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Biogas from dedicated energy crops in Northern Italy: electric energy generation costs

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Abstract

Agricultural anaerobic digestion facilities are increasing in many EU member States and biomass supply is sometimes an issue. Dedicated energy crops (DEC) (mainly Maize, Triticale and Sorghum) are often used to integrate other substrates, such as agricultural residues, manure and organic waste. However, DEC production includes onerous agricultural operations (soil preparation, harvest, transport and storage) and may result in high unit costs (UC) of electric energy (EE, € kWhe^{-1}), compared to other renewable sources. In this work, seven different types of DEC (4 different combinations of crop successions) were cultivated in 30 different parcels, distributed along the Po Valley (northern Italy), using different varieties of seeds for each crop type. All agricultural operations were accounted for their costs (988–3346 € ha^{-1}). Biomass production was measured and reported as average of different parcels for each type of crop (31.2–187 Mg ha^{-1}). Biomass dry matter content and biogas potential were measured on representative samples and the EE obtainable was calculated (7.9–35.3 MWhe ha^{-1}), by assuming conservative factors (CH_4 contents in biogas and electric generation yields). The costs of ensiled biomass sensibly varied (13.8–40 € Mg^{-1}) among crop solutions, as well as the same UC of EE (0.068–0.150 € kWhe^{-1}). These costs were considered together with typical plant management and investment costs (plant size: 0.5–1 MWe): total UC of EE generation through anaerobic digestion (considering 100% DEC) varied in a relatively wide range (0.143–0.279 € kWhe^{-1}). When the biomass mix is 'blended' with low-cost residues or organic waste, this range could be lowered to 0.096–187 € kWhe^{-1}. Only this strategy and strong efforts in reducing technological investment/management costs can candidate biogas-based EE as a really competitive renewable alternative to traditional sources, in the next future.

Keywords: anaerobic digestion, bioenergy, biogas, biomass supply, energy crops, renewable electricity

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Introduction

Anaerobic digestion (AD) is nowadays, a well-established technology for renewable fuel and/or electric energy (EE, kWhe) production. In the EU, at the end of 2011, the production of primary energy from biogas was set over 10 Mtoe per year, with an increase of nearly 20% compared to 2009 (EurObserv'ER, 2012). The main contribution (nearly 50%) to this important result comes from Germany and in particular from agricultural biogas facilities; other 17% of the production comes from the UK, but mainly from landfill and sewage sludge biogas; Italy comes third with nearly 10% both from landfill and agricultural facilities (EurObserv'ER, 2012). In the last 2 years (2011–2013), agricultural AD facilities in Italy had a surprising increase (nearly 300%), thanks to a particularly favorable incentive to EE generation from biogas; the number of biogas facilities increased from 314 (end of 2010) to 994 (end of 2012) and the electric power from 176 to 756 MW (Fabbri *et al.*, 2013). These plants are typically related to farms and biogas production rely mainly on three types of biomass sources: (i) biomass by-produced by the farm (such as animal slurries, agricultural residues, straw); (ii) agro-industrial byproducts and residues coming mainly from food industry; and (iii) dedicated biomass produced specifically for energetic purposes. In Germany, the production of over 5 Mtoe of primary energy from biogas strongly relies on dedicated energy crops (DEC); by 2009, 98% of on-farm digesters in Germany utilized DEC as a substrate (Wilkinson, 2011), with 530 000 ha dedicated (i.e. 4.4% of total arable

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land). In Italy, a recent survey indicated that around 80% of the agricultural AD facilities (nearly 1000 in 2012) use almost the same DEC, in different weights on their total feed (Carrosio, 2013).

The importance of DEC in the EU biogas sector imposes more attention on the real sustainability of the crop systems adopted, simultaneously under economical, energetic and environmental points of view. Several studies about DEC for biogas are available in recent literature, including some proposing a complete LCA approach to evaluate different aspects concerning the sustainability of DEC (Gerin *et al.*, 2008; Blengini *et al.*, 2011; Buratti *et al.*, 2013). The first concern is environmental/energetic, regarding both greenhouse gas (GHG) emissions and primary resources utilization (such as fertile soils, water and ecosystems). Recently, Jury *et al.* (2010) compared the production of bio-methane from crops with natural gas, stating the substantial positive balance of bio-methane, for what concerns both emissions and environmental issues in general. This happens, of course, when no native ecosystem is converted into crop, as stated by Fargione (2008). The use of arable land and traditional crop systems based on cereals (mainly maize and triticale) were reported to achieve positive environmental/energetic balances, even for electricity generation from biogas; also thanks to soil fertility preservation granted by the organic matter and nutrients contained in digestates returned to the land (Schumacher *et al.*, 2010). While the environmental/energetic balances have been often demonstrated to be generally positive (Fargione, 2008; Jury *et al.*, 2010; Schumacher *et al.*, 2010; Shortall, 2013), the economic aspect, i.e. the acceptability of production costs in comparison with the other actually available renewable energy sources, is still sometimes an issue. In the last decade, EU member States have been granting public support (incentives) to speed up the development of innovative renewable energy generation, within the 20-20-20 Agenda. In this context, biogas generation from DEC has been economically viable and the production costs have been often covered by generous tariffs, mainly based on EE generated from biogas. On the other side, the trend of future policy in the EU will aim at reducing public support, to promote efficiency and reduction of production costs. In Italy, for example, after 3 years of relatively generous support (0.28 € kWhe^{-1} as tariff for EE generation from biogas in the period 2009–2012), starting from 2013 the tariff was strongly reduced (0.16–0.26 € kWhe^{-1}, depending on plant size and type of treated biomass) and a number of limitations on the use of DEC were introduced (DM 6 July 2012). For these reasons and, in any case, in a horizon of optimization to compete with traditional fossil fuels and other forms of renewable electricity, the production UC of EE from biogas must be reduced as much as possible in the next future and biomass supply is the most important cost item. Recently, Schievano *et al.* (2009) reported the contribution of biomass supply to the UC of biogas produced from various organic materials, comparing DEC to agricultural/industrial byproducts and residues (BR) and organic waste (OW) and considering their prices on the market. On the other hand, the large majority of biogas plants in Italy rely on self-production of DEC, resulting in lower costs, compared to the market prices.

For these reasons, the aim of this work was to provide on-field data about DEC self-production supply solutions, their productivity and their production costs, to draw the actual viability of EE from biogas in comparison with other forms of renewable electrical power generation.

Materials and methods

Crop trials

This work took into consideration the more diffused and viable crops obtainable in the Po Valley (Northern Italy). Both spring–summer crops and autumn–winter crops were taken into consideration and evaluated both as singular crop and as part of a specific crop system. Among winter crops, two different varieties of triticale, two of rye and three different grass (with different varietal composition, i.e. including both *graminceae* and *leguminous*) were considered. For what concerns the summer crop species, a variety of sorghum, 20 maize hybrids of FAO 600/700 cycle, as reported in Table S1.

These crops were realized in parcels of 1500–2500 m^2. Thirty parcels (Table S1) were distributed homogeneously along the Po Valley (Northern Italy), choosing locations as much representative of the whole territory, in terms of climatic and environmental conditions. For every site, an agronomic and pedologic profile was drawn, for choosing the best crop technique to be used. Nine different main sites were chosen as indicated in Fig. 1: Cavenago D'Adda (A), Cherasco (B), Dompè (C), Vottignasco (D), Cardè (E), Porto Tolle (F), Monteggiana (G), Viadana (H), Pizzighettone (I); more details of the GPS coordinates, harvest period, plant variety, seed and harvest dates were reported in Table S1. The winter crops were seeded between 20th and 30th October. The maize parcels were seeded in three different periods, depending on the crop succession. The first planting time (hereafter 1st crop) was between the 20th of March and the 10th of April; the second planting time (hereafter 2nd crop) was between the 15th and the 25th of May, in succession to a grass crop; the third planting time (hereafter 3rd crop) was between 10th and 20th of June, in succession to a winter cereal.

Field data and sample collection

In parallel with crop trial implementation, data acquisition about agronomic techniques was performed and all operations and their relative costs are reported in Table 1. These data were used for calculating crop production cost. For each trial, the fol-

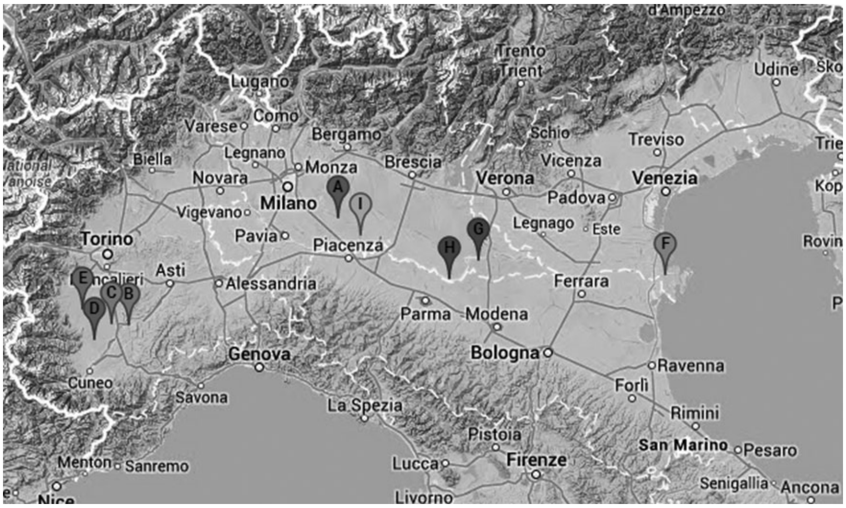

Fig. 1 Geographical location of the parcels studied. Details and coordinates are reported in Table S1.

lowing details were registered: type of soil, crop succession, type of soil preparation, seeding period, investment, fertilization, irrigation and harvest period. Eventual land renting costs and/or partial biomass acquisition from third parties were excluded, to avoid high fluctuations of market prices to influence the study. Soil preparation included plowing at 30 cm depth, vertical harrowing and pneumatic precision sowing. Maize underwent hoeing at 4th leaf and earthing up at 8th leaf. Nitrogen, phosphorous, potassium and sulfur supply was ensured by fertilization with different chemical fertilizers and by digestate distribution to land as basic fertilizer and soil amendment. Harvest operations were performed through a direct chopping on the field and horizontal ensiling. Details of all operations for every crop was reported in Table 1. All agronomic operations were accounted for what concerns their costs and the total cost of DEC was calculated as cumulative biomass costs per ha (€ ha^{-1}) (Table 1). All investment costs for capital goods were not accounted here as DEC supply cost, but they were added later, in the calculation of the total electricity production cost.

During harvest operations, quantitative production of each DEC was determined by weighting and extrapolating the biomass production per ha (Mg ha^{-1}). After approximately 2 months from harvest, for each parcel, homogeneous and representative samples were collected from the soil, immediately stored at 4 °C and sent to be analyzed. Dry matter content was determined for each sample according to standard procedures (APHA, 1998).

Biogas and electric power productivity of crop materials

Biogas and EE productivity of all DEC samples was determined by applying the anaerobic biogasification potential (ABP) test, at lab scale. This biological test provides a direct measurement of the maximum potential biogas that can be produced from any organic matrix through mesophilic anaerobic digestion, by optimized lab-scale process. The ABP test was performed as suggested by Schievano *et al.* (2008, 2009). Briefly, batch anaerobic digesters of 500 ml total capacity were inoculated with 200 ml of digested slurry (3–4% DM content) in stable methanogenic activity, 2 g dry sample suspended in 100 ml tap water were added and the digesters incubated at 37 ± 1 °C until production plateau was reached. Quantitative biogas production was estimated by withdrawing extrapressure gas with a 60 ml syringe. This procedure was always performed at controlled temperature of 37 °C; the residual gas pressure in the batches, after the gas extraction, was always detected and the measured volume were reported to standard temperature (25 °C) and pressure (1 atm). Qualitative analyses of the biogas were performed by a gas-chromatograph (Micro GC 3000, Agilent Technology, Les Ulis Cedex, France), for determining the CH_4 concentrations (v/v) in the biogas. All the tests were performed in duplicate.

As reported in Schievano *et al.* (2011), AD full-scale processes must be considered as less efficient as compared to the lab-scale ABP test. For this reason, the ABP measured on crop samples were corrected by a factor proposed by Schievano *et al.* (2011), i.e. the bio-methane yield BMY, defined as the yield of degradation achieved in the full-scale process, with respect to the potential obtained by the optimized test at lab scale. In that contribution, the measured BMY, for three observed full-scale AD case studies, ranged from 87% to 93%. Here, BMY = 87% was chosen and applied to all ABP, as more conservative. The resulting data were defined as biogas productivity as shown in Equation 1:

$$\text{BP}(\text{Nm}^3_{\text{biogas}}/\text{Mg}_{\text{DM}}) = \text{ABP} \times \text{BMY} = \text{ABP} \times 0.87; \qquad (1)$$

where BP = biogas productivity in full-scale conditions.

To calculate EE production, biogas was assumed with an average concentration of methane of 55.0% v/v for all samples, as a conservative value that can be measured in biogas produced at full scale (Schievano *et al.*, 2011). Inferior heat power

Table 1 Details of field operations performed and relative costs incurred (field data)

Crops		Maize (early harvest)		Maize (midterm harvest)		Maize (late harvest)		Rye		Grass		Triticale		Sorghum	
		1–6		7–13		14–20		21–22		23–25		26–27		28–30	
Parcels	UC	*n*	C	*n*	C	*n*	C	*n*	C	*n*	C	*n*	C	*n*	C
Soil preparation															
Plowing	140	1	140	1	140	1	140	1	140	1	140	1	140	1	140
Harrowing	65	1	65	1	65	1	65	1	65	1	65	1	65	1	65
Fertilization															
Digestate distribution	120	1	120	1	120	1	120	1	120	1	120	1	120	2	240
Chemical fertilization	30	1	30	1	30	1	30	1	30	1	30	1	30	1	30
Fertilizers	€ kg^{-1}	kg ha^{-1}		kg ha^{-1}		kg ha^{-1}		kg ha^{-1}		kg ha^{-1}		kg ha^{-1}		kg ha^{-1}	
Urea	0.60	450	270	350	210	350	210	0	0	180	108	0	0	0	0
Ammonium Nitrate	0.60	0	0	0	0	0	0	175	105	0	52	260	156	130	52
diammonium phosphate	0.42	200	84	150	63	150	63	80	32	0	0	130	52	0	0
Potassium sulfate	0.40	0	0	0	0	0	0	100	40	0	0	100	40	0	0
Potassium chloride	0.35	320	112	200	70	200	70	0	0	150	53	0	0	150	52.5
Seeding															
Sowing		1	90	1	90	1	90	1	70	1	50	1	70	1	70
Seeds		75 000 s ha^{-1}	165	75 000 s ha^{-1}	165	75 000 s	ha^{-1}	165	200 kg ha^{-1}	160	60 kg ha^{-1}	60	200 kg ha^{-1}	160	60 kg ha^{-1}
Operations															
Hoeing	60	1	60	1	60	1	60	0	0	0	0	0	0	0	0
Earthing up	70	1	70	1	70	1	70	0	0	0	0	0	0	0	0
Flooding irrigation	70	5	350	3	210	3	210	0	0	0	0	0	0	4	280
Sprinkler irrigation	320	0	0	1	320	1	320	0	0	0	0	0	0	0	0
Weeding	30	1	30	1	30	1	30	1	30	0	0	1	30	0	0
Weed killers		1	100	1	100	1	100	1	40	0	0	1	30	0	0
Harvest															
Chopping/ loading	170	1	170	1	170	1	170	1	170	1	210	1	170	2	340
Transportation (20 km) and ensiling	90	1	90	1	90	1	90	1	90	1	90	1	90	2	180
Other management costs			600		300		300		300		300		300		300
CAP incentive			−410		−205		−205		−205		−205		−205		−205
Total cost			2136		2098		2098		1187		998		1248		1654

n, number of operations; UC, unit cost of single operation (€ ha^{-1}); C, cost of operation (€ ha^{-1}); CAP, EU community agricultural policy financial support.

of methane (8.7917 kWh $Nm^{-3}CH_4$) was used to calculate total the energy content of the produced biogas; electrical generation yield by internal combustion engines was assumed of 39%, as recently reported by Schievano *et al.* (2011). These calculations are resumed in Equation 2.

$$\mathrm{EE\,(kWh)} = \mathrm{BP\,(Nm^3_{biogas})} \times 0.55 \times 8.7917 \times 0.39. \qquad (2)$$

Production costs of biomass, biogas and electric energy

Cumulative costs per hectare (€ ha^{-1}) and biomass productions per hectare (Mg ha^{-1}) were used to calculate biomass unit costs (€ Mg^{-1}). Then, the UC (€ Nm^{-3} and € $kWhe^{-1}$) of biogas and EE were calculated from the biogas/EE productivities and total cost per hectare, through Equation 3:

$$UC_{biogas} = \frac{c}{B}/BP\ (€Nm^{-3}) \text{ and } UC_{EE} = \frac{c}{B}/EE\ (€kWhe^{-1}); \quad (3)$$

where C = cumulative cost per hectare (€ ha^{-1}), B = biomass production per hectare (Mg ha^{-1}), ABP = EE = electric energy productivity kWhe Mg^{-1}.

These UC were defined as biomass supply costs. To determine the total UC of the biogas/EE production, the UC of all management/maintenance operations to be sustained in the biogas facility and the unit costs of the investment depreciation were added, as suggested by Riva *et al.* (2014). These UC (€ Nm^{-3} and € kWh^{-1}) depend on the plant size and in this article 1 and 0.5 MW electrical power capacity were considered as target sizes. According to Riva *et al.* (2014), the UC were assumed as follows: for 1 MW, 0.029 € $kWhe^{-1}$ of management/maintenance and 0.046 € $kWhe^{-1}$ of depreciation charge; for 0.5 MW, 0.048 € $kWhe^{-1}$ of management/maintenance and 0.081 € $kWhe^{-1}$ of depreciation charge.

These data were compared to biogas/energy production UC from other kinds of biomass, such as agro-industrial byproducts and residues (BR) and organic waste (OW) material, coming from separated collection of municipal waste and wastewater sludge. Data regarding supply costs of this kind of biomass were found in Schievano *et al.* (2009) and Riva *et al.* (2014). The UC regarding management/maintenance and investment of a biogas facility treating OW were different from those of a DEC/BR based facility. Riva *et al.* (2014) reported, for CSTR-wet type AD facilities treating OW, for 1 MW power capacity the following UC: 0.094 € $kWhe^{-1}$ of management/maintenance/pretreatments and 0.065 € $kWhe^{-1}$ of depreciation charge, while OW supply cost was assumed null, as soon as covered by waste treatment tariff (Riva *et al.*, 2014).

Results

Crops productivities

All single results obtained in the different parcels regarding production yields, chemical characterization and the potential biogas tests were reported in the Supporting Information (Table S2). In Table 2, the average values for each type of crop were reported, together with 4 crop successions that are normally used for land use optimization in DEC production.

The fresh matter (FM) production per hectare strongly varied depending on the crop, from 30 to 122 Mg ha^{-1} (Table 2). Sorghum, in particular, gave high FM productions (122.5 ± 10 Mg ha^{-1}), thanks to double harvest. On the other hand, the average DM content of each crop material (Table 2) outlined a different scenario in terms of DM production per hectare. The most productive single crop resulted Maize (1st crop) with 21.5 ± 0.9 MgDM ha^{-1} followed by 2nd and 3rd crop Maize and Sorghum (Table 2). The best crop succession was Triticale and Maize (3rd crop), with 34.1 ± 1.4 MgDM ha^{-1}. These characteristics and productivities are confirmed in other studies and simi-

Table 2 Average production yields obtained for each crop type and for crop successions

	Biomass production yield	DM content*	DM production yield	ABP*		Biogas yield	EE yield	Agricultural land needed
	MgFM ha^{-1*}	kgDM kg^{-1}FM	MgDM ha^{-1}	Nm^3 Mg^{-1}FM	Nm^3 Mg^{-1}DM	Nm^3 ha^{-1}	MWhe ha^{-1} a^{-1}	ha $GWhe^{-1}$ a^{-1}
Single crops								
Maize (1st crop)	70.8 ± 7.0	0.304 ± 0.029	21.5 ± 0.9	211 ± 13	694 ± 43	12 969 ± 812	24.46 ± 1.53	41 ± 3
Maize (2nd crop)	65.4 ± 9.4	0.308 ± 0.023	20.1 ± 2.7	181 ± 19	589 ± 62	10 315 ± 1081	19.45 ± 2.04	51 ± 5
Maize (3rd crop)	56.2 ± 5.3	0.314 ± 0.018	17.6 ± 1.7	184 ± 36	588 ± 116	9019 ± 1783	17.01 ± 3.36	59 ± 12
Rye	31.2 ± 23.5	0.334 ± 0.146	8.7 ± 3.3	185 ± 5	556 ± 15	4199 ± 117	7.92 ± 0.22	126 ± 4
Grass	49.8 ± 3.3	0.218 ± 0.010	10.9 ± 0.3	126 ± 6	576 ± 28	5447 ± 260	10.27 ± 0.49	97 ± 5
Triticale	90.3 ± 6.0	0.183 ± 0.004	16.5 ± 1.4	124 ± 15	677 ± 79	9718 ± 1139	18.33 ± 2.15	55 ± 6
Sorghum	122.5 ± 10.0	0.151 ± 0.024	19.4 ± 1.2	64 ± 13	423 ± 87	7121 ± 1460	13.43 ± 2.75	74 ± 15
Crop successions								
Rye + Maize (3rd crop)	82.2 ± 23.5	0.320 ± 0.146	26.3 ± 3.3	185 ± 5	577 ± 15	13 217 ± 353	24.93 ± 0.66	40 ± 1
Grass + Maize (2nd crop)	112.2 ± 9.4	0.276 ± 0.023	31.0 ± 2.7	161 ± 17	584 ± 62	15 762 ± 1665	29.73 ± 3.14	34 ± 4
Triticale + Sorghum	187.0 ± 10.0	0.166 ± 0.024	31.0 ± 1.2	89 ± 14	540 ± 87	14 561 ± 2340	27.46 ± 4.41	36 ± 6
Triticale + Maize (3rd crop)	136.3 ± 6.0	0.250 ± 0.004	34.1 ± 1.4	158 ± 20	631 ± 79	18 737 ± 2357	35.33 ± 4.44	28 ± 4

*FM, Fresh matter; DM, Dry matter; ABP, Anaerobic biogasification potential.

lar yields in other EU contexts were used as reference for LCA evaluations of DEC (Schumacher *et al.*, 2010).

The average values resulted from the ABP tests (all single results in Tables S2), indicated specific production of biogas somehow different between different crops (Table 2). The highest ABP values, considered on DM unit, were measured for Maize (1st crop) and Triticale (>650 $\mathrm{Nm^3_{biogas}}$ $\mathrm{Mg^{-1}DM}$), but if considered on FM unit, Maize and Rye were the highest (>180 $\mathrm{Nm^3_{biogas}}$ $\mathrm{Mg^{-1}FM}$). For what concerns crop successions, the most productive was Triticale + Maize (3rd crop) on DM unit (631 ± 79 $\mathrm{Nm^3_{biogas}}$ $\mathrm{Mg^{-1}DM}$), while Rye + Maize (3rd crop) on FM unit (185 ± 5 $\mathrm{Nm^3_{biogas}}$ $\mathrm{Mg^{-1}FM}$) (Table 2).

These data allowed calculating the performances per hectare in terms of biogas yields and therefore of electric power obtainable by internal combustion generators. Maize (early harvest) resulted the best single crop, with nearly 13 000 $\mathrm{Nm^3_{biogas}}$ $\mathrm{ha^{-1}}$, i.e. 24 458 ± 1531 kWhe $\mathrm{ha^{-1}\ a^{-1}}$ of EE. The other Maize harvests yielded slightly lower than the early harvest (Table 2) and only triticale reached similar results (9718 ± 1139 $\mathrm{Nm^3_{biogas}}$ $\mathrm{ha^{-1}}$, 18 327 ± 2149 kWhe $\mathrm{ha^{-1}\ a^{-1}}$). The other crops were sensibly less productive (Table 2). The best productivity was reached by crop combinations with biogas productivity always over 13 000 $\mathrm{Nm^3_{biogas}}$ $\mathrm{ha^{-1}}$ and electricity productivity over 24 000 kWhe $\mathrm{ha^{-1}\ a^{-1}}$ (Table 2). The most productive combination resulted from Triticale as winter crop and Maize (late harvest), with nearly 19 000 $\mathrm{Nm^3_{biogas}}$ $\mathrm{ha^{-1}}$, i.e. 35 335 ± 4444 kWhe $\mathrm{ha^{-1}\ a^{-1}}$ (Table 2).

These results can be considered also as land area needed per EE unit. Maize (early harvest) was the best performing single crop, with 41 ha $\mathrm{GWhe^{-1}\ a^{-1}}$ (Table 2). Rye, on the other hand, was the single crop requiring more land for the same amount of EE, i.e. 126 ha $\mathrm{GWhe^{-1}\ a^{-1}}$ (Table 2). Crop combinations allow lowering land use for the same energy production and all combinations resulted under 40 ha $\mathrm{GWhe^{-1}\ a^{-1}}$ (Table 2). The best one was Triticale + Maize (late harvest), with only 28 ha $\mathrm{GWhe^{-1}\ a^{-1}}$, while Rye + Maize (late harvest) resulted in 40 ha $\mathrm{GWhe^{-1}\ a^{-1}}$ (Table 2).

Production costs

The resulting total production costs per hectare were reported as average obtained for each crop type and crop successions in Table 3. These costs, as above mentioned, include all agricultural operations performed to obtain the silage ready for use in the AD process. The most expensive crop was Maize (around 2000 € $\mathrm{ha^{-1}}$), with slight differences between different harvests (Table 3). Grass showed the lowest production cost, little lower than 1000 € $\mathrm{ha^{-1}}$ (Table 3). Crop successions showed cumulated costs in the range 2900–3400 € $\mathrm{ha^{-1}}$ and the most expensive resulted Titicale + Maize (late harvest) (Table 3).

Taking into account biomass productivity, the production cost of biomass was calculated, both on FM and DM basis (Table 3). The lowest costs were found for Triticale and Sorghum, even if Triticale was the cheapest if considered on DM basis (76 € $\mathrm{Mg^{-1}DM}$), while the highest cost was found for Rye, i.e. 45.6 € $\mathrm{Mg^{-1}FM}$ and 137 € $\mathrm{Mg^{-1}DM}$. The cheapest biomass obtained by crop combinations resulted from Triticale + Sorghum, with 15.5 € $\mathrm{Mg^{-1}FM}$ and 94 € $\mathrm{Mg^{-1}DM}$ (Table 3).

However, the most interesting and significant way of looking at the production costs is calculating the UC of biogas ($\mathrm{Nm^3_{biogas}}$) and/or EE (kWhe) produced. The lowest UC of biogas/EE produced resulted from Triticale

Table 3 Production costs obtained on-field for each type of crop and crop succession

	Production cost	Biomass cost		UC of biogas	UC of EE
	€ $\mathrm{ha^{-1}}$	€ $\mathrm{Mg^{-1}}$	€ $\mathrm{Mg^{-1}DM}$	€ $\mathrm{Nm^{-3}}$	€ $\mathrm{kwhe^{-1}}$
Single crops					
Maize (1st crop)	2106	29.8	98	0.162	0.086
Maize (2nd crop)	2098	32.1	104	0.203	0.108
Maize (3rd crop)	2098	37.3	119	0.233	0.123
Rye	1187	45.6	137	0.283	0.150
Grass	988	19.8	91	0.181	0.096
Triticale	1248	13.8	76	0.128	0.068
Sorghum	1655	12.9	86	0.232	0.123
Crop successions					
Rye + Maize (3rd crop)	3285	40.0	125	0.249	0.132
Grass + Maize (2nd crop)	3086	27.5	100	0.196	0.104
Triticale + Sorghum	2903	15.5	94	0.199	0.106
Triticale + Maize (3rd crop)	3346	24.5	98	0.179	0.095

(0.128 € $Nm^{-3}{}_{biogas}$ and 0.068 € $kWhe^{-1}$, Table 3), while the most expensive was Rye (0.283 € $Nm^{-3}{}_{biogas}$ and 0.150 € $kWhe^{-1}$, Table 3). Concerning crop successions, Triticale + Maize (3rd crop) gave the cheapest methane/EE (0.179 € $Nm^{-3}{}_{biogas}$ and 0.095 € $kWhe^{-1}$, Table 3), while Rye + Maize (3rd crop) resulted in the highest UC (0.249 € $Nm^{-3}{}_{biogas}$ and 0.132 € $kWhe^{-1}$, Table 3).

Influence of crop cost on total energy production cost

DEC production cost must be considered as only part of the total cost of biogas/energy production in an AD facility. As recently reported by Riva *et al.* (2014), to biomass supply/treatment other costs must be added, i.e. plant management, maintenance of mechanical and structural elements of the facility, digestate management and investment depreciation charges. Depending on plant size, these costs vary their incidence on the total cost of biogas or EE. Considering data reported by Riva *et al.* (2014), regarding biogas facilities with electric power capacity of both 1 and 0.5 MW, the total UC was reported in Fig. 2, in the hypothesis of 100% feeding with DEC. In biogas facilities of 1 MW capacity, the UC ranged from 0.143 € $kWhe^{-1}$ (0.270 € $Nm^{-3}{}_{biogas}$) for Triticale and 0.225 € $kWhe^{-1}$ (0.424 € $Nm^{-3}{}_{biogas}$) for Rye (Fig. 2). Due to higher impact of management/maintenance and investment costs on the 0.5 MW capacity, the total UC of the EE (or biogas) produced ranged from 0.197 € $kWhe^{-1}$ (0.372 € $Nm^{-3}{}_{biogas}$) for Triticale and 0.279 € $kWhe^{-1}$ (0.526 € $Nm^{-3}{}_{biogas}$) for Rye (Fig. 2).

The production costs of DEC differently influenced the total energy production UC, as reported in Fig. 2. In facilities of 1 MW power capacity, DEC accounted for 47–67% of the total UC, while in facilities of 0.5 MW power capacity, for 34–54% (Fig. 2).

Considering BR and OW as biomass source (data reported by Riva *et al.*, 2014 and Schievano *et al.*, 2009), lower or null (in the case of OW) biomass supply UC determined sensibly lower total UC of energy production (Fig. 2). The UC ranged from 0.096 € $kWhe^{-1}$ (0.181 € $Nm^{-3}{}_{biogas}$) and 0.159 € $kWhe^{-1}$ (0.3 € $Nm^{-3}{}_{biogas}$). In particular, mixing DEC and BR resulted in lowering the UC, compared to the average of DEC (0.146 € $kWhe^{-1}$ and 0.275 € $Nm^{-3}{}_{biogas}$).

Discussion

The productivities of biomass/biogas/EE per hectare found in this study are relatively high, as compared to other studies (Amon *et al.*, 2007; Seppala *et al.*, 2009; Sieling *et al.*, 2013). These authors report biogas yields in other pedo-climatic contexts such as Austria, Ger-

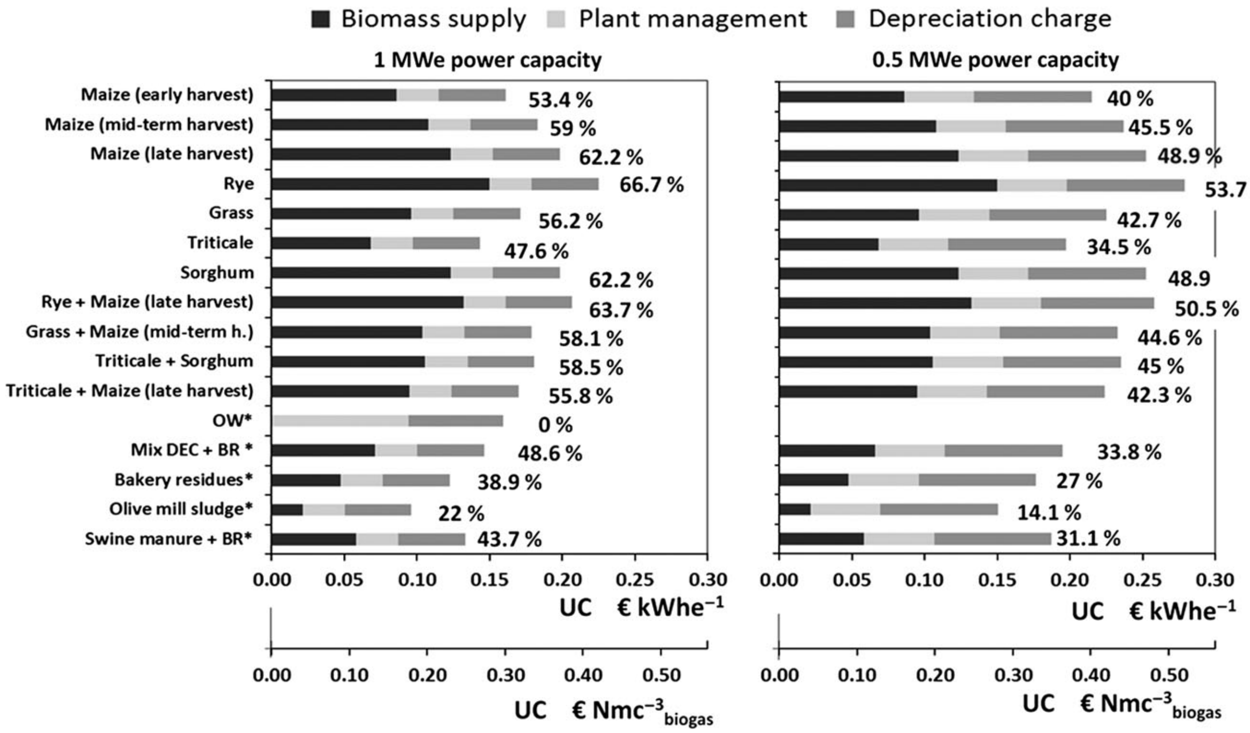

Fig. 2 Influence of biomass supply costs (indicated as percentage) on total EE generation UC. DEC are considered to cover 100% of feed. Data marked with (*) were reported in previous literature contributions (Schievano *et al.*, 2009 and Riva *et al.*, 2014).

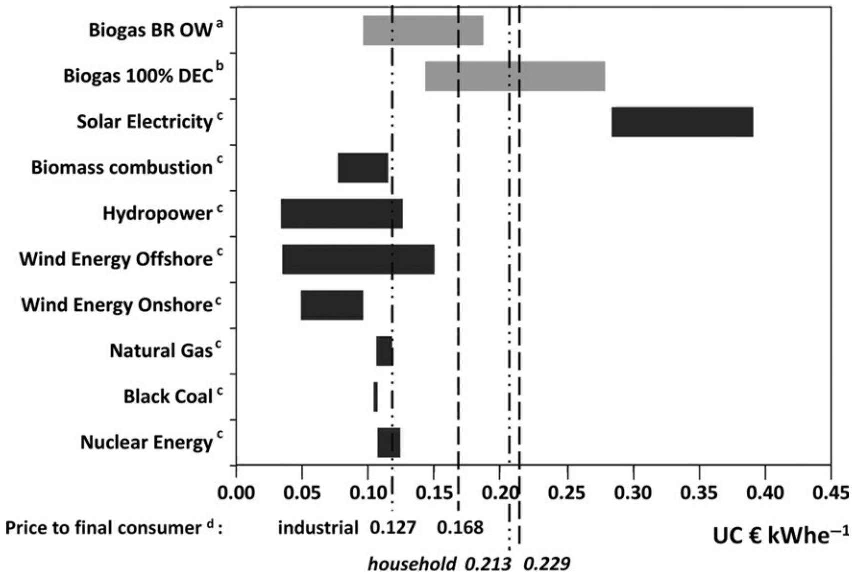

Fig. 3 UC ranges for EE production. Comparison between biogas produced from 100% DEC (this study, a), biogas produced from mixtures of DEC, BR and OW (reported by Schievano *et al.*, 2009 and Riva *et al.*, 2014; b), traditional sources and other renewables (reported by Libertini, 2013; c). Lines indicate average annual price (year 2013; Eurostat, 2014, d) of electricity to final consumer (dash lines for EU-area and dash/dot lines for Italy; regular font for industrial consumers and italic for households).

many or Sweden, of nearly 15–20% lower than in this study. This is probably due to the particular productivity of the Po-valley area that counts on high water and nutrients abundance, soil fertility and favorable climate conditions. On the other hand, all conversion factors adopted in this study were conservative and the obtained results in terms of energy production costs can be considered as reference ranges for production UC of EE from biogas. At the same time, if less conservative transformation factors were considered (CH_4 content in biogas = 65%, BMY = 93%, electrical generation yield = 42%), EE production UC (Table 3) would be reduced by mean of nearly 20%.

The UC of biogas produced from DEC were sensibly lower (0.128–0.283 € $Nm^{-3}{}_{biogas}$) than those previously published by Schievano *et al.* (2009) (0.190–0.430 € $Nm^{-3}{}_{biogas}$). In that case, Schievano *et al.* considered DEC supply cost equal to their sell prices on agricultural market. In this work, the costs of DEC production were measured directly on field, to consider the real costs of producing energy from AD of biomass, as soon as market prices are volatile and most of crops are self-produced (Ecobiogas Project, 2013).

It is important to note that single crops resulted sometimes in lower UC of biogas/energy, as the example of Triticale shows (Table 3; Fig. 2). Considering DEC, Triticale resulted in the lowest biomass supply UC (0.068 € $kWhe^{-1}$ and 0.128 € $Nm^{-3}{}_{biogas}$) and thereby in the lowest total production UC (Fig. 2). These costs resulted comparable to those obtainable from BR and OW (Fig. 2). Crop successions resulted generally in higher biomass supply UC (0.095–0.132 € $kWhe^{-1}$) and total energy UC (0.170–0.207 € $kWhe^{-1}$ for 1 MW power facilities, Fig. 2).

On the other hand, production costs must be optimized together with the minimization of land use. Between the considered DEC, the best solution appears the succession Triticale + Maize (3rd crop), with a relatively low UC (0.095 and 0.179 € $Nm^{-3}{}_{biogas}$, Table 3) and a largely lower impact on land use (28 ± 4 ha $GWhe^{-1}$ a^{-1}, Table 2). This solution would allow, in a 1 MW power facility generating around 8 GWhe a^{-1}, the production of renewable EE with 0.170 € $kWhe^{-1}$, using arable land for around 224 ha. Both cost and land use could be optimized when part of the DEC was substituted with adequate BR and/or OW (as shown in Fig. 2) and this is what should be the aim and the advantage of AD facilities. In fact, under the environmental point of view, AD compared to biomass combustion, has the important advantage of allowing the restitution of organic matter and nutrients to soil through the agronomic use of digestates and thereby preserving soil fertility.

In general, considering the range of electric power of 0.5–1 MW, electric power generation from biogas, when produced 100% from DEC, can be performed with UC that vary in the range 0.143–0.279 € $kWhe^{-1}$. When the biomass mix is 'blended' with appropriate BR and/or OW, this range could be lowered to 0.096–187 € $kWhe^{-1}$

(Figs 2 and 3). These costs can be considered for useful comparisons with other fossil-based and renewable EE sources. In a recent report, Libertini (2013) collected from different literature and institutional sources, interesting data to compare different technologies in terms of EE production costs. In this article, these data regarding some different renewable and traditional sources were reported in Fig. 3, to compare them to UC ranges resulted for biogas as electrical power generation source.

When considering biogas production from 100% DEC, EE resulted in all cases in higher UC compared to other forms of electricity, except solar electricity (Fig. 3). On the other hand, as demonstrated by a recent survey (Ecobiogas Project, 2013), feed made of 100% DEC are 'border line' cases; in Italy, over 90% of AD facilities were reported to codigest DEC with consistent amounts of BR/OW (especially animal manure). When BR and OW are considered in biomass supply mix, the production UC can be comparable to the other forms of both fossil and renewable electricity and lower than current (year 2013) prices of electricity (Eurostat, 2014) to final industrial consumers in Italy (0.168 € kWhe^{-1}) and in the EU-area (0.127 € kWhe^{-1}) (Fig. 3). This happens especially when scale factor is favorable (1 MW instead of 0.5 MW), for what concerns management/maintenance and investment UC, and when biomass supply UC are at least lower than 0.06–0.07 € kWhe^{-1}. Such low biomass supply UC can also be obtained in some case with appropriate and low-cost DEC (i.e. Triticale), but land use per energy unit could often be unacceptably high (see Triticale in Table 2).

Only a strong introduction of OW and BR and/or other biomass supply solutions could respond to the need of lowering production costs to compete with traditional/other energy sources; at the same time this would lead to reduce energy inputs, natural resources use, environmental impacts and land use per energy unit. Simultaneously, other very important steps forward must be done regarding the adopted technologies to allow strong reductions in management/maintenance and investment costs, especially for small-sized facilities (<0.5 MW). The reduction in technology costs would allow realizing biogas production at smaller scales and thereby optimizing the use of agricultural residues and local byproducts.

Finally, in the next future EU biogas sector should move, as much as possible, in the following directions:

1. adopt as much as possible the lowest-cost traditional DEC and, eventually, new crop solutions, considering at the same time also their environmental (use of primary resources and impact on soil/water ecosystems) and territorial impact (land use per energy unit);
2. progressively substitute part of DEC with available and appropriate BR and OW. This would allow simultaneous positive effects on both production costs and environmental/territorial sustainability. To drive this change to its real potentials, clearer legislation and easier procedures for the use of BR and OW should be available to operators;
3. push more efforts in research and development to allow a strong reduction in technological costs, especially for small-scale applications, which have the potential of more efficiently exploit locally available BR and OW.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Set of crops and relative parcels used for field data collection.

Table S2. Production yields, DM content and ABP obtained for each sample crop/parcel studied.