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Logistics in the Biomass Supply Chain of Bio-energy Plants in Southern Italy

Demetrio Antonio Zema*, Claudio Marcianò, Serafina Andiloro, Vincenzo Tamburino

University Mediterranea of Reggio Calabria, Department “Agraria”, Loc. Feo di Vito, I-89122 Reggio Calabria (Italy)
dzema@unirc.it

In order to enhance the competitiveness of the bio-energy sector, the costs of the supply chain of agricultural residues feeding the energy plants must be properly estimated and possibly minimised. This study proposes simple models to estimate the storage and transportation costs of the substrates for bio-energy plants in small agricultural districts. The models were verified in a case study of Calabria (Italy), representative of the agricultural contexts of the Mediterranean basin. The analysis revealed that the use of poultry manure and maize straw/stover appears to be the most convenient choice to feed the bio-energy plants (total cost between 12.77 and 15.58 € ton^{-1} of dry matter, DM). The agro-industrial wastewater has the highest storage and transport costs (up to 132.42 € ton_{DM}^{-1}). A sustainable choice is feeding the plants on swine and bovine manure (total cost of 25.80 and 31.22 € ton_{DM}^{-1}, respectively) or on citrus peel and grape marc (17,27 and 18,59 € ton_{DM}^{-1}). These estimation methods provided a database of unit logistic costs and are a useful tool for decision makers to improve the biomass supply chains in agricultural districts of the Mediterranean basin.

1. Introduction

The cost of the biomass supply chain (including several activities, such as cultivation, harvesting, pre-processing, transportation, handling, and storage) is one of the most important barriers to the development of the bio-energy sector in the World. Such costs, if high, oppose market penetration and inhibit fair competition with the traditional energy sources like fossil fuels (De Meyer et al., 2015). While research on crop production and conversion processes is well developed, the actors concerned realized only recently that the Achilles' heel of the planned bio-energy production systems could be logistics (Ba et al., 2016). Despite the widely agreed potential of bio-energy utilization and the relatively low price of agricultural biomasses feeding bio-energy plants, key problems related to a timely and adequate availability of biomass at the bio-energy plant strongly affect their economic and energy performances. For agricultural and livestock residues, the limited time availability, owing to biomass seasonality, and the scattered geographical distribution require collection, transport and storage operations, which, if the biomass supply chain is not efficient, are complex and expensive (Caputo et al., 2005).

Therefore, farmers and bio-energy businessmen must minimize costs related to the storage (needed to reduce the temporal variability of biomass production, giving an almost constant availability of substrate throughout the year), and to transportation (from the production site to the digester). Since the economic equilibrium of the whole system critically depends on the logistic costs, an efficient supply chain must be implemented, limiting the costs of storage and transport of agricultural biomasses. The performance indicator of the efficiency of the biomass supply chain is the total cost (sum of the partial costs over the different stages of the chain, Ba et al., 2016). To make crop residues an economically attractive feedstock for bio-energy market, the logistics cost should be less than 25% of the total bio-energy production cost (Ebadian et al., 2011).

In order to give indications on the economic and technical factors mostly influencing the biomass supply chain in Mediterranean agricultural areas, this work proposes simple models to estimate the storage and transportation costs of substrates feeding bio-energy plants in small agricultural districts. The related equations are based on a low number of easy-to-survey input parameters (e.g. bulk density and unit dry weight of biomass, unit costs of storage systems and means of transportation, etc.), which are available in

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literature. The proposed models estimate: (i) the unit transportation costs of substrates as a function of plant position, biomass physical properties and type of means of transportation; (ii) the unit storage costs, as a function of biomass physical properties, type of storage systems and diagram of temporal availability of substrates throughout the year. The models have been applied and verified in Calabria (Southern Italy) through a case study (representative of the Mediterranean agricultural districts), suggesting the values of some important economic parameters. The proposed models support strategic decisions about the viability of bio-energy plants by helping the evaluation of its profitability.

2. Materials and methods

2.1 Estimation of biomass storage and transport costs

Storage and transport costs of biomass were evaluated with reference to the Total Solids (TS, equal to the dry matter content of biomass) unit weight. The work hypothesis was the proportionality of energy yield of each biomass to its TS content by a good approximation, which makes possible to express the energy recovery potential to dry weight unit cost and put the different substrates on a comparable basis (Dagnall et al., 2000). A literature survey allowed to estimate for each of the crop and cattle residues considered: (i) the wet weight (WW) unit (equal to the bulk density); (ii) the average TS content (that is, the quantity of feedstock that can be theoretically converted into energy, excluding water); (iii) the dry weight (DW) unit, equal to the ratio between the WW unit and the TS content of each biomass. Although these parameters are affected by a significant variability (due to several factors, such as crop species, cultivation practices, ripening stage for crops, as well as cattle diets and breeding modalities for livestock), only the average values were taken into account.
For agricultural and agro-industrial residues, storage is required to synchronize the production calendar (which shows a high seasonal variability due to the seasonality of crops) with the production plan of bio-energy plant, thus assuring a continuous feeding rate of the substrates throughout the year: the at-plant storage acts as a buffer to cope with supply shocks and prevents the conversion process from starvation (Ebadian et al., 2011). Storage costs depend on many factors, such as the site characteristics as well as the facilities and machinery available in the agro-industry or livestock farm. Storage costs of a bio-energy plant (C_S, € year^{-1}), usually estimated on a yearly basis, was assumed to be equal to the sum of the annual amortization of facilities and machinery as well as of the labour for handling, by the following equation:

$$C_S = c_S \, s \, W \qquad (1)$$

where "c_S" is the storage cost of the substrate unit weight (€ ton$_{TS}^{-1}$), "s" (0÷1) is the annual biomass share to be stored, and "W" is the annual production of substrate (ton$_{TS}$ year $^{-1}$). The parameter "s" can be easily estimated from temporal diagram of the residues production and it is equal to the incidence of substrate excess over the average monthly production. The costs of the storage facilities were calculated by quantity surveying of the related building and labour costs based on market prices of materials and manpower and using the straight line method, as suggested by Browne et al. (2011).
Also transport costs (C_T, € year^{-1}) are usually estimated on a yearly basis. The transfer from a production site to the bio-energy plant location depends on several factors, such as distance, road characteristics, size and type of transport, loading and unloading times. Like in industrial logistics, several transport modes can be used, the fleet of vehicles is often limited and the number of travels per period is restricted by vehicle range and driving time regulations; in agricultural districts road transport is often the only solution for production sites with limited accessibility, and truckload operations are systematic due to the large amounts handled (Ba et al., 2016). The economic incidence on running operations of the bio-energy plant depends noticeably on transport costs per weight unit (c_T, € ton$_{TS}^{-1}$). This unit cost consists of a fixed (K_f, € ton$_{TS}^{-1}$) and a variable share (K_v, € ton$_{TS}^{-1}$ km^{-1}) - this latter related to the transport distance (L, km), - according to the equation:

$$C_T = c_T \, W = (K_f + K_v \, L) \, W \qquad (2)$$

For "L" some Authors indicate a viable maximum distance of 25 km (Poliafico and Murphy, 2007), which must be reduced to 10 km for substrates with low TS content (<10%) (Dagnall et al., 2000). The values of "K_f" and "K_v" coefficients were estimated from local market prices of insurance, labour for loading, unloading, driving, fuel, lubricants and maintenance, beside machine amortization.

2.2 Model application to the Calabria region

Preliminarily, a survey was carried out in order to identify the most important agricultural, agro-industrial and livestock sectors in Calabria: the annual productions of tree and herbaceous crops as well as the number of livestock animals were estimated from the last report of the Sixth Agricultural Census issued by the Italian

National Institute of Statistics (ISTAT). Thus, the following productive sectors were considered: (i) within the tree crops, olive, citrus and grape residues processed by the agro-food industries; (ii) bovine, swine and poultry, in the livestock sector; (iii) wheat, barley and maize, within the herbaceous crops.
As regards the agro-food industries, olive, citrus and grape processing produces wastewater and solid residues (pomace, citrus peel and marc for olive oil mills, citrus processing facilities and wineries, respectively). Wastewater is a blend of water produced by fruit, machine and plant washing and fruit processing (that is, water contained into fruits and used for their processing) (Zema et al., 2012). Solid residues consist of fruit organic residues and other compounds used for processing (e.g. sulphites in wineries). Manure with high water content is produced in livestock breeding farms. For cereal crop residues after grain harvesting, straw and stover were considered in this study.

3. Results and discussions

Considering the last statistical data (2015) of agriculture, olives, citrus and grape represent 50%, 8% and 4%, respectively, of the total fruit tree production in Calabria; 98% (olives and grapes) and 36% (citrus) of these amounts are destined to the industrial transformation. Poultry (68% on the total regional number), cows (6%) and swine (3%) are the most numerous livestock animals. Wheat (63% of the total regional production), barley (13%) and maize (12%) are the most diffused herbaceous crops (ISTAT, 2016).
The agricultural, agro-industrial and livestock residues taken into consideration show a wide range of water content (from 8-9% of cereal straw to 94-97% of olive oil mill and citrus processing wastewaters). This high variability often suggests the most suitable energy conversion technique (e.g. combustion and gasification for drier residues and anaerobic digestion or alcoholic fermentation for wetter biomasses, Caputo et al., 2005). Conversely, the calculated DW unit of the analyzed biomasses is characterized by a lower variability (from 0.03 $tons_{TS}$ m^{-3} of citrus processing wastewater to 0.29 $tons_{TS}$ m^{-3} of grape marc) (Table 1).

Table 1: Main properties of some agricultural, agro-industrial and livestock residues (from literature data).

Crop/cattle	Residue	Wet weight unit [tons m^{-3}]	Total Solids [-]	Dry weight unit [$tons_{TS}$ m^{-3}]
Olive	Wastewater	1.04 (a)	0.06 (a)	0.06
	Pomace	0.45 (b)	0.22 (g)	0.10
Citrus	Wastewater	1.02 (c)	0.03 (h)	0.03
	Peel	0.90 (d)	0.23 (d)	0.21
Grape	Marc	0.47 (b)	0.61 (j)	0.29
Bovine	Manure	1.00 (e)	0.09 (e)	0.09
Swine		0.99 (e)	0.11 (e)	0.11
Poultry		1.00 (e)	0.22 (e)	0.22
Wheat	Straw	0.11 (f)	0.92 (f)	0.10
Barley		0.10 (f)	0.93 (f)	0.09
Maize	Straw and stover	0.15 (f)	0.92 (f)	0.14

Notes: (a) Mekki et al., (2008); (b) Madejon et al. (2002); (c) personal measurements; (d) Tamburino and Zema (2009); (e) ASAE (2003); (f) Mani et al. (2006); (g) Poschl et al. (2010); (h) Guzman et al. (2016); (j) Dinuccio et al. (2010).

However, the physical and chemical properties of both agro-industrial residues and animal manure show a very large variability, which mainly depends on the processing technology (e.g. Zema et al., 2016) and on husbandry practices (Dagnall et al., 2000). Therefore, the logistic biomass costs discussed below may be affected by additional variability factors, beside those depending on the residue types.
Regarding the costs of substrate supply to a bio-energy plant, storage unit costs (c_S) were estimated for typical facilities of the rural territory of Southern Italy by economic evaluations in the field. Only for livestock farms "c_S" is null, due to the continuous production of manure throughout the year. The use of a waterproof earth tank was assumed for storage of wastewater produced by olive oil mills and citrus processing industries, while storage in horizontal tanks made of reinforced concrete was hypothesized for solid residues (olive pomace, citrus peel and grape marc), as it is common in Calabria (Zema, 2017). Amortization costs of earth and concrete tanks were estimated in 0.20 € m^{-3} $year^{-1}$ over 10 years and 1.50 € m^{-3} $year^{-1}$ over 20 years, respectively (Table 2). A cover using a fixed structure (such as a greenhouse) would require an additional cost

of 0.90 € m^{-3} year^{-1} approximately, but it would allow biomass shadowing against precipitation as well as evaporation maximization (thus increasing the TS content) and minimization of bad smell exhalations. For cereal crop residues, storage into a hay barn covered by a plastic sheet was assumed, whose unit cost was estimated in 0.10 € m^{-3} year^{-1}. The biomass share to be stored compared to the annual amount is expressed by the parameter "s": in Calabria the incidence of substrate excess over the average monthly production was equal to 55% for olive oil mills and 51% for citrus processing industries. Conversely, for both grape marc and cereal residues, a production concentrated in one month or slightly more was estimated and therefore the annual share to be stored is equal to 92% of the total production. The resulting "c_S", excluding the null cost of animal manure storage, varied from a minimum value of 0.93 € ton$_{TS}^{-1}$ for cereal residues (straw and stover) to a maximum of 8.33 € ton$_{TS}^{-1}$ for pomace produced by olive oil mills (Table 2); this variability mainly depends on the storage facility type (concrete tank has a 7.5-fold cost compared to earth tank) and, secondarily, on different TS contents of residues.

Table 2: Parameters related to storage unit costs of some agricultural, agro-industrial and livestock residues in Calabria.

Crop/cattle	Residue	Storage annual share [s, -]	Storage unit cost of wet biomass [€ m^{-3}]	Incidence of storage cost on total biomass [€ m^{-3}]	Storage unit cost of dry biomass [c_s, € ton$_{TS}^{-1}$]
Olive	Oil mill wastewater	0.55	0.20	0.11	1.76
	Pomace		1.50	0.83	8.33
Citrus	Processing wastewater	0.51	0.20	0.10	3.33
	Peel		1.50	0.77	3.70
Grape	Marc	0.92	1.50	1.38	4.81
Bovine					
Swine	Manure		0.00		
Poultry					
Wheat	Straw	0.92	0.10	0.09	0.93
Barley					
Maize	Straw and stover				

Concerning the transport costs, tankers for liquid substrate and trucks for solid residues are commonly used in Calabria (Zema, 2017); straw and stover of cereals are transported by trucks as well, but separation layers in trucks are used to maximize their loading capacity (which halves the fixed cost). The following values of the coefficients of equation (2) for calculating transport costs were estimated: (i) for K_f, 1.45 € m^{-3} for tankers and 1.56 € m^{-3} for trucks (0.78 € m^{-3} in the case of cereal residues transportation); (ii) for K_v, 0.10 € m^{-3} km^{-1} for tankers and 0.05 € m^{-3} km^{-1} for trucks (0.03 € m^{-3} for cereal residues) (Table 3).

Based on the different TS contents of the agricultural, agro-industrial and livestock residues, the lowest "c_T" was found in general for citrus peel and grape marc as well as for poultry manure and maize straw and stover; conversely, the transport of agro-industrial wastewater was less convenient, because these residues require the highest unit cost, mainly due to the low TS content (Table 3). However, to choose the bio-energy plant feed, one should bear in mind that some substrates contain inhibiting compounds (for example polyphenols in the residues of olive oil mills and essential oils in those of citrus industries), which may noticeably slowdown or even block bio-energy production rates. To avoid these problems in the energy conversion processes, the concentration of such residues in the bio-energy plant feed must be limited by diluting them with water or blending the self-produced biomass with other substrates, mainly supplied from external sources.

Finally, a simulation of the total logistic cost was operated by hypothesizing transport distances of 10 and 25 km for the analyzed residues. This simulation showed that, at least with reference to the logistic costs of the biomass supply chain in Calabria, the use of poultry manure and maize straw/stover is the most convenient choice to feed the bio-energy plants, since the total cost (storage + transportation) is between 12.77 and 15.58 € ton$_{TS}^{-1}$. Conversely, the most expensive residue is agro-industrial wastewater and, in particular, the effluent of citrus industries, whose total logistic cost is 132.42 € ton$_{TS}^{-1}$. Feeding the bio-energy plants on swine and bovine manure (total cost of 25.80 and 31.22 € ton$_{TS}^{-1}$, respectively) or on citrus peel and grape marc (17.27 and 18.59 € ton$_{TS}^{-1}$, respectively) is also a sustainable choice; in this latter case, the possible reduction of the bio-energy yield must be considered, due to the possible inhibition of bio-chemical process (Figure 1). Moreover, since manure is rich in nitrogen and basically alkaline, livestock residues are able to assure a balanced value of C/N ratio and pH in the digester feed.

Table 3: Parameters related to transport unit costs of some agricultural, agro-industrial and livestock residues in Calabria.

Crop/cattle	Residue	Transport cost coefficients K_f		K_v	
		[€ km^{-1}]	[€ ton_{TS}^{-1}]	[€ m^{-3} km^{-1}]	[€ ton_{TS}^{-1} km^{-1}]
Olive	Oil mill wastewater	*1.45*	23.24	0.10	1.60
	Pomace	1.56	15.76	0.05	0.51
Citrus	Processing wastewater	1.45	47.39	0.10	3.27
	Peel	1.56	7.54	0.05	0.24
Grape	Marc	1.45	5.06	0.10	0.35
Bovine	Manure	1.56	17.33	0.05	0.56
Swine			14.33		0.46
Poultry			7.09		0.23
Wheat	Straw	0.78	7.85	0.05	0.50
Barley			8.56		0.55
Maize	Straw and stover		5.73		0.37

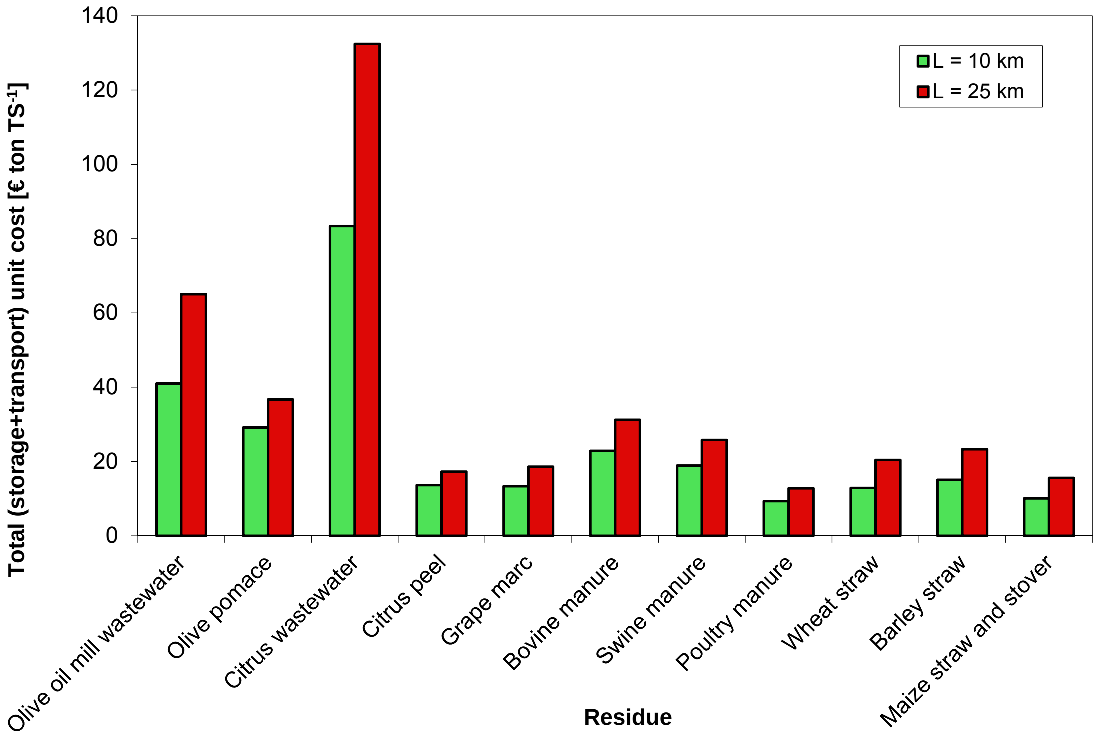

Figure 1: Values of the total unit costs of some agricultural, agro-industrial and livestock residues in Calabria (for the transport distance "L" the values of 10 and 25 km were assumed).

4. Conclusions

Logistics of biomass supply chains, a challenging task for the optimization of the bio-energy sector in the agricultural districts, require the evaluation of the related costs. Simple models to estimate the storage and transportation costs of substrates feeding the bio-energy plants in small agricultural districts were proposed and based on a low number of input parameters, available in literature. The application of these models to small agricultural districts of Calabria (Southern Italy) allowed the estimation of the storage and transport unit costs of the most abundant agricultural, agro-industrial and livestock residues in this territory.

In the case study the use of poultry manure and maize straw/stover is the most convenient choice to feed the bio-energy plants (total cost between 12.77 and 15.58 € ton_{TS}^{-1}), while agro-industrial wastewater showed the highest storage and transport costs (up to 132.42 € ton_{TS}^{-1}). A sustainable choice is feeding the bio-energy plants on swine and bovine manure (total cost of 25.80 and 31.22 € ton_{TS}^{-1}, respectively) or on citrus peel and grape marc (17.27 and 18.59 € ton_{TS}^{-1}, respectively). These estimations provided a database of unit costs, which may represent a useful tool for decision makers; by such way, it is easier to improve the logistics system in terms of feedstock quantity and quality, costs of substrate delivery to bio-energy plants, delivering times as well as the environmental impact of the supply chain (Ebadian et al., 2011).

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