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A Local Multi-Criteria Assessment of Alternative Feeds for Biogas Plants in Calabria (Southern Italy)

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Energy production by the anaerobic digestion of residual biomasses is strategic for the economic and environmental sustainability of the agricultural sector, provided that the most suitable digester feed is properly chosen. This option may be adopted by the use multi-criteria techniques, which are able to take into account a number of variability factors influencing the biomass supply chains. This study proposes a simple Multi-Criteria Assessment Model, integrating the Analytic Hierarchy Process and the Simple Additive Weighting methods. By the proposed model the biogas yield, economic efficiency and profitability of alternative substrates/blends to feed biogas plants were evaluated in an integrated way. The model was verified in a case study, identified in a 300-kW biogas plant operating in an agricultural district of Calabria (Southern Italy). By comparing the four alternative blends/substrates, the model showed the highest convenience of feeding a medium-sized biogas plant with self-produced residues of animal origin. The integration of the digester feed with external residues resulted in a slightly worst management option, if citrus peel is used. Feeding the biogas plant with a limited share of olive oil mill wastewater must be excluded, since this choice gave the worst synthetic performance index in the model.

1. Introduction

The production of renewable energy in agriculture represents an important opportunity for rural areas, since it allows farmers both to diversify their own productive activities and to integrate their income, besides other externalities (e.g. reduction of CO_2 emission and energy dependence on fossil fuels) (Zema, 2017). Moreover, the use of residues produced by the agricultural, agro-industrial and breeding farms for energy conversion leads to the reduction of the negative impacts linked to their disposal in the environment. Hence, sustainable use of residual biomass for energy production is of great importance from both economic and environmental perspectives (Al-Hamamre et al., 2017).

Today, among the several energy conversion methods of residual biomass, anaerobic digestion has become a sustainable, commercially mature, and attractive source of renewable energy, due to reduced technological cost and increased process efficiency (Thamsiriroj et al., 2012). Biogas is the major energy output of anaerobic digestion and it can be burned directly on site for heat or electricity generation or can be upgraded to bio-methane. However, supply of substrates to a biogas plant has a considerable logistical and economic cost for bio-energy companies; for anaerobic digesters treating primarily residual biomasses, this is one of the reasons for their poor economic performance (Asam et al., 2011). Therefore, it is important to ascertain which residual biomass is the best substrate to feed a biogas plant, considering its availability within any territory. Moreover, long-term and strategic energy plans, supporting decision making processes of bio-energy entrepreneurs, should be integrated by other evaluations related to the design and management of anaerobic digestion plants.

In agricultural districts agro-energy businessman must take into account many factors of different nature to adopt the most suitable management solution. In these contexts the evaluation of possible supplying sources of residual biomasses is an important and difficult activity, influencing noticeably the technical-economic sustainability of an agro-energy business. As a matter of fact, this choice is linked to many variability factors, such as the physical and chemical characteristics of feedstock as well as their market prices and

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transport/storage costs. The evaluation of such variability factors should be carried out in an integrated way by multi-criteria analysis, useful decision aiding tools that help finding solutions for real-world problems also in the bio-energy sector (Carriço et al., 2014). For instance, Multi-Criteria Decision Making (MCDM) techniques, belonging to the general class of operations research models, may support decision problems under the presence of a number of evaluation criteria. An interesting state-of-the-art of the multi-criteria analysis applied to bio-energy plants is reported in the works of Mardani et al., (2017), Taha and Daim (2013) and Wang et al., (2009). Shortly, these techniques are widely applied for evaluating the feasibility of the renewable energy from non-agricultural sources (such as hydro-electric, wind, solar source and urban waste, Ahmad and Tahar, 2014; Akash Bilal et al., 1999) and for assessing the performance of different anaerobic digestion processes, suitable for the urban waste organic fraction (Bottero et al., 2011; Karagiannidis et al., 2009).
This study proposes a simple MCDM methodology targeted to the choice of the most convenient substrate for biogas plants operating in Mediterranean agricultural districts. The methodology, integrating the Analytic Hierarchy Process and the Simple Additive Weighting methods, was verified in a case study, identified in a 300-kW biogas plant operating in an agricultural district of Calabria (Southern Italy). By this methodology four alternative substrates and/or blends of substrates (consisting of agro-industrial and livestock residues), able to feed the anaerobic digester, were assumed as examples of possible digester feeds and compared by three evaluation criteria.

2. Materials and methods

In this study, we focused the case study of an agro-industrial owner or breeding farmer, who wants to operate a biogas plant by exploiting the residual biomass produced by his facility. The work hypothesis was the availability of a small-sized biogas plant, operating in an agricultural district typical of Calabria and fed by alternative substrates or by a blend of them, supplied either from the facility or external sources. The size of the biogas plant was set according to the findings of Zema (2017), who found a value of 300 kW as the most profitable nominal power in small agricultural contexts.

2.1 The Multi-Criteria Assessment model (MCAM)

As mentioned above, the proposed Multi-Criteria Assessment Model (henceforth MCAM) integrates the Analytic Hierarchy Process (AHP) (Saaty, 1988) and the Simple Additive Weighting (SAW) (Hwang and Yoon, 1981). AHP was structured in three steps: i) identification of three evaluation criteria (see section 2.2); (ii) pair-wise comparison of the subjective assessments (in a 3 x 3 matrix) about the importance of each evaluation criterion compared to another criterion; (iii) calculation of the weights for each criterion through matrix normalization (by geometric mean). In our study the subjective assessments of the criteria were achieved by interviewing a sample of four agro-industrial businessmen and/or breeding farmers operating in the agricultural district and potentially interested to a bio-energy installation. SAW, a weighted linear combination or scoring method, was applied to our case study according to Adriyendi (2015) and structured in the following steps: (i) construction of a decision matrix, consisting of four alternatives (in our case the substrates feeding the biogas plant) and the three evaluation criteria; (ii) matrix weighting through normalisation; (iii) calculation of the score of each alternative (called in our study "Global Performance Index", GPI [-]), given by the linear combination of the values of the alternatives, weighted by the evaluation criteria according the weights given by AHP results; (iv) ranking of the different alternatives based on the calculated GPI (Figure 1).

2.2 Evaluation criteria of the MCAM model

The following evaluation criteria (corresponding to as many parameters) were identified: (i) Biogas Yield (BY, [Nm^3 ton_{TS}^{-1}]), a parameter directly linked to the energy potential of the blend/substrate; (ii) Economical Efficiency Level (EL [-], Famuyide et al., 2014), which quantified the profit given by the biogas plant per unit cost; (iii) Profitability Index (PI [-], or return on sales, Mbah, 2012), which measured the profit per unit revenue from the digester. Among other possible criteria, neither the technical efficiency nor the total capital investment of the biogas plant were taken into account: although these parameters are very important parameters for bio-energy plant design, the digester and the combined heat and power unit adopted were previously installed in the facility and however they were the same among the different blends/substrates evaluated. In other words, as being a management procedure, the decision making process was focused mainly on the choice of the most suitable feed for the existing biogas plant rather than on the evaluation of an investment done in the past.

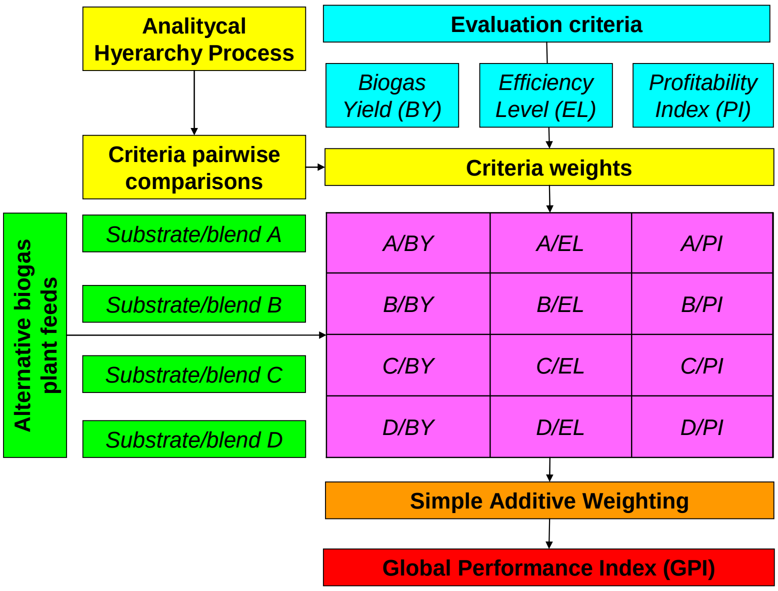

Figure 1: Scheme of the Multi-Criteria Assessment Model for evaluating alternative substrates/blends as biogas plant feed.

2.3 Alternative substrates/blends of the biogas plant

Table 1 reports the four substrates/blends selected to feed the biogas plant of the analysed case study. The selection was suggested by the following considerations. An anaerobic digester is usually fed by self-produced biomass, since this option minimizes feedstock transportation costs. In general, livestock residues are the most common feed for biogas plants, as assumed in the substrate "A". However, it may happen that the annual amount is not sufficient for the theoretical annual energy production; moreover, in the case of biogas plants fed by agro-industrial residues, as happen in Mediterranean areas (mostly devoted to olive or citrus growing), it could be necessary to blend the self-produced biomass with other feedstock, in order to limit the content of inhibiting compounds, which reduce biogas production rates (Zema, 2017).

Table 1: Characteristics of the substrates/blends of a biogas plant evaluated by the Multi-Criteria Assessment Model in the case study of an agricultural district (Calabria, Southern Italy).

Substrate/blend	Substrate	Ratio substrate/blend (w/w) [%]	Supplying source	Distance supplying source-biogas plant [km]
A	Bovine manure	100	Internal	-
B	Bovine manure	70	Internal	-
	Citrus peel	30	External	4
C	Bovine manure	85	External	26
	OMW	15	Internal	-
D	Bovine manure	30	External	4
	Citrus peel	70	Internal	-

In the analysed case study, we hypothesized to blend bovine manure with shares of 30% and 70% of citrus peel (blends "B" and "D", respectively) or with 15% of olive oil mill wastewater (OMW) (blend "C"), all of which supplied from external sites; these percentages are under the limits reported by Athanasoulia et al. (2012) and Forgács (2012), suggesting maximum values of 20% of olive residues and 70% of citrus waste in the digester blends to avoid noticeable reduction of biogas yield.

2.4 Calculation of "BY" parameter

The parameter "BY" was calculated as the sum the biogas yield of each substrate weighted by the related substrate content in the digester blend, and it was measured in biogas volume (at standard temperature and pressure conditions) produced per unit weight of Total Solids (TS). The average biogas yield of each substrate was estimated at 350 Nm^3 ton_{TS}^{-1} for OMW, 600 Nm^3 ton_{TS}^{-1} for citrus peel, and 250 Nm^3 ton_{TS}^{-1} for bovine manure, as suggested by Forgács (2012), Bordoni et al. (2010) and Mantovi et al. (2013).

2.5 Calculation of "EL" and "PI" parameters

The parameter "EL" was calculated as the ratio between the annual profit (P) and costs (C), while the parameter "PI" was calculated as the ratio between "P" and total revenues (R). Postponing more detailed information to the paper of Zema (2017), the calculation methods of R, C and P are summarized below.
Revenues, almost totally deriving from sale of electrical energy, were calculated as the product of the subsidized unit price - according to the Italian Ministry Decree 6/7/2012 - to the annual production of electrical energy; revenues from sale of digestate/compost production (another option to valorize the agricultural residues) were not considered, since they are usually much lower compared to energy revenues (Zema, 2017) and in the agricultural districts of Calabria this practice is not common. The following costs were estimated: (i) plant amortization; (ii) management costs (labour, plant maintenance, insurance and taxes); (iii) costs of substrate supply (sum of storage and transportation costs), for which the related unit costs reported by Zema et al. (2018) were assumed; transport unit cost consists of a fixed (K_f, [€ ton_{TS}^{-1}]) and a variable share (K_v, [€ ton_{TS}^{-1} km^{-1}]), this latter related to the transport distance [km]. Plant amortization and management costs were estimated as a function of the plant nominal power, as suggested by Zema (2017). As for revenues, the costs of digestate transport and land spreading were neglected. Finally, P was the difference between R and C.

3. Results and discussions

The preliminary estimation of storage and transport unit costs (that was necessary because of the high incidence of the related costs on the biomass supply chain and thus on the profitability of a biogas plant management, De Meyer et al., 2014) revealed that: (i) storage unit costs were higher for citrus peel (3.70 € per ton of stored dry matter) and null for bovine manure (since excrements are daily produced by the livestock); (ii) transport unit costs of citrus peel and manure were noticeably lower than liquid biomass, depending on the higher TS content of these solid or semi-solid residues compared to OMW (Table 2). These costs strongly weighed on the results of MCAM, since the cost of substrate supply was a significant share of the total annual costs.

Table 2: Parameters related to storage and transport unit costs of some agro-industrial and livestock in Calabria (Southern Italy) used for the Multi-Criteria Assessment Model implementation in the case study (source: Zema et al., 2018).

Crop/cattle	Residue	Total Solids [%]	Storage unit cost of dry biomass [€ ton_{TS}^{-1}]	Transport cost coefficients			
				K_f		K_v	
				[€ km^{-1}]	[€ ton_{TS}^{-1}]	[€ m^{-3} km^{-1}]	[€ ton_{TS}^{-1} km^{-1}]
Olive	Wastewater	6.1	1.76	1.45	23.24	0.10	1.60
Citrus	Peel	23.2	3.70	1.56	7.54	0.05	0.24
Bovine	Manure	9.0	0.00	1.56	17.33	0.05	0.56

Note: TS = Total Solids; K_v, K_f = fixed and variable coefficients used to calculate the transport costs per TS unit weight.

Concerning AHP, the analysis of the weights assigned to the evaluation criteria showed that, for the sample of the local entrepreneurs interviewed, the most important criteria was "EL" (weight = 0.51), followed by "PI" (0.34), while BY criterion resulted in a minor weight (0.15); the weight sum is one. This may be somewhat expected, since bio-energy business-men are usually more interested to cost, revenue and profit optimisation rather than to the technical parameters (such as biogas yields of digester feed), which instead influence heavily the economic sustainability of a bio-energy plant.
The implementation of SAW to the alternative substrates/blends evaluated identified as the best solution the choice of the substrate "A" (that is, biogas plant fed by bovine manure only), which scored a "GPI" of 0.93. In this case, in spite of the lowest biogas yield (250 Nm^3 ton_{TS}^{-1}), the convenience of this option was enhanced by the absence of storage and transport cost, and this evidently raised up the plant cost-effectiveness: a profit of 0.38 € per unit cost of the energy produced (measured by "EL") was achieved, while each euro coming from energy sale gave a profit of 0.57 € (PI), as indicated by the "PI" criterion (Table 3). Feeding the biogas plant with a blend of bovine manure and citrus peel (70% and 30% as in blend "B" and the inverse percentages as

in blend "D", respectively) - this latter supplied from an external source (Table 3) - gave an acceptable convenience ("GPI" of 0.87, blend "B", and 0.89, blend "D"); in these cases, the cost of substrate supply was higher compared to the substrate "A", because the external biomass must be transported and stored, and this cost balanced the other evaluation parameters. Under these alternatives, "PI" (0.52-0.53) and "EL" (1.11-1.16) showed very similar values, 10% (for "PI") and 5% ("EL") lower than substrate "A", while "BY" value was significantly lower (by about 30%) in the blend "B" (355 Nm^3 ton_{TS}^{-1}) than in the blend "D" (495 Nm^3 ton_{TS}^{-1}) (Table 3). The option of feeding the biogas plant with the blend "C" (85% of bovine manure and 15% of OMW) must be excluded: although the "BY" value could be considered as acceptable (265 Nm^3 ton_{TS}^{-1}, similar to the substrate "A", but much lower than blends "B" and "D"), "PI" and "EL" values are very low (60-90% less than in the substrate "A", respectively, Table 3). This suggests a very low convenience of OMW use as anaerobic digester feed, unless the energy conversion of this olive residue is needed as depuration system.

Table 3: Parameters calculated for the related evaluation criteria of the Multi-Criteria Assessment Model implemented in the case study of an agricultural district (Calabria, Southern Italy).

Substrate/blend	BY [Nm^3 ton_{TS}^{-1}]	PI [-]	EL [-]	GPI [-]
A	250	0.57	1.38	0.93
B	355	0.52	1.16	0.89
C	265	0.05	0.53	0.31
D	495	0.53	1.11	0.87

Notes: BY = Biogas Yield; EL = Economic Efficiency Level; PI = Profitability Index; GPI = Global Performance Index; TS = Total Solids.

In general, the verification of the MCAM in the case study by the comparison of the four alternative blends/substrates showed the highest convenience of feeding a medium-sized biogas plant with self-produced residues of animal origin. The integration of the digester feed with external residues resulted in a slightly worst management option, if citrus peel was used. The synthetic performance index, used for the evaluation of the different options, decreased to a very low value when OMW was supplied in the digester blend from external sources (also in a low percentage).

4. Conclusions

Since the choice of the most suitable feed for a biogas plant is a difficult task for bio-energy business-men of the agricultural sector, it is useful to analyze by a multidisciplinary approach (using, for instance, MCMD techniques) the feasibility of some options consisting of alternatives blends/substrates, whose technic and economic feasibility depend on many factors.

This study combined AHP and SAW methods (belonging to the set of MCMD techniques) to evaluate in an integrated way four alternative substrates/blends to feed a medium size (nominal power of 300 kW) biogas plant. More specifically, after identifying three evaluation criteria, AHP was used to evaluate the related weights by interviewing a group of local entrepreneurs of the bio-energy sector, while SAW provided a synthetic performance index that allowed to rank the substrates/blends.

The verification of the proposed model in a case study (identified in an agricultural district of Southern Italy) showed that it is most convenient to feed the biogas plant with self-supplied bovine manure, since this option minimizes the biomass management costs; supplying a share of blend with substrates of different origin (in our case citrus peel) represents a slightly less convenient choice for the digester feed. Integration of bovine manure with oil mill wastewater must be excluded, because storage and transport costs influence negatively the profitability of the whole energy conversion process. However, in this investigation some important variability factors, affecting the sustainability of energy conversion of agricultural residues, were not taken into account, such as the environmental and social issues. Under these points of view, future work is needed to complete the evaluation approach; this may be carried out, for instance, considering also the social aspects (e.g. providing local jobs) and the environmental issues (e.g. the minimisation of greenhouse gas emissions, waste management and prevention of pollution) for their integration within the technical and economic analyses and/or other decentralised strategies to valorise the digestion by-products, such as composting.

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