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**Planning the optimal site, size and feed of a biogas plant in agricultural districts**

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Review

# 1 Planning the optimal site, size and feed of a biogas plant in 2 agricultural districts

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## 10 ABSTRACT

11  
12 In agricultural districts biogas production is a sustainable way to valorise agro-zootechnical residues  
13 and integrate farm incomes. Biogas plant power and location strictly depend on the variability in  
14 time and space of feedstocks over a rural district. The logistic chain of feedstocks should be  
15 optimised, in order to assure the right size and the maximum profitability of the planned biogas  
16 plant.

17 A simple method is proposed to plan a biogas plant and identify the optimal blend, reducing the  
18 complexity of design and management operations. The method, requiring a reduced number of  
19 easy-to-survey input parameters, has been verified by an application to an agricultural district of  
20 Southern Italy, considering two cases usually occurring in rural areas of the Mediterranean basin.

21 If the planned plant is fed by a prevalent substrate from a single farm, the most convenient power is  
22 300 kW, this size depending also on the Italian subsidy system to renewable energy. In the case of a  
23 centralised plant, supplied by a blend of substrates, the method has provided: (i) the optimal plant  
24 location (the district barycentre weighed by the biogas potential production of each farm); (ii) the  
25 annual amounts of the different substrates in the digester blend, maximizing the plant annual profit  
26 and complying with technical-economic constraints; (iii) the nominal power of the plant (480 kW);  
27 (iv) the related annual revenues, costs and profits. The method can be applied also for other  
28 agricultural biomasses (i.e. ensiled crops or energy species available at a competitive cost, as in  
29 Northern Italy).

30  
31 **KEYWORDS:** Biomass; anaerobic digester; optimisation; logistics costs; agro-industry; livestock  
32 farm.

## 1 INTRODUCTION

Anaerobic digestion for biogas production is a commercially proven technology widely used for treating high moisture content substrate (Caputo et al., 2005), especially in rural districts where agriculture is the main activity. The substrate to be utilised in a biogas plant usually consists of energy crops (e.g. sweet sorghum, miscanthus, rape, sunflower) and/or conventional crops (e.g. maize, wheat, sugar beet), but also organic wastes can be used (e.g. agro-industrial and livestock residues, sludge from wastewater treatment plants).

The biogas plant size and location strictly depends on the variability in time and space of feedstock over a given territory; this availability should be optimised in order to assure the maximum profitability for the planned biogas plant. Often, according to the feedstock availability, a biogas plant does not operate on a specified input stream, but rather on a combination of different substrate input streams, with variable composition, which constitute the "substrate mixture" (Karellas et al., 2010). Thus, the optimal choice for identifying the most suitable substrate for a digester must take into account the variability of the physical and chemical characteristics of substrates as well as their market prices, logistic costs and local availability.

Logistics of substrate and digestate (the main by-product of anaerobic digestion) is an important determinant for biogas system to be economically, environmentally and socially viable. Biogas plants fed mainly by crops and agro-industrial residues must support costs related to storage (needed to reduce the temporal variability of substrate production) and mainly transportation (from the production sites to the plant) operations. Moreover, agro-industrial and livestock residues show a low content of dry matter per unit volume, which makes particularly expensive storage and transportation. In spite of the widely agreed potential of bioenergy utilization, these critical logistic aspects together with the optimal choice of the digester substrate strongly affect the economic and energy performances of bio-energy conversion systems, introducing limitations on their suitability (Caputo et al., 2005).

Literature reports technical and economic methods for biogas plant design and management, whose a comprehensive review is available in De Meyer et al. (2014). For instance, Caputo et al. (2005) investigated the economical feasibility of substrate utilization for direct production of electric energy by means of combustion and gasification-conversion processes over a capacity range from 5 to 50 MW. An investment decision kit for economic evaluation of biogas plant projects based on agricultural substrates was proposed by Karellas et al. (2010). The use of resource mapping to assist

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2  
3 66 in the siting of centralised anaerobic digestion schemes and to identify sources of collectable  
4 67 farmyard manure is outlined by Dagnall et al. (2000). In a work of Walla and Schneeberger (2008),  
5 68 a relationship between the capacity of a combined heat and power unit and its electrical efficiency is  
6 69 provided and a model was developed to derive cost curves for the unit costs of biogas and  
7 70 electricity production and for the transport costs for maize silage and biogas slurry. Sturmer et al.  
8 71 (2011) analysed the impacts of biogas plant performance factors on total substrate costs for two  
9 72 common biogas plant sizes in Austria and proposed a nonlinear optimization model to analyze the  
10 73 impact of alternative substrates, machinery chains, and field distances on total substrate costs of a  
11 74 250 kW and a 500 kW biogas plant.

12 75 However, many of these methods seem to be more suitable for detailed installation projects rather  
13 76 than for a preliminary feasibility assessment. In fact, these methods often require a large number of  
14 77 input variables, whose determination could be difficult and time consuming at the preliminary  
15 78 design stage. Conversely, simpler and quicker procedures, easy to implement by means of a low  
16 79 number of easy-to-survey input parameters, may be useful tools in strategic decision making (De  
17 80 Meyer et al., 2014), that is for deciding whether or not a biogas plant is viable and for assessing its  
18 81 profitability given the availability of substrate in time and space. Thus, these methods may be a  
19 82 support for stakeholders, decision makers and designers to help identify the most suitable technical  
20 83 and economic solution for each specific case before its adoption.

21 84 This work proposes an integrated method for estimating the nominal power and the profitability of  
22 85 biogas plants and, in the case of a plant fed by a number of substrates, for identifying the most  
23 86 convenient location and the optimal blend. The method requires a reduced number of easy-to-  
24 87 survey input parameters, being easy to be implemented in each specific case, but considers as many  
25 88 as possible of the variability factors mentioned above. Finally, the method has been applied and  
26 89 verified in a case study typical of many agricultural districts of Southern Italy.

27 90 The paper is organised as follows: section 2 reports the theoretical approach of the method,  
28 91 consisting of components for sizing a plant fed by a prevalent substrate (sub-section 2.1) as well as  
29 92 for positioning and sizing a plant supplied with a blend of substrates (sub-section 2.2). This latter  
30 93 component includes a sub-component for choosing the plant optimal location (sub-section 2.2.1),  
31 94 for calculating the logistic costs of substrates (sub-section 2.2.2) as well as for sizing the plant and  
32 95 choosing its optimal blend (sub-section 2.2.3). Section 3 reports the method implementation in the  
33 96 case study (sub-section 3.1), identifying the optimal size of a plant fed by a prevalent substrate (sub-  
34 97 section 3.2) and planning a plant supplied with a blend of substrates (sub-section 3.3); in the latter

case, the site (sub-section 3.3.1), the size and its optimal blend (sub-section 3.3.2) are identified in the analysed agricultural district.

## 2 METHODS

### 2.1 Foreword on the economic evaluations

In this study the economic evaluations are based on some assumptions. A simple indicator of the economic viability of the biogas plant ( $p_U$ , € kWh<sup>-1</sup>, the profit per unit of produced electrical energy, suggested also by Walla and Schneeberger, 2008) has been preferred to the traditional figures of the financial attractiveness of an investment (as the net present value, the internal rate of return and the payback period). These indicators are mainly of interest for economic analysts, rather than for technical managers to whom this work, mainly focussed on preliminary design and planning operations of plant management, is addressed. However,  $p_U$  takes into account the financial items that an investment must be consider, as the project's capital cost, projected energy (electricity and thermal energy) output and annual revenues from product (energy and digestate) sale as well as the expenses (operating costs, including substrate and financing costs) (Karellas et al., 2010). Moreover, this indicator is directly comparable with the unit subsidy - expressed in € kWh<sup>-1</sup> - to biogas production provided by the national policy to renewable energy enhancement of many countries, as Italy.

The economic evaluation of the biogas plant has considered revenues ( $R$ , € year<sup>-1</sup>) and costs ( $C$ , € year<sup>-1</sup>). The profit ( $P$ , € year<sup>-1</sup>) of the biogas plant is thus given by the difference between  $R$  and  $C$ . In general, revenues ( $R$ ) mainly derive from sale of the electrical energy ( $R_E$ , € year<sup>-1</sup>) and can be calculated as the product of the subsidized unit price to the annual production of electrical energy:

$$R_E = p_E P_n \Delta t \quad [1]$$

where:

$p_E$  = unit price of electrical energy (€ kWh<sup>-1</sup>)

$\Delta t$  = annual operating time (h year<sup>-1</sup>)

$P_n$  = nominal electrical power of the plant (kW).

131

132 When biogas slurry is sold to farmers in the vicinity of the biogas plant, the related revenue ( $R_s$ , €  
133 year<sup>-1</sup>) should be estimated and added to  $R_E$ :

134

$$135 \quad R_s = p_s S = p_s y V \quad [2]$$

136

137 being  $S = yV$  and:

138

139  $p_s$  = unit market price of slurry dry matter (DM, € t<sub>DM</sub><sup>-1</sup>)

140  $S$  = average amount of biogas slurry produced by the biogas plant (t<sub>DM</sub> year<sup>-1</sup>)

141  $y$  = slurry yield of the substrate (t<sub>DM</sub> of slurry per t<sub>DM</sub> of substrate supplied to the biogas plant)

142  $V$  = amount of substrate supplied to the biogas plant (t<sub>DM</sub> year<sup>-1</sup>).

143

144 The parameter "y" depends on eventual silage and degradation rate during fermentation; its value  
145 can be assumed equal to about 0.80 for crops (Sturmer et al., 2011) and 0.90 for organic residues  
146 (Ragazzoni, 2013).

147 Costs have been classified in Total Capital Investment (TCI, € year<sup>-1</sup>) and Total Operating Costs  
148 (TOC, € year<sup>-1</sup>) (Caputo et al., 2005).

149 Concerning the Total Capital Investment (TCI), Caputo et al. (2005) state that in general the  
150 purchased equipment costs ( $C_{PE}$ ) can be correlated to a characteristic equipment parameter (PE) by  
151 the exponential equation:

152

$$153 \quad C_{PE} = aPE^b \quad [3]$$

154

155 These Authors parameterize the costs of the different equipments (e.g. power generation, substrate  
156 storage handling, fumes treatment) in function of the plant net electric power output, the power  
157 generated by steam cycle, the gas turbine power, the substrate flow rate feeding the gasifier and the  
158 steam flow rate produced by heat recovery steam generator. In equation [3] the coefficients "a" and  
159 "b" should be calibrated in local conditions through a comparison with the market values of the  
160 electromechanical equipments or at least literature data.

161 In a simpler but reliable way, TCI, including all the equipments required by a biogas plant, can be  
162 estimated as a function of  $P_n$  by the equation reported by Ragazzoni (2013):

163

$$164 \quad TCI = C_0 \left( \frac{P_n}{P_{n0}} \right)^{2/3} \quad [4]$$

165

166 where  $C_0$  and  $P_{n0}$  are regression coefficients. This Author has calibrated this equation by the data of  
 167 35 biogas plants installed in Italy, finding for  $C_0$  and  $P_{n0}$  the values of 4 million Euros and 1 MW  
 168 respectively.

169 TCI is subject to evolutionary trends, that tend to reduce costs of the smaller biogas plants  
 170 compared to the larger plants. Therefore, equation [4] should be updated case by case considering  
 171 the actual market costs of the facilities (Zema et al., 2016).

172 Generally, the investment costs are supported partly by private funds (by a ratio "f") and partly by  
 173 recurring to the capital market; the related financial costs (FC) must be shared yearly along the plant  
 174 life by multiplying the expression  $(1 - f) TCI$  for a coefficient "m" giving the annual payment,  
 175 according to the following equation:

$$177 \quad FC = m (1 - f) TCI = \frac{rq^n}{q^n - 1} (1 - f) TCI \quad [5]$$

178

179 being:

180

181  $r =$  interest rate (%)182  $q = 1 + r$ 183  $n =$  investment duration (years), assumed to be equal to the plant lifespan.

184

185 The amortisation of the private funds ( $AP = f/n TCI$ , € year<sup>-1</sup>) supporting TCI can be simply  
 186 calculated dividing the related share by the plant lifespan "n" (years).

187 For "n", values in the range from 13-15 (Walla and Schneeberger, 2008; Tricase and Lombardi,  
 188 2009) to 20 (Caputo et al., 2005; Jenkins, 1997; Gebrezgabher et al., 2010) are suggested.

189

190 Total Operating Costs (TOC) can be classified in (Caputo et al., 2005):

- 191 - Management Costs (MC), consisting in operating labour (manpower), plant maintenance,  
 192 insurance and taxes;
- 193 - costs of substrate supply to the biogas plant (BC);

1  
2  
3 194 - costs of slurry transport and land spreading (SC), when it is not sold to farmers and enough  
4 195 land is available.

5  
6 196 Values of MC are difficult to be evaluated, being such costs strictly related to each specific case. In  
7  
8 197 general, it can be assumed that the unit MC (that is the management cost per unit power of the  
9  
10 198 plant) increases with the reduction of the plant size, due to the presence of fixed costs (Ragazzoni,  
11  
12 199 2013). The same Author, by using the data of the analysed biogas plants, integrated by literature  
13  
14 200 data, reports that on the Italian market unit MC can be approximately expressed as a function of  $P_n$   
15  
16 201 by an equation with the same mathematical structure of [3]:

17 202  
18 203  $MC = 0.3P_n^{-1/3}$  [6]

19 204  
20  
21 205 BC include substrate purchase, storage and transport costs, which weigh noticeably on the plant  
22  
23 206 profit and must be analysed in detail for each specific case. These costs will be evaluated in the  
24  
25 207 following with reference to the DM unit weight.

26 208 Often the biogas slurry is returned to the suppliers of the substrate (Walla and Schneeberger, 2008)  
27  
28 209 or directly used by the plant owners as soil conditioner/fertiliser (Sturmer et al., 2011), provided  
29  
30 210 that enough land for its spreading is available. In the first case, the transport costs of slurry are  
31  
32 211 charged to suppliers, while in the latter case transport and land spreading costs must be evaluated.

33 212 SC depend on many factors, as the nitrogen requirements of crops, the nitrogen concentration of  
34  
35 213 biogas slurry, the transport distance and the capacity of the slurry spreader (Sturmer et al., 2011) as  
36  
37 214 well as the environmental constraints limiting nitrogen application on soils (for instance in Nitrate  
38  
39 215 Vulnerable Zones, Dagnall et al., 2000) or nitrogen leaching in surface and deep water bodies.  
40  
41 216 Sturmer et al. (2011) reports an analytical method for evaluating slurry spreading costs for biogas  
42  
43 217 plants fed by energy crops as a function of different parameters (transport distances to fields, trailer  
44  
45 218 transport capacity, crop dry matter content, nitrogen content in the biogas slurry, nitrogen losses  
46  
47 219 during manure spreading, silage intake, degradation rate during fermentation and substrate yields).  
48  
49 220 Considering the number of these factors and the peculiarity of each case, SC is generally very  
50  
51 221 difficult to evaluate. For preliminary feasibility assessment, as in this study, a simplified procedure  
52  
53 222 can be suggested, as follows:

54 223  
55 224  $SC = yV (c_{LS} + c_T)$  [7]

56 225  
57 226 where SC is measured in  $\text{€ year}^{-1}$  and:

227

228  $c_{LS}$  = cost of slurry land spreading per weight unit ( $\text{€ t}_{DM}^{-1}$ )229  $c_T$  = transport costs per weight unit ( $\text{€ t}_{DM}^{-1}$ )

230

231 A method for evaluating  $c_T$  will be presented in the next section.

232

233

234 **2.2 Sizing a biogas plant fed by a prevalent substrate**

235

236 This is the case that a firm owner wants to produce electrical energy by a biogas plant exploiting the  
 237 residual substrate from its agro-industrial or livestock activity (in the following indicated as "self-  
 238 produced" or "prevalent" substrate). Thus, the biogas plant is located in the same site and fed  
 239 prevalently by the self-produced substrate. Size (i.e. the nominal electric power  $P_n$ ) and the plant  
 240 profit per unit of produced electrical energy ( $p_U$ ) can be evaluated as follows. Of course,  $P_n$  is the  
 241 value which maximizes  $p_U$ .

242 Showing most of agro-industrial by-products a high variability in time (seasonal and inter-annual),  
 243 storage is needed to assure a continuous feeding rate of substrate to the digester along the year.  
 244 Storage costs depend on many factors, as the site characteristics as well as facilities and machinery  
 245 availability in the agro-industry or livestock farm. Storage costs ( $C_S$ ,  $\text{€ year}^{-1}$ ) can be assumed equal  
 246 to the annual amortisation of facilities and machinery as well as manpower for handling and  
 247 estimated as:

248

249 
$$C_S = c_S s W \quad [8]$$

250

251 where:

252

253  $c_S$  = storage cost of the substrate unit weight ( $\text{€ t}_{DM}^{-1}$ )254  $s$  = incidence of substrate excess over the average monthly production ( $0 \div 1$ )255  $W$  = production of substrate ( $\text{t}_{DM} \text{ year}^{-1}$ ).

256

257 Of course,  $W$  must not be lower than the amount fed into the digester ( $V$ ).

258 In some cases, the produced substrate contains inhibiting compounds (for example polyphenols in  
 259 the residues of olive oil mills and essential oils in those of citrus industries), which may induce

260 block or noticeable slowdown of biogas production rates in the digester. To avoid these problems in  
 261 the biochemical processes, the concentration of such residues in the digester feed must be limited by  
 262 dilution with water or blending the self-produced biomass with other substrates (mainly supplied  
 263 from external sources). Athanasoulia (2012) and Forgács (2012) report limits of 20% of olive  
 264 residues and 70% of citrus wastewater and by-products in the digester blend.

265 The profit from the plant management ( $P$ , € year<sup>-1</sup>) is:

$$266 \quad P = R_E + R_S - AP - m(1-f)TCI - MC - C_S - SC \quad [9]$$

268  
 269 Expanding [9], the following equation is obtained:

$$270 \quad P = p_E k Y V + p_S y V - \left( \frac{f}{n} + \frac{r q^n}{q^n - 1} (1-f) \right) C_0 \left( \frac{P_n}{P_{n0}} \right)^{2/3} - 0.3 P_n^{-1/3} - c_S s W - y V (c_{LS} + c_T) \quad [10]$$

272  
 273 where:

274  
 275  $k$  = coefficient of conversion of the produced biogas volume in electrical energy (kWh m<sup>-3</sup>)

276  $Y$  = biogas yield of the substrate DM unit (m<sup>3</sup> t<sub>DM</sub><sup>-1</sup>).

277  
 278 As suggested by Dagnall et al. (2000) and Jenkins, 1997, the potential production of  
 279 biogas/methane can be directly related to DM content of the substrates and the energy yield of each  
 280 substrate expressed per DM unit. In other words, the annual production of electrical energy is given  
 281 by the product of the biogas yield by the amount of substrate supplied to the digester (which gives  
 282 the annual biogas production) and the electricity yield of the biogas unit volume.

283 In this study, the estimates of methane yield of the biogas plant has been estimated from literature  
 284 data, since a reliable value of plant technical performance can not be obtained at the preliminary  
 285 design stage. Conversely, in subsequent design steps, - as, for example, in the executive project  
 286 drafting, - the efficiency of the biogas plant is known and thus the real biogas and electrical energy  
 287 yields can be precisely evaluated.

288 The coefficient “ $k$ ” is usually assumed in 1.9 kWh per m<sup>3</sup> of produced biogas (Tricase and  
 289 Lombardi, 2009), but it also must consider the reduction of the gross power output due to the  
 290 energy requirement for plant's auxiliary equipment running (pumps, blowers, fans, feeding systems,

291 separators, etc., Karellas et al., 2010). This reduction has been assumed equal to 80% (Tricase and  
292 Lombardi, 2009) or 85% (Karellas et al., 2010).

293

294 P can also be expressed in relation to the total energy produced per year, thus obtaining  $p_U$ :

295

$$296 \quad p_U = \frac{P}{P_n \Delta t} \quad [11]$$

297

298 The total energy produced per year by a renewable energy plant is strongly dependent on  $\Delta t$  (Zema  
299 et al., 2016); literature suggests values from 6750-7000 (Jenkins, 1997; Walla and Schneeberger,  
300 2008) to 8000-8200 (Caputo et al., 2005; Sturmer et al., 2011) hours per year.

301  $P_n$  can be expressed as:

302

$$303 \quad P_n = \frac{kYV}{\Delta t} \quad [12]$$

304

305 Obviously, the biogas plant size corresponds to  $P_n$  maximizing the profit ( $P$  or  $p_U$ ). It can be  
306 calculated as the value of  $P_n$  which makes null the derivative function of [10], after replacing  $V$ ,  
307 which is a function of  $P_n$  (see equation [12]), in [10]). A flow-chart reporting the different steps of  
308 the proposed method is shown in Figure 1a.

309

310

### 311 **2.3 Positioning and sizing a biogas plant supplied with a blend of substrate**

312

#### 313 *2.3.1 Choice of the biogas plant optimal location*

314

315 An alternative to a single biogas plant installed within a firm could be a *consortium* of various firm  
316 owners; they can decide to share their production of wastewater and by-products to feed a common  
317 biogas plant. This allows the increase of the plant power and the reduction of technical problems  
318 due to the presence of inhibiting compounds in the digester feed.

319 In this case the planned biogas plant is fed by a blend of different substrates supplied from various  
320 sites. Therefore, it is required to identify the optimal location of the centralised plant, in order to  
321 minimize the total logistic costs.

322 When considering centralised biogas plants, the logistic issues are complicated in that several  
 323 substrate types, having different DM compositions, are involved; as biogas production may be  
 324 assumed to be proportional to the DM content, data are produced on a tonnes DM basis in order to  
 325 put the different substrates on a comparable basis (Dagnall et al., 2000).

326 For identifying the most convenient plant site, one of the locating *criteria* could be identified in  
 327 locating the biogas plant in the geometric barycentre of the supplying district. However, this  
 328 *criterion* may be misleading, since the annual availability and the biogas yield of each substrate are  
 329 not considered in calculations. In this study an alternative *criterion* is proposed, considering the  
 330 biogas potential production of each substrate source (agro-industries and livestock farms) in a given  
 331 district.

332 If the biogas plant is fed only by one type of substrate supplied from different production sites, the  
 333 annual substrate availability at each supplying site can be utilised as weight for calculating the  
 334 position of the barycentre. In this case the coordinates  $\bar{X}$  and  $\bar{Y}$  of the district barycentre are given  
 335 by the following formulas:

$$337 \quad \bar{X} = \frac{\sum_{i=1}^t W_i x_i}{\sum_{i=1}^t W_i} \quad [13]$$

$$338 \quad \bar{Y} = \frac{\sum_{i=1}^t W_i y_i}{\sum_{i=1}^t W_i} \quad [14]$$

339

340 where:

341

342  $x_i, y_i$  = geographical coordinates of the biomass production source "i"

343  $t$  = number of biomass production sources

344  $W_i$  = biomass production sources [ $t_{DM} \text{ year}^{-1}$ ]

345

346 If the biogas plant is instead fed by a blend of different substrates, it is necessary to take into  
 347 account not only the substrate availability, but also the biogas yield of each substrate. In this case  
 348 the weight for barycentre calculation could be the product of annual substrate availability to the

349 biogas yield of each substrate; in other words, the weight is the biogas potential production of each  
 350 supplying site. In this case the coordinates  $\bar{X}$  and  $\bar{Y}$  of the district barycentre are the following:

351

$$352 \quad \bar{X} = \frac{\sum_{i=1}^t W_i Y_i X_i}{\sum_{i=1}^t W_i Y_i} \quad [15]$$

$$353 \quad \bar{Y} = \frac{\sum_{i=1}^t W_i Y_i Y_i}{\sum_{i=1}^t W_i Y_i} \quad [16]$$

354

355 being  $Y_i$  the biogas yield of the substrate produced by the source "i" ( $\text{m}^3 \text{t}_{\text{DM}}^{-1}$ ).

356

357 In economical evaluations, the fees for rental or the purchase amortisation of land hosting the  
 358 biogas plant should be considered. However, its value being often low (for instance, in Calabria  
 359 region the purchase price of the agricultural or pasture land ranges from 1 to 5 € per squared metre),  
 360 this share can be neglected.

361

362

### 363 2.3.2 Calculation of the substrate costs

364

365 In relation to the logistics aspects, beside substrate storage costs, also purchase prices (except when  
 366 substrate has null market values) and transport costs must be considered.

367 Purchase price of the substrates at the production sites varies noticeably. Generally, agro-industrial  
 368 and livestock residues are available at null price; some substrates (e.g. the organic fraction of urban  
 369 waste) show even negative prices, that could be assumed equal to disposal costs. Agro-industrial  
 370 wastes from food processing and preparation activities are usually assumed to be available at the  
 371 costs of transport (Dagnall et al., 2000).

372 Substrate and digestate transport has a significant effect on biogas plant economy. The costs of  
 373 these transport operations should therefore be minimized.

374 Transport costs ( $C_T$ , € year<sup>-1</sup>) from a production site to the biogas plant location depend on several  
 375 factors, as distance, road characteristics, size and type of means of transport, load and unloading  
 376 times. The economical incidence on running operations of the biogas plant depends noticeably on

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2  
3 377 transport costs per weight unit ( $c_T$ , €  $t_{DM}^{-1}$ ). This unit cost consists of a fixed ( $K_f$ , €  $t_{DM}^{-1}$ ) and a  
4 378 variable share ( $K_v$ , €  $t_{DM}^{-1} km^{-1}$ ) - this latter related to the transport distance ( $L$ , km), according to  
5  
6 379 the equation:  
7

8 380

$$9 \quad 381 \quad c_T = K_f + K_v L \quad [17]$$

10  
11 382

12  
13 383 Therefore, operations for substrate supplying from different sources (in the following indicated as  
14 384 "external" or "additional" substrates) show an annual cost ( $C_A$ , €  $year^{-1}$ ) equal to:  
15

16 385

$$17 \quad 386 \quad C_A = C_P + C_T = (c_P + c_T) V' = (c_P + K_f + K_v L) V' \quad [18]$$

18  
19 387

20  
21 388 where  $C_P$  is the total cost (€  $year^{-1}$ ) and  $c_P$  is the unit price (€  $t_{DM}^{-1}$ ) for purchasing the additional  
22 389 substrate amount ( $V'$ ,  $t_{DM} year^{-1}$ ), coming from external sources, to feed the digester.

23  
24 390 An equation with the same mathematical structure of [17] allows also the evaluation of the unit cost  
25 391  $c_{LS}$  to be used for the analysis of the economic incidence of slurry land spreading, provided that the  
26 392 fixed and the variable unit costs of the related operations are input. The distance of slurry land  
27 393 spreading ( $l$ , km) can be evaluated by the following equation (suggested by Walla and  
28 394 Schneeberger, 2008), hypothesing that the available land has a circular shape of radius " $l$ " and its  
29 395 center is located on the biogas plant site:  
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$$36 \quad 397 \quad l = 10 \sqrt{\frac{y V'}{\pi s_{max}}} \quad [19]$$

37  
38  
39 398

40  
41 399 In equation [19]  $s_{max}$  ( $t_{DM} ha^{-1} year^{-1}$ ) is the maximum soil application rate of slurry dry matter,  
42 400 which can be adopted (generally according to national rules), in order to avoid pollution of soils and  
43 401 water bodies. The parameter  $s_{max}$  is often expressed in tons of nitrogen; conversion from units of N  
44 402 to DM contained in the slurry can be made for example by the method reported by Sturmer et al.  
45 403 (2011) for energy crops or by other procedures available in literature for residual substrates.

46 404 For the parameters " $L$ " and " $l$ " some Authors indicate a viable maximum distance of 15-25 km (e.g.  
47 405 Poliafico and Murphy, 2007), which must be reduced to 10 km for substrates with low DM content  
48 406 (<10%, Dagnall et al., 2000).  
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### 2.3.3 Size of the biogas plant and choice of the optimal blend

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411 After siting the biogas plant, its size (in terms of  $P_n$ ) and the amounts of different substrates in the  
 412 blend to be yearly supplied from each production site must be quantified. The choice must take into  
 413 account not only the annual availability and biogas yield of each substrate, but also other technical-  
 414 economic constraints.

415 The optimal solution must maximize the annual profit ( $P$ ) of the plant. This solution can be found  
 416 by a non linear programming algorithm, given the functional dependence of  $P$  on the power  
 417 expression of equations [4], [6] and [19]. The annual amounts of the different substrates composing  
 418 the digester blend are chosen as independent variables and the technical-economic constraints are  
 419 mathematically specified.

420 The maximum  $P$  could be found by the following equation:

421

$$422 \max P = \max [R - AP - m(1-f)TCI - MC - BC - SC] = \max [R_E + R_S - AP - m(1-f)TCI - MC - C_S - C_P - C_T - SC] \quad [20]$$

423

424 Expanding [16], the following equation is obtained:

425

$$426 \max P = \max \left\{ p_E k \sum_{i=1}^N Y_i V_i + p_S y V - \left[ \left( \frac{f}{n} + \frac{r q^n}{q^n - 1} (1-f) \right) C_0 \left( \frac{P_n}{P_{n0}} \right)^{2/3} \right] - 0.3 P_n^{-1/3} - \sum_{i=1}^N c_{S,i} V_i - \sum_{i=1}^N C_{P,i} V_i - \sum_{i=1}^N (K_{r,i} + K_{v,i} L_i) V_i \right\} - \quad [21]$$

$$- y V \left[ c_{LS} + \left( K_{r,S} + 10 K_{v,S} \sqrt{\frac{y V}{\pi S_{max}}} \right) \right]$$

427

428 with the following mathematical conditions:

429

$$430 V = \sum_{i=1}^N V_i \quad [22]$$

431

$$432 0 \leq V_i \leq D_i \quad [23]$$

433

$$434 z_i = V_i / V \leq \bar{z}_i \quad [24]$$

435

436 or

437

$$j_i = V_i/V \geq \bar{j}_i \quad [25]$$

439

440 where:

441

442  $Y_i$  = biogas yield of the substrate "i" ( $\text{m}^3 \text{t}_{\text{DM}}^{-1}$ )443  $V_i$  = amount of the substrate "i" ( $\text{t}_{\text{DM}} \text{year}^{-1}$ )444  $V$  = total amount of the digester blend ( $\text{t}_{\text{DM}} \text{year}^{-1}$ )445  $N$  = number of substrates in the digester blend446  $c_{p,i}$  = purchase price of the substrate "i" ( $\text{€ t}_{\text{DM}}^{-1}$ )447  $c_{s,i}$  = storage unit cost of the substrate "i" ( $\text{€ t}_{\text{DM}}^{-1}$ )448  $K_{f,i}$  = unit fixed cost for transport of the substrate "i" ( $\text{€ t}_{\text{DM}}^{-1}$ )449  $K_{v,i}$  = unit variable cost for transport of the substrate "i" ( $\text{€ t}_{\text{DM}}^{-1} \text{km}^{-1}$ )450  $K_{f,S}$  = unit fixed cost for transport of the biogas slurry ( $\text{€ t}_{\text{DM}}^{-1}$ )451  $K_{v,S}$  = unit variable cost for transport of the biogas slurry ( $\text{€ t}_{\text{DM}}^{-1} \text{km}^{-1}$ )452  $L_i$  = transport distance for the substrate "i" (km)453  $D_i$  = available amount of the substrate "i" at the firm ( $\text{t}_{\text{DM}} \text{year}^{-1}$ )454  $z_i$  = incidence of the substrate "i" in the digester blend ( $0 \div 1$ )455  $\bar{z}_i$  = maximum incidence of the substrate "i" in the digester blend ( $0 \div 1$ )456  $\bar{j}_i$  = minimum incidence of the substrate "i" in the digester blend ( $0 \div 1$ ).

457

458 Equation [23] establishes that the amount of each substrate supplied to the digester must be always  
 459 positive or null and lower than its annual availability at the production site (which could be slightly  
 460 different from the production "W", see equation [8] in section 2.2). Equations [24] and [25] express  
 461 eventual minimum or maximum limits of the content of a given substrate in the blend due to  
 462 technological constraints (for instance the presence of inhibiting compounds) and/or  
 463 legislative/economic constraints (for instance the minimum/maximum percentages of some types of  
 464 substrates in the blend reported by some national rules, as M.D. 6/7/2012 in Italy). Of course,  
 465 equations [24] and [25] must be consistent with the additional condition:

466

$$\sum_{i=1}^N x_i = \frac{1}{V} \sum_{i=1}^N V_i = 1 \quad [26]$$

468

1  
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3 469 In other words, the sum of the incidence ( $0 \div 1$ ) of each substrate in the blend to supply from external  
4 470 sites must be equal to 1.

5  
6 471 Finally, the nominal power of the biogas plant  $P_n$  can be calculated by the following equation:  
7

8 472

9  
10 473 
$$P_n = \frac{k}{\Delta t} \sum_{i=1}^N Y_i V_i$$
 [27]  
11  
12

13 474

14 475 Figure 1b reports the scheme of the proposed method.  
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## 18 478 **3 RESULTS AND DISCUSSIONS**

19 479

### 20 480 **3.1 Method implementation in the case study**

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22  
23 482 The method has been applied and verified in an agricultural district of Calabria, Southern Italy, in  
24 483 which the following largest agro-industries and livestock farm have been selected (Figure 2):

- 25  
26 484 - an olive oil mill processing 3350 t of olives per year;  
27 485 - four citrus processing industries with a working capacity ranging from 5000 to 10000 t of  
28 486 oranges per year;  
29 487 - a livestock farm with about 1000 cows.  
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37 489

Figure 2

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39 491 The following work hypotheses have been adopted:

- 40  
41 492 - the Total Capital Investment (TCI) of the biogas plant is supported by private funds (20%)  
42 493 and a 20-year loan (80%);  
43 494 - the interest rate on the borrowed capital is assumed equal to 4.5% (current average value for  
44 495 the Italian capital market);  
45 496 - a share of the 85% of the electrical energy produced is sold to GSE ("Gestore Servizi  
46 497 Energetici", the Italian agency for energy service management), while the remaining part is  
47 498 consumed in the plant (see also section 2.2);  
48 499 - for the plant lifespan and the annual operation time ( $\Delta t$ ) the values of 20 years and 8000  
49 500 hours have been adopted (see also section 2.2);  
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3 501 - the average biogas yields have been estimated in  $350 \text{ m}^3 \text{ t}_{\text{DM}}^{-1}$  for the olive residues,  $600 \text{ m}^3$   
4 502  $\text{t}_{\text{DM}}^{-1}$  for the citrus residues,  $250 \text{ m}^3 \text{ t}_{\text{DM}}^{-1}$  for livestock residues, as suggested by Forgács  
5  
6 503 (2012); Bordoni et al. (2010); Mantovi et al. (2013).

7  
8 504 Concerning the plant revenue from the electricity sale ( $R_E$ ), the following subsidized prices have  
9  
10 505 been assumed (drawn from the M.D. 6/7/2012 for the energy production system in Italy):

- 11 506 -  $0.236 \text{ € kWh}^{-1}$  for  $1 < P_n \leq 300 \text{ kW}$   
12  
13 507 -  $0.206 \text{ € kWh}^{-1}$  for  $301 < P_n \leq 600 \text{ kW}$   
14  
15 508 -  $0.178 \text{ € kWh}^{-1}$  for  $601 < P_n \leq 1000 \text{ kW}$ .

16 509 The use of the digestate as soil conditioner/fertilizer has not be considered in this case study,  
17  
18 510 because in Southern Italy usually digestate production is returned to the suppliers of the substrate  
19  
20 511 (about 40-50%) and to external farmers (for the remaining part) and directly used as soil  
21  
22 512 conditioner/fertiliser by farmers/suppliers without costs or revenues for the biogas plant owners.

23 513 In relation to the costs of substrate supply to the biogas plant (BC), the storage unit costs ( $c_S$ ) have  
24  
25 514 been estimated for typical facilities of the rural territory of Southern Italy by economical  
26  
27 515 evaluations on field. For livestock farms  $c_S$  is null, due to the continuous production of manure and  
28  
29 516 livestock wastewater along the year. As it usually happens in Calabria and Sicily, for the olive oil  
30  
31 517 mill and the citrus processing industries the use of a waterproof earth tank has been hypothesized  
32  
33 518 for storage of wastewater, while storage in horizontal tanks made of reinforced concrete has been  
34  
35 519 assumed for solid by-products (olive pomace and orange peel). Earth and concrete tanks have got  
36  
37 520 amortisation costs of  $0.2 \text{ € m}^{-3} \text{ year}^{-1}$  in 10 years and of  $1.5 \text{ € m}^{-3} \text{ year}^{-1}$  in 20 years respectively  
38  
39 521 (both calculated by market prices of materials). About 55% (olive oil mills) and 50% (citrus  
40  
41 522 processing industries) of the substrate production must be stored each year: these values represent  
42  
43 523 the percentages of biomass exceeding the average annual production of residues in the aggro-  
44  
45 524 industries. Therefore,  $c_S$  vary from  $1.22 \text{ € t}_{\text{DM}}^{-1}$  (olive oil mill wastewater) to  $2.04 \text{ € t}_{\text{DM}}^{-1}$  (citrus  
46  
47 525 processing wastewater) and from  $6.95 \text{ € t}_{\text{DM}}^{-1}$  (citrus peel) to  $8.25 \text{ € t}_{\text{DM}}^{-1}$  (olive pomace) and this  
48  
49 526 variability depends on the different DM content. Based on these ranges, in our calculations a mean  
50  
51 527 value of  $4.74 \text{ € t}_{\text{DM}}^{-1}$  (olive oil mill) and  $4.50$  (citrus processing industries) for  $c_S$  have been  
52  
53 528 assumed (Table 1).

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532 **3.2 Optimal size of a biogas plant fed by a prevalent substrate**

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534 By applying the method reported in the sections 2.1 and 2.2, the estimation of the optimal size of a  
535 biogas plant fed by a prevalent substrate has been operated separately for the olive oil mill, the  
536 citrus processing industries and the livestock farm.

537 The most convenient  $P_n$  has been estimated in 300 kW; this value corresponds to the upper limit of  
538 the subsidized prices for the smallest biogas plants (that is between 1 and 300 kW) provided by the  
539 Italian laws (Figure 3). For this optimal plant power (300 kW), the livestock farm shows the  
540 maximum unit profit ( $p_U = 0.137 \text{ € kWh}^{-1}$ ), due to the absence of storage costs, while the olive oil  
541 mill and the citrus processing industries provide  $p_U$  lower than 6% and 3.5% compared to the  
542 livestock farm (Table 1).

543

Table 1

544

545 For the other slots of nominal power, the most profitable  $P_n$  are 600 (301-600 kW) and 1 MW (601-  
546 1000 kW) (Figure 3);  $p_U$  decreases by 7-8% ( $P_n = 600 \text{ kW}$ ) and 19-20% ( $P_n = 1 \text{ MW}$ ) compared to  
547 plants with  $P_n$  equal to 300 kW.

548

549

Figure 3

550

551 Figures 4a, b and c report for different plant size the unit cost, revenue and profit of a biogas plant  
552 installed in the agro-industries (olive oil mill or citrus processing industries) and livestock farm  
553 exploiting prevalently self-produced residues. Total unit costs follow an exponential variability law  
554 (which can be interpolated,  $r^2 > 0.98$ , by the equation  $\text{TOC} = 0.658 P_n^{-0.332}$ , (Ragazzoni, 2013), very  
555 similar to the variability law of the management costs. MC and financial costs represent about 90%  
556 of total unit costs.

557

558

Figure 4a, b, c

559

560 The unit profit ( $p_U$ ) varies with the same mathematical law as total unit costs ( $r^2 > 0.98$ ). Exponents  
561 of the regression equations in each range of  $P_n$  (corresponding to the subsidy slots provided by the  
562 Italian law) decreases from 0.73 (olive oil mill, in the range 0-300 kW) to 0.07 (livestock farm, in

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3 563 the range 601-1000 kW) with slight differences among the three types of agro-industries/livestock  
4 564 farms studied.

5  
6 565 The method allows also the estimation of the substrate requirement and the consequent working  
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8 566 capacity (giving the maximum profit from energy exploitation) of a given firm. This capacity can be  
9  
10 567 simply estimated from the biomass production of the firms, divided by the coefficients of residue  
11  
12 568 yield (wastewater and pomace/peel for the agro-industries or manure for the livestock farms) and  
13 569 the unit content of DM in these residues (easy to find in literature).

14 570 This working capacity is about 2000 animals for the livestock farm (Table 1). For the olive oil mill  
15 571 and citrus industries the calculated working capacity (about 19500 t year<sup>-1</sup> of processed olives and  
16 572 citrus, Table 1) is only theoretical, because it is necessary to take into account the presence of  
17 573 inhibiting compounds in these agro-industrial residues. Therefore, it is necessary to supply substrate  
18 574 from external sources, in order to achieve the biogas plant optimal power.

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20  
21 575 Table 2 reports the nominal power and the unit profit of a biogas plant, located in one of the six  
22 576 firms of the case study and using prevalently the self-produced substrate. These parameters have  
23 577 been evaluated by the method previously arranged for their average working capacity; the required  
24 578 substrate amounts have been also quantified.

25 579

26 580

Table 2

27 581

28 582 Due to the relatively low firm size, in order to size the biogas plant power at 300 kW, additional  
29 583 amounts of substrate must be purchased and transported from external sources. Purchase costs ( $C_P$ )  
30 584 have been considered null.

31 585 In the analysed district transports are usually operated by tankers for liquid substrate and trucks for  
32 586 solid residues. The values of  $K_f$  and  $K_v$  have been estimated from local market prices of insurance,  
33 587 manpower (loading, unloading, driving), fuel, lubricants and maintenance, beside machine  
34 588 amortisation. Thus, the following values of the parameters for calculating  $C_T$  have been estimated:  
35 589 for the fix share ( $K_f$ ), 1.00 € m<sup>-3</sup> for tankers and 1.20 € m<sup>-3</sup> for trucks, while, for the variable share  
36 590 ( $K_v$ ), 0.08 € m<sup>-3</sup> km<sup>-1</sup> for tankers and 0.09 € m<sup>-3</sup> km<sup>-1</sup> for trucks. Based on the different DM contents  
37 591 of the agro-industrial and livestock residues, in our calculations the following values of  $C_T$  have  
38 592 been used (Table 2): for  $K_f$  11.56, (olive residues), 15.56 (citrus residues) and 9.16 (livestock  
39 593 residues) € t<sub>DM</sub><sup>-1</sup>, while, for  $K_v$ , 0.89 (olive residues), 1.22 (citrus residues) and 0.71 (livestock  
40 594 residues) € t<sub>DM</sub><sup>-1</sup> km<sup>-1</sup>.

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3 595 Furthermore, it has been hypothesized that the agro-industries supply the additional substrate from  
4 596 the livestock farm (in order to avoid problems for biochemical processes into the digester due to the  
5 597 presence of inhibiting compounds in substrate), while the livestock farm transports the additional  
6 598 feed from the closest citrus industry (“A”); the maximum incidence of olive residues and citrus by-  
7 599 products into the digester feed have been limited to 20 and 70% respectively (see section 2.2).  
8 600 Plant power of the olive oil mill (201 kW) is limited by the insufficient livestock residues; for the  
9 601 other firms all the self-produced substrate can be exploited by the optimal size of the planned biogas  
10 602 plant (300 kW) (Table 2). In spite of that, the agro-industries must supply much of the required  
11 603 substrate from external sources (from 57%, for citrus industry "C", to 80%, for the olive oil mill,  
12 604 Table 2) with high costs for transportation.  
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### 23 607 **3.3 Design of a biogas plant supplied with a blend of substrates**

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26 609 In the case of a centralised biogas plant, the digester is supplied by a blend of the different residues  
27 610 produced by the *consortium*, whose percentages should be planned. Moreover, the most convenient  
28 611 plant site must be chosen and the optimal power must be sized.  
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#### 34 614 **3.3.1 Choice of the optimal site**

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37 616 Considering the values of the biogas yield for the different substrates, as reported in section 3.1, the  
38 617 potential energy production of each supplying firm has been evaluated; this parameter has been  
39 618 considered as the weight for calculating the barycentre of the agricultural district where to locate  
40 619 most conveniently the biogas plant. In our case study, the barycentre provided by the calculations is  
41 620 located 2 km from the citrus industry “D” (Figure 2).  
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#### 49 623 **3.3.2 Size of the biogas plant and choice of the optimal blend**

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52 625 By applying the algorithm of Generalized Reduced Gradient for nonlinear optimisation (developed  
53 626 by Lasdon and Waren, 1978) as algorithm of operational research reported in section 2.3.3, the  
54 627 amounts of the different substrates composing the digester blend have been quantified; these  
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628 percentages provide the optimal solution which maximizes the plant profit and comply to the  
629 technical-economic constraints mentioned above (annual amounts lower than the availability,  
630 incidence of olive and citrus residues in the digester blend lower than 20% and 70%).

631 The results of the case study show that the biogas plant should be fed by all the by-products and  
632 wastewater produced by the livestock farm, the citrus industries “A”, “B” and “D” and the olive oil  
633 mill. Conversely, the residues produced by the citrus industry “C” should be entirely discarded due  
634 to the high distance (more than 20 km) of the firm from the planned plant site. From equations [17]  
635 and [20], the percentage of each substrate calculated for the digester blend are 12% (olive residues),  
636 39% (citrus residues) and 49% (livestock residues).

637 The nominal power ( $P_n$ ) of the biogas plant, estimated by equation [27], is 480 kW and its TCI is  
638 2.45 M€ (from equation [4]). From Table 3, which reports the revenues, costs and profit of the  
639 planned biogas plant, it is evident that TCI weighs on the total costs by 38%, while MC and BC  
640 (composing TCO) represent shares of 32.5% and 29.5% respectively. The incidence of BC on total  
641 costs of this case study is comparable with findings by Karellas et al. (2010) (27.3%) and much  
642 lower than the values reported by Caputo et al. (2005) and Walla and Schneeberger (2008) (> 50%).  
643 The installation of two smaller biogas plants (each one of  $P_n$  close to 300 kW) could be evaluated as  
644 an alternative to the power calculated for a single plant (480 kW), in order to further maximize the  
645 profitability of the entire investment. The optimal location of each biogas plant can be identified by  
646 applying the method (for locating the barycentre and calculate costs and profits) to two separate  
647 areas of the agricultural district.

648

649

Table 3

650

#### 651 **4 CONCLUSIONS**

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653 A method is proposed to size a biogas plant as well as to locate it and identify the optimal blend (in  
654 case of plant fed by different substrates) for energy production from substrate. It has been verified  
655 by an application in agro-industries (olive oil mills and citrus industries) and livestock farms of an  
656 agricultural district of Southern Italy.

657 If the biogas plant is fed by a prevalent substrate produced by a single farm, it emerges that the most  
658 convenient nominal power is 300 kW; this outcome strictly depends on the subsidy system to  
659 renewable energy in Italy. The livestock farm shows the maximum unit profit. Due to the relatively  
660 low firm size of the case study, the effective power of the planned biogas plants is lower than the

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3 661 optimal value and, in the case of  $P_n$  equal to 300 kW, additional amounts of substrate must be  
4 662 transported from external sites.

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6 663 If the biogas plant is supplied by a blend of substrate, the method has provided: (i) the optimal plant  
7 664 site (identified in the barycentre of the agricultural district weighed by the biogas potential  
8 665 production of each supplying site); (ii) the nominal power of a single biogas plant (480 kW),  
9 666 maximizing the profit from energy production; (iii) the amounts of the different substrates in the  
10 667 digester blend (in our case study 12% of olive residues, 39% of citrus residues and 49% of livestock  
11 668 residues); (iv) the revenues, costs and profits of the planned biogas plant.

12  
13 669 The method has been developed and tested for agro-industrial and livestock residues, but it can be  
14 670 applied also for other agricultural biomasses (i.e. ensiled and energy crops available at a  
15 671 competitive cost, as in Northern Italy).

16 672 On the whole, this work provides guidelines and design criteria for firm owners, designers and  
17 673 managers, in order to reduce the complexity of planning and managing biogas plants in agricultural  
18 674 districts; moreover, the developed decision support system is easy to be implemented in each  
19 675 specific case, thanks to the reduced number of easy-to-survey input parameters required.

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23 679

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## 752 LIST OF ABBREVIATIONS

- 51 753  
52  
53 754 AP = amortisation of the private funds (€ year<sup>-1</sup>)  
54 755 BC = costs of substrate supply to the digester (€ year<sup>-1</sup>)  
55 756 C = total costs (€ year<sup>-1</sup>)  
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3 757  $C_A$  = total costs of substrate supplying ( $\text{€ year}^{-1}$ )  
4 758  $c_{LS}$  = cost of slurry land spreading per weight unit ( $\text{€ t}_{DM}^{-1}$ )  
5  
6 759  $c_P$  = unit price for substrate purchase ( $\text{€ t}_{DM}^{-1}$ )  
7  
8 760  $C_P$  = total cost for substrate purchase ( $\text{€ year}^{-1}$ )  
9  
10 761  $c_{P,i}$  = purchase price of the substrate “i” ( $\text{€ t}_{DM}^{-1}$ )  
11 762  $C_{PE}$  = purchased equipment costs ( $\text{€}$ )  
12  
13 763  $c_S$  = storage cost of the substrate unit weight ( $\text{€ t}_{DM}^{-1}$ )  
14 764  $c_{S,i}$  = storage unit cost of the substrate “i” ( $\text{€ t}_{DM}^{-1}$ )  
15  
16 765  $C_S$  = storage costs ( $\text{€ year}^{-1}$ )  
17  
18 766  $c_T$  = transport costs per weight unit ( $\text{€ t}_{DM}^{-1}$ )  
19 767  $C_T$  = transport costs ( $\text{€ year}^{-1}$ )  
20  
21 768  $D_i$  = available amount of the substrate “i” at the firm ( $\text{t}_{DM} \text{ year}^{-1}$ )  
22  
23 769  $f$  = share of private funds for equipment purchase (%)  
24 770  $FC$  = annual share of the financial costs ( $\text{€ year}^{-1}$ )  
25  
26 771  $\bar{j}_i$  = minimum incidence of the substrate “i” in the digester blend ( $0 \div 1$ )  
27  
28 772  $k$  = coefficient of conversion of the produced biogas volume into electrical energy ( $\text{kWh m}^{-3}$ )  
29  
30 773  $K_f$  = unit fixed cost for substrate transport ( $\text{€ t}_{DM}^{-1}$ )  
31 774  $K_{f,i}$  = unit fixed cost for transport of the substrate “i” ( $\text{€ t}_{DM}^{-1}$ )  
32 775  $K_{f,S}$  = unit fixed cost for transport of the biogas slurry ( $\text{€ t}_{DM}^{-1}$ )  
33 776  $K_v$  = unit variable cost for substrate transport ( $\text{€ t}_{DM}^{-1} \text{ km}^{-1}$ )  
34 777  $K_{v,i}$  = unit variable cost for transport of the substrate “i” ( $\text{€ t}_{DM}^{-1} \text{ km}^{-1}$ )  
35 778  $K_{v,S}$  = unit variable cost for transport of the biogas slurry ( $\text{€ t}_{DM}^{-1} \text{ km}^{-1}$ )  
36  
37 779  $l$  = distance of slurry land spreading (km)  
38 780  $L$  = transport distance (km)  
39 781  $L_i$  = transport distance for the substrate “i” (km)  
40  
41 782  $m$  = coefficient for calculation of the annual payment for an investment (-)  
42 783  $MC$  = Management Costs ( $\text{€ year}^{-1}$ )  
43 784  $n$  = plant lifespan (years)  
44  
45 785  $N$  = number of substrates in the digester blend  
46 786  $P$  = total profit ( $\text{€ year}^{-1}$ )  
47 787  $p_E$  = unit price of the electrical energy ( $\text{€ kWh}^{-1}$ )  
48 788  $P_n$  = nominal electrical power of the biogas plant (kW)  
49 789  $p_S$  = unit market price of the slurry dry matter (DM,  $\text{€ t}_{DM}^{-1}$ )  
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3 790  $p_U$  = profit per unit of produced electrical energy (€ kWh<sup>-1</sup>)  
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5 791  $q = 1 + r$   
6  
7 792  $r$  = interest rate (%)  
8  
9 793  $R$  = total revenues (€ year<sup>-1</sup>)  
10  
11 794  $R_E$  = revenue from sale of the electrical energy (€ year<sup>-1</sup>)  
12  
13 795  $R_S$  = revenue from sale of the biogas slurry to farmers (€ year<sup>-1</sup>)  
14  
15 796  $s$  = incidence of the substrate excess over the average monthly production (0÷1)  
16  
17 797  $s_{max}$  = maximum soil application rate of the slurry dry matter (t<sub>DM</sub> ha<sup>-1</sup> year<sup>-1</sup>)  
18  
19 798  $S$  = average amount of biogas slurry produced by the biogas plant (t<sub>DM</sub> year<sup>-1</sup>)  
20  
21 799  $SC$  = costs of slurry transport and land spreading (€ year<sup>-1</sup>)  
22  
23 800  $t$  = number of substrate production sources  
24  
25 801  $TCI$  = Total Capital Investment (€ year<sup>-1</sup>)  
26  
27 802  $TOC$  = Total Operating Costs (€ year<sup>-1</sup>)  
28  
29 803  $V$  = amount of substrate supplied to the digester or amount of the digester blend (t<sub>DM</sub> year<sup>-1</sup>)  
30  
31 804  $V_i$  = amount of the substrate "i" (t<sub>DM</sub> year<sup>-1</sup>)  
32  
33 805  $V'$  = additional amount of substrate supplied from external sources (t<sub>DM</sub> year<sup>-1</sup>)  
34  
35 806  $W$  = average production of substrate at the firm (t<sub>DM</sub> year<sup>-1</sup>)  
36  
37 807  $W_i$  = substrate production sources [t<sub>DM</sub> year<sup>-1</sup>]  
38  
39 808  $x_i, y_i$  = geographical coordinates of the biomass production source "i"  
40  
41 809  $\bar{X}, \bar{Y}$  = geographical coordinates of the district barycentre  
42  
43 810  $y$  = slurry yield of the substrate (t<sub>DM</sub> of slurry per t<sub>DM</sub> of substrate supplied to the digester)  
44  
45 811  $\bar{y}_i$  = minimum incidence of the substrate "i" in the digester blend  
46  
47 812  $W_i$  = biomass production sources (t<sub>DM</sub> year<sup>-1</sup>)  
48  
49 813  $Y$  = biogas yield of the substrate DM unit (m<sup>3</sup> t<sub>DM</sub><sup>-1</sup>)  
50  
51 814  $Y_i$  = biogas yield of the substrate "i" (m<sup>3</sup> t<sub>DM</sub><sup>-1</sup>)  
52  
53 815  $z_i$  = incidence of the substrate "i" in the digester blend (0÷1)  
54  
55 816  $\bar{z}_i$  = maximum incidence of the substrate "i" in the digester blend (0÷1)  
56  
57 817  $\Delta t$  = annual operation time of the biogas plant (hours year<sup>-1</sup>).  
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## 818 TABLES

819

820 Table 1 – Economical evaluation of a biogas plant installed in firms exploiting prevalently self-  
 821 produced residues firm (case study of an agricultural district of Southern Italy).

822

Technical/economic parameter	Firm		
	Olive oil mill	Citrus processing industry	Livestock farm
Nominal electric power ( $P_n$ , kW)	300		
Purchased equipment costs ( $C_{PE}$ , €)	1793758		
Incidence of private capital ( $f$ , %)	20		
Amortisation of private capital (AP) ( $\text{€ year}^{-1}$ ) ( $\text{€ kWh}^{-1}$ )	17938		
	0.007		
Annual operation time of the biogas plant ( $\Delta t$ , hours year <sup>-1</sup> )	8000		
Management costs (MC) ( $\text{€ year}^{-1}$ ) ( $\text{€ kWh}^{-1}$ )	109618		
	0.046		
Interest rate ( $r$ , %)	0.045		
Plant lifespan ( $n$ , years)	20		
Financial costs (FC) ( $\text{€ year}^{-1}$ ) ( $\text{€ kWh}^{-1}$ )	110318		
	0.046		
Storage cost of the substrate unit weight ( $C_S$ , $\text{€ t}_{DM}^{-1}$ )	4.74	4.50	0
Biogas yield of the substrate DM unit ( $Y$ , $\text{m}^3 \text{t}_{DM}^{-1}$ )	350	600	250
Coefficient of conversion of the produced biogas volume into electrical energy ( $k$ , $\text{kWh m}^{-3}$ )	1.615		
Substrate amount ( $V$ , $\text{t}_{DM} \text{year}^{-1}$ ) <sup>(1)</sup>	4246	2477	5944
Storage costs ( $C_S$ ) ( $\text{€ year}^{-1}$ ) ( $\text{€ kWh}^{-1}$ )	20126	11146	0
	0.008	0.005	0.000
Total costs (C) ( $\text{€ year}^{-1}$ ) ( $\text{€ kWh}^{-1}$ )	257999	249019	237873
	0.107	0.104	0.099
Revenue from sale of the electrical energy ( $R_E$ ) ( $\text{€ year}^{-1}$ ) ( $\text{€ kWh}^{-1}$ )	566400		
	0.236		
Total profit (P) ( $\text{€ year}^{-1}$ ) ( $\text{€ kWh}^{-1}$ )	308401	317381	328527
	0.129	0.132	0.137
Firm working capacity	19561 <sup>(2)</sup>	19350 <sup>(3)</sup>	2013 <sup>(4)</sup>

823 Notes: <sup>(1)</sup> corresponding to the annual requirement; <sup>(2)</sup> processed olives ( $\text{t year}^{-1}$ ); <sup>(3)</sup> processed citrus ( $\text{t year}^{-1}$ ); <sup>(4)</sup> number  
 824 of animals.

Table 2 – Economical evaluation of a biogas plant installed in a single firm and fed by a blend of substrates (case study of an agricultural district of Southern Italy).

Technical/economic parameter	Firm					
	Olive oil mill	Citrus processing industry				Livestock farm
		A	B	C	D	
<i>Self-produced substrate (prevalent)</i>	Olive oil mill wastewater and pomace	Citrus processing wastewater and peel				Zootechnical wastewater and manure
<i>Substrates to supply from external sources (additional)</i>	Zootechnical wastewater and manure	Zootechnical wastewater and manure				Citrus processing wastewater and peel
<i>Incidence of the prevalent substrate in the blend (%)</i>	20.0	29.8	25.6	42.6	21.3	70.3
<i>Nominal electric power (<math>P_n</math>, kW)</i>	201	300				
<i>Purchased equipment costs (<math>C_{PE}</math>, €)</i>	1373453	1793758				
<i>Incidence of the private capital (<math>f</math>, %)</i>	20					
<i>Amortisation of the private capital (AP) (<math>\text{€ year}^{-1}</math>)</i>	13735	17938				
<i>(<math>\text{€ kWh}^{-1}</math>)</i>	0.009	0.007				
<i>Annual operation time of the biogas plant (<math>D_b</math>, hours year<sup>-1</sup>)</i>	8000					
<i>Management costs (MC) (<math>\text{€ year}^{-1}</math>)</i>	83821	109618				
<i>(<math>\text{€ kWh}^{-1}</math>)</i>	0.05	0.046				
<i>Interest rate (<math>r</math>, %)</i>	0.045					
<i>Plant lifespan (<math>n</math>, years)</i>	20					
<i>Financial costs (FC) (<math>\text{€ year}^{-1}</math>)</i>	84469	110318				
<i>(<math>\text{€ kWh}^{-1}</math>)</i>	0.05	0.05				
<i>Biogas yield of the prevalent substrate (<math>Y</math>, m<sup>3</sup> t<sub>DM</sub><sup>-1</sup>)</i>	350	600			250	
<i>Coefficient of conversion of the produced biogas volume into electrical energy (<math>k</math>, kWh m<sup>-3</sup>)</i>	1.615					

Amount of the substrate supplied to the digester ( $V$ , $t_{DM} year^{-1}$ )	3688	3002				4199
Amount of the prevalent substrate ( $W$ , $t_{DM} year^{-1}$ )	738	896	768	1280	640	2952
Storage unit cost of the prevalent substrate ( $c_s$ , $€ t_{DM}^{-1}$ )	4.74	4.50				0.00
Storage cost of the prevalent substrate ( $C_s$ ) ( $€ year^{-1}$ ) ( $€ kWh^{-1}$ )	3496	4032	3456	5760	2880	0
	0.002	0.002	0.001	0.002	0.001	0.000
Biogas yield of the additional substrates ( $Y$ , $m^3 t_{DM}^{-1}$ )	250	250	250	250	250	600
Amount of the additional substrates ( $V'$ , $t_{DM} year^{-1}$ )	2950	2106	2234	1722	2362	1247
Storage unit cost of the additional substrates ( $C_s$ , $€ t_{DM}^{-1}$ )	0	0	0	0	0	4.62
Storage cost of the additional substrates ( $C_s$ ) ( $€ t_{DM}^{-1}$ ) ( $€ kWh^{-1}$ )	0	0	0	0	0	5760
	0	0	0	0	0	0.002
Transport distance ( $L$ , km)	26	4	12	35	19	6
Unit fixed cost for substrate transport ( $K_f$ , $€ t_{DM}^{-1}$ )	11.56	15.56				9.16
Unit variable cost for substrate transport ( $K_v$ , $€ t_{DM}^{-1} km^{-1}$ )	0.89	1.22				0.71
Transport costs ( $C_T$ ) ( $€ year^{-1}$ ) ( $€ kWh$ )	102369	43050	68289	99703	91510	17084
	0.064	0.018	0.028	0.042	0.038	0.007
Total costs ( $C$ ) ( $€ year^{-1}$ ) ( $€ kWh^{-1}$ )	287889	284955	309619	343336	332263	260717
	0.179	0.119	0.129	0.143	0.138	0.109
Revenue from sale of the electrical energy ( $R_E$ ) ( $€ year^{-1}$ ) ( $€ kWh^{-1}$ )	379488	566400	566400	566400	566400	566400
	0.236	0.236	0.236	0.236	0.236	0.236
Total profit ( $P$ ) ( $€ year^{-1}$ ) ( $€ kWh^{-1}$ )	91599	281445	256781	223064	234137	305683
	0.057	0.117	0.107	0.093	0.098	0.127

Table 3 – Economical evaluation of the biogas plant (480 kW) planned in the case study (agricultural district of Southern Italy).

Technical/economic parameter	Firm					
	Citrus processing industry	Olive oil mill	Citrus processing industry			Livestock farm
			A	B	C	
<i>Self-produced substrate (prevalent)</i>	Citrus processing wastewater and peel	Olive oil mill wastewater and pomace	Citrus processing wastewater and peel			Zootechnical wastewater and manure
<i>Substrates to supply from external sources (additional)</i>	Zootechnical wastewater and manure	Zootechnical wastewater and manure	Zootechnical wastewater and manure			Citrus processing wastewater and peel
<i>Purchased equipment costs (<math>C_{PE}</math>, €)</i>	2454852					
<i>Incidence of the private capital (f, %)</i>	20					
<i>Amortisation of the private capital (AP, € year<sup>-1</sup>)</i>	24549					
<i>Financial costs (FC, € year<sup>-1</sup>)</i>	150976					
<i>Management costs (MC, € year<sup>-1</sup>)</i>	150254					
<i>Interest rate (r, %)</i>	0.045					
<i>Plant lifespan (n, years)</i>	20					
<i>Amount of the prevalent substrate (W, t<sub>DM</sub> year<sup>-1</sup>)</i>	640					
<i>Biogas yield of the prevalent substrate (Y, m<sup>3</sup> t<sub>DM</sub><sup>-1</sup>)</i>	600					
<i>Storage unit cost of the prevalent substrate (cs, € t<sub>DM</sub><sup>-1</sup>)</i>	4.74					
<i>Total storage cost of the prevalent substrate (C<sub>S</sub>, € year<sup>-1</sup>)</i>	3034					
<i>Amount of the additional substrate (V', t<sub>DM</sub> year<sup>-1</sup>)</i>	640	738	896	768	0	2954

Amount of the substrate supplied to the digester ( $V$ , $t_{DM} year^{-1}$ )	5996					
Purchase price of the additional substrate ( $c_P$ , $€ t_{DM}^{-1}$ )	0	0	0	0	0	0
Cost for substrate purchase ( $C_P$ , $€ year^{-1}$ )	0	0	0	0	0	0
Unit fixed cost for substrate transport ( $K_f$ , $€ t_{DM}^{-1}$ )	0.00	11.56	15.56	15.56	15.56	9.16
Unit variable cost for substrate transport ( $K_v$ , $€ t_{DM}^{-1} km^{-1}$ )	0.00	0.89	1.22	1.22	1.22	0.71
Transport distance ( $L$ , km)	0	13.1	9.4	14.4	20.9	12.3
Transport substrate costs ( $C_T$ , $€ year^{-1}$ )	0	17136	24175	25387	0	52856
Total transport costs ( $C_T$ , $€ year^{-1}$ )	119554					
Storage unit cost of the additional substrate ( $C_S$ , $€ t_{DM}^{-1}$ )	0.00	0.00	0.00	0.00	0.00	0.00
Storage cost of the additional substrate ( $C_S$ , $€ year^{-1}$ )	0	0	0	0	0	0
Biogas yield of the additional substrate ( $Y$ , $m^3 t_{DM}^{-1}$ )	600	350	600	600	600	250
Unit price of the electrical energy ( $p_E$ , $€ kWh^{-1}$ )	0.206					
Coefficient of conversion of the produced biogas volume into electrical energy ( $k$ , $kWh m^{-3}$ )	1.615					
Available amount of substrate at the firm ( $D$ , $t_{DM} year^{-1}$ )	640	738	896	768	1280	2954
Maximum incidence of the substrate in the digester blend ( $\bar{z}$ )	1	0.2	0.7	0.7	0.7	1
Annual operation time of the biogas plant ( $\Delta t$ , hours $year^{-1}$ )	8000					
Revenue from sale of the electrical energy ( $R_E$ , $€ year^{-1}$ )	791536					
Nominal electric power ( $P_n$ , kW)	480					
Costs of substrate supply to the digester ( $BC$ , $€ year^{-1}$ )	122587					
Total costs ( $C$ , $€ year^{-1}$ )	448365					
Total profit ( $P$ , $€ year^{-1}$ )	340137					
Incidence of substrate in the blend ( $z$ , %)	0.11	0.12	0.15	0.13	0.00	0.49

**FIGURE CAPTIONS**

Figure 1 - Flow chart of the methods for planning a biogas plant using a prevalent substrate (a) or a blend of substrates (b).

Figure 2 – Map of the agricultural district of Southern Italy analysed in the case study; the main roads connecting the sample agro-industries and the livestock farm are reported.

Figure 3 – Variability of the unit profit as a function of the nominal power for a biogas plant installed in agro-industries/livestock farms exploiting prevalently self-produced residues.

Figure 4 – Variability of the unit cost, revenue and profit of a biogas plant installed in olive oil mills (a), citrus processing industries (b) and livestock farms (c) (exploiting prevalently self-produced residues) as a function of the nominal power.

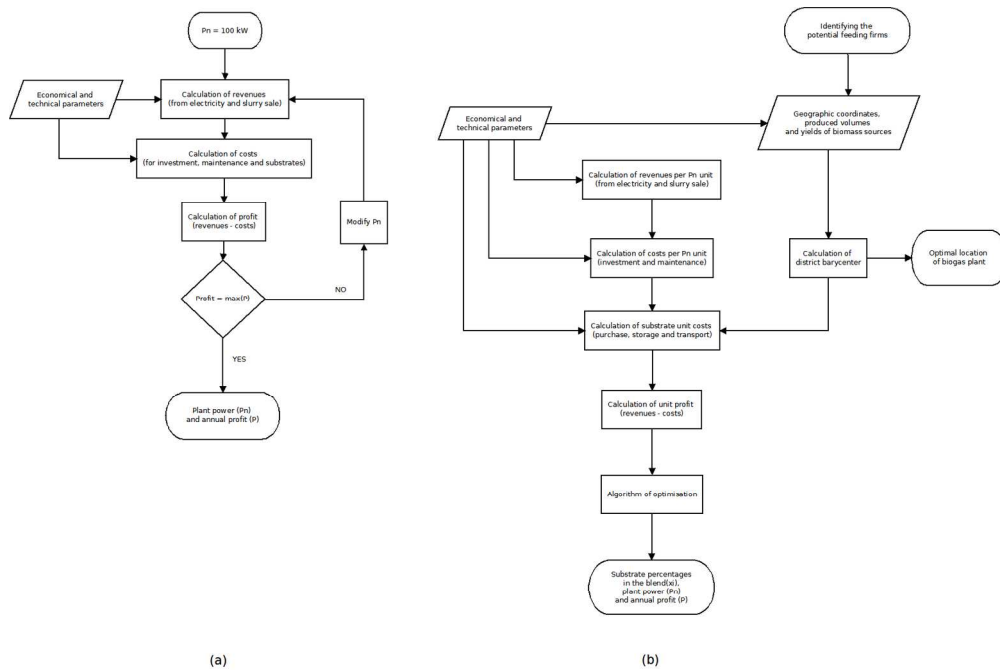


Figure 1 - Flow chart of the methods for planning a biogas plant using a prevalent substrate (a) or a blend of substrates (b).

479x326mm (96 x 96 DPI)



Figure 2 – Map of the agricultural district of Southern Italy analysed in the case study; the main roads connecting the sample agro-industries and the livestock farm are reported.

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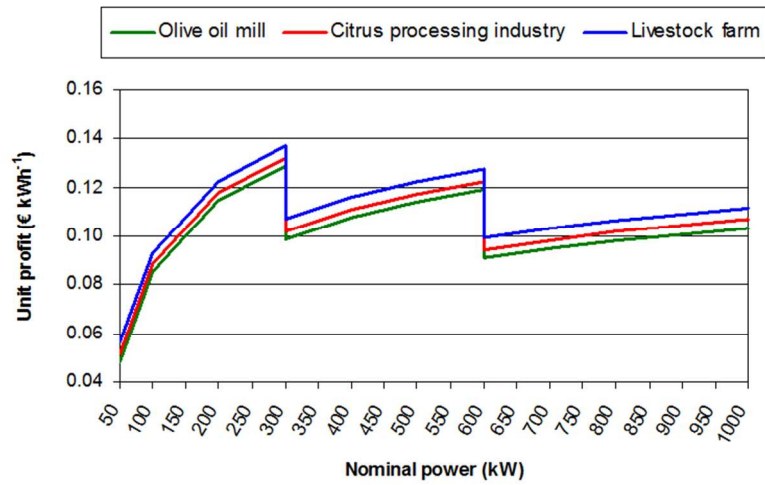


Figure 3 – Variability of the unit profit as a function of the nominal power for a biogas plant installed in agro-industries/livestock farms exploiting prevalently self-produced residues.

254x190mm (96 x 96 DPI)

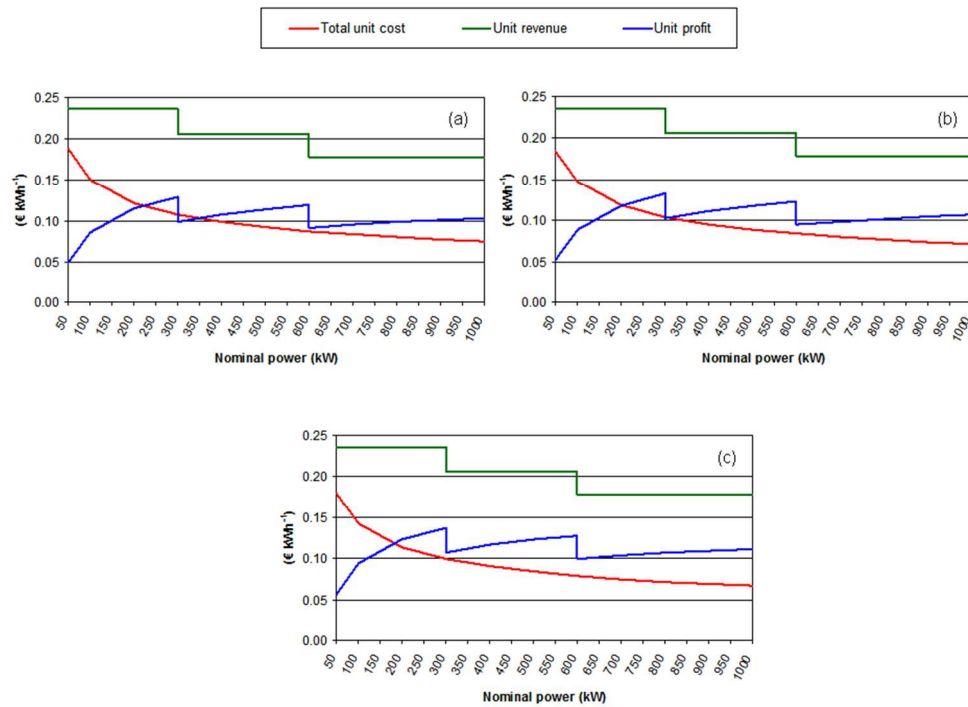


Figure 4 – Variability of the unit cost, revenue and profit of a biogas plant installed in olive oil mills (a), citrus processing industries (b) and livestock farms (c) (exploiting prevalently self-produced residues) as a function of the nominal power.

254x190mm (96 x 96 DPI)