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Eco-efficiency assessment of farm-scaled biogas plants

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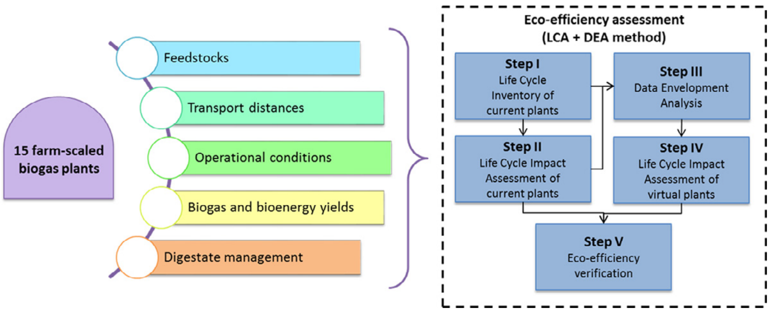
HIGHLIGHTS

- An eco-efficiency analysis was applied to 15 agricultural biogas plants.
- The five-step life cycle assessment + data envelopment analysis method was applied.
- 60% of the plants were identified to operate in an eco-efficient way.
- Reduction targets enhanced the environmental profile of the most polluting plants.
- Eco-efficiency depends on a number of factors more than one operational parameter.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this study was to analyse the eco-efficiency of 15 agricultural biogas plants located in Northern Italy. For this, the combination of life cycle assessment (LCA) and data envelopment analysis (DEA) methodologies was considered with the purpose of identifying efficient operational plants and proposing improvement measures for the inefficient ones. The environmental profile of both the original and the virtual plants (obtained after the improvement measures) were compared in order to identify the net environmental gains linked with the inputs reduction. As a result of improvement measures, the production of electricity from biogas in all plants would imply environmental benefits compared with the average electricity production in the Italian grid. In light of the results obtained, special attention should be paid to the feedstock selection since it has a key role in the overall eco-efficiency of the plant, due to their different origin and composition.

1. Introduction

The European Union began promoting the production of renewable energy according to the Directive 2001/77/EC, following later the Directive 2009/28/EC. In this context, supported by policy programs aimed at enhancing energy security and sustainability, biogas has become an important form of bioenergy (Mela and Canali, 2014). As a result, more than 10 thousand biogas plants were already operating in Europe at the end of 2013, with 9.2 million tonnes oil equivalent (Mtoe) of biogas (EurObserv'ER, 2014). Despite the fact that the production of biogas has been encouraged as an environmental beneficial technology for bioenergy

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Abbreviations: ALO, agricultural land occupation; CC, climate change; CCR, Charnes-Cooper-Rhodes; CHP, co-generation heat and power; CRS, constant return to scale; DEA, data envelopment analysis; DMU, decision making unit; FE, freshwater eutrophication; FU, functional unit; GHG, greenhouse gas; HRT, hydraulic retention time; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; Mtoe, million tonnes of oil equivalent; ME, marine eutrophication; OFMSW, organic fraction of municipal solid waste; OLR, organic loading rate; SBM, slacks-based measure; TA, terrestrial acidification; TAN, total ammonia nitrogen; TN, total nitrogen; TP, total phosphorus; TS, total solids; TVS, total volatile solids; VRS, variable return to scale; WWTP, wastewater treatment plant.

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production, the impact mitigation may be counteracted due to the environmental burdens that arise from different stages of the process, i.e. the cultivation of crops, the delivery of feedstock, the production and use of biogas and the management of digestate (Poeschl et al., 2012a, 2012b). Furthermore, the efficient operation of the biogas plant is another key factor in order to guarantee the best environmental performance, ensuring maximum substrate utilisation and minimum residual methane potential in order to optimise bioenergy production while reducing emissions from the management of the digestate (Ruile et al., 2015). The key parameters for this optimum conversion are the type of feedstock, the operating temperature, the hydraulic retention time (HRT), the organic loading rate (OLR) and the stability of the biological process (Naik et al., 2014).

Within this framework, life cycle assessment (LCA) is considered as the appropriate methodology to evaluate the environmental performance of bioenergy systems (European Commission, 2010). As a result, several LCA studies analysing the environmental impacts of biogas production systems can be found in the literature (De Vries et al., 2012a; Fantin et al., 2015; Lijó et al., 2014; Poeschl et al., 2012a, 2012b). These studies agreed in the identification of the most polluting stages of the biogas systems including energy crops cultivation and digestate management (Poeschl et al., 2012a, 2012b). Nevertheless, large variations in environmental results can be found in these studies due to the variability of feedstock, the final use of biogas and the wide range of management strategies for digestate, but also due to methodological differences such as different functional units or system boundaries.

The data envelopment analysis (DEA) is a methodology used to evaluate the productive efficiency of multiple similar entities (Cooper et al., 2007). In this sense, DEA enables the identification of inefficient operating points, promoting technological improvements under the perspective of an efficient operation performance. With this regard, Madlener et al. (2009) analysed the performance of agricultural biogas production applying multi-criteria and DEA. The study demonstrated that both methodologies can be applied in a complementary way to help to improve the operation of agricultural biogas plants.

In the last years, the combined implementation of DEA and LCA has been proposed in order to more effectively detect and sort out the technical inefficiencies that are sources of unnecessary environmental impact (Lozano et al., 2009). This combined methodology allows the assessment of the operational and environmental performance of multiple units (Iribarren et al., 2010) and it has been applied to different production processes such as wine production (Vázquez-Rowe et al., 2012) and fisheries (Vázquez-Rowe et al., 2010) and even to wastewater treatment plants (WWTPs) (Lorenzo-Toja et al., 2015). However, to the best of our knowledge, the combined method DEA + LCA has not been applied to agricultural biogas production. Therefore, the goal of the current study was to apply LCA and DEA methodologies at 15 Italian agricultural biogas plants. The analysis was conducted in order to (i) detect operationally inefficient biogas plants, (ii) benchmark target input consumption levels for the inefficient plants and (iii) quantify the environmental benefits of moving towards operational efficiency in biogas production. The results of the study will bring insights for improving the operation of agricultural biogas plants in an eco-efficient way.

2. Materials and methods

2.1. Definition of the case study

The 15 biogas plants under study are all located in the Po Valley, a large flat area in Northern Italy with special relevance due to its industrial, agricultural and livestock activities (Carrosio, 2013). As a result of the favourable public subsidy framework, numerous biogas plants which use energy crops and animal waste are located in this region. In fact, 1000 out of the 1800 plants operating in Italy are located in the Po valley (Bacenetti et al., 2016).

Regarding the 15 biogas plants under study, most of them adopt a co-digestion approach based on energy crops (maize, triticale, ryegrass and sorghum) and animal waste (pig, cow and chicken manure) in different ratios. As it can be seen in Table 1, in terms of wet mass digested, out of these 15 plants, 2 biogas plants use an energy crop as the only input (100%), 5 co-digest energy crops in a ratio higher than 75% and 6 plants between 25% and 75%. Consequently, only 2 biogas plants digest energy crops in a ratio lower than 25%. In Table 1, the biogas plants have been gathered in three categories regarding the ratio of energy crops and organic waste digested referred to wet mass. Maize silage, due to its high energy density (Negri et al., 2016), is by far the most widely used energy crop, being digested in all the biogas plants. Other plants include the digestion of other organic residues or co-products such as the organic fraction of municipal solid waste (OFMSW), food waste or glycerol. Throughout the year, the daily composition of the input energy crops and agro-residues is variable, depending on their

Table 1
Feedstock characteristics and plant grouping

Plant ID	Energy crops				Residues				Total			
	Maize	Triticale	Maize flour	Other	Pig waste	Cattle waste	Chicken waste	Food waste	Substrate	Energy Crops	Residues	Plant Category*
	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(t/d)	(%)	(%)	
1	19.0	13.0	–	–	28.0	–	–	–	60.0	53%	47%	B
2	54.0	–	–	–	45.0	–	–	–	99.0	55%	45%	B
3	36.5	–	–	–	–	–	–	–	36.5	100%	0%	A
4	43.9	4.98	–	–	12.6	–	1.35	–	62.9	78%	22%	A
5	9.86	–	–	–	178	–	–	76.7	265	4%	96%	C
6	45.0	–	–	–	45.0	10.0	–	4.00	104	43%	57%	B
7	50.0	–	–	–	50.0	–	–	–	100	50%	50%	B
8	47.1	2.95	–	–	–	14.2	0.39	–	64.6	77%	23%	A
9	38.0	–	0.02	–	7.00	3.00	–	–	48.0	79%	21%	A
10	–	–	7.00	–	30.0	8.60	–	–	46.1	15%	85%	C
11	45.3	1.88	–	3.77	1.06	2.37	0.80	–	55.2	92%	8%	A
12	46.3	4.32	–	0.10	–	6.41	1.35	–	58.5	87%	13%	A
13	58.5	–	–	–	44.0	–	–	–	102.5	57%	43%	B
14	45.2	–	–	–	23.4	–	–	–	69.9	65%	35%	B
15	10.0	–	3.00	–	–	–	–	–	13.0	100%	0%	A

* A = Energy crops > 75%; B = 75% > Energy crops < 25%; C = Energy crops < 25%.