0	+638
Avoided emission (TOTAL)	**+65**	**-65**	**-3**	**+275**

VIII. CONCLUSIONS

Renewable energy plants are strongly encouraged by European legislation but their effect on air quality and their sustainability in terms of CO_2 emissions, in particular for biogas plants, could be negative, specifically for compromised areas such as Northern Italy. The analysed energy scenarios for the Province of Cuneo point out that, in order to obtain benefits in terms of CO_2, energy crops should be avoided in favour of manure and agricultural waste products, thermal energy cogenerated by anaerobic digestion plants should be totally recovered to replace existing heating plants and the post-methanation production should be exploited. These conditions can help achieving CO_2 targets at 2020 but are not enough to ensure a positive or neutal emissive balance at the local scale, that is a condition of primary importance in northern Italy. To this end, NOx emissions from the internal combustion engine should be minimized by means of SCR, cogeneration of thermal energy maximized and digestate nitrogen content should be properly treated in order to reduce ammonia emissions (covered storage tank, immediate incorporation/use of deep injectors for land-spreading) and/or produce a fertilizer (stripping-absorbing towers, dryers and/or evaporators) to be used in a more effective way if compared to traditional manure or digested materials. It is important to note that these conclusions are directed to the specific high criticality conditions of Province of Cuneo and North of Italy, but their qualitative meaning can also be extrapolated to other European situations of similar agro – industrial economy. A promising alternative solution that could ensure better environmental compatibility to AD is the production of biomethane by means of upgraded biogas. This solution could be very expensive in terms of gas purification chiefly, the advantages in terms of economic benefits from renewable energy production (green certificates) should be lost, but a better global environmental balance could be obtained, and a local emission impact should be avoided.

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