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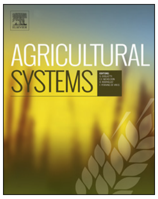

Optimization of agricultural biogas supply chains using artichoke byproducts in existing plants

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ABSTRACT

The development of biogas production exacerbated the competition for land availability between crops dedicated to human consumption and those intended for energy production. Residual biomasses have been often proposed for their positive outcomes in terms of reduced pressure on land use. However, literature did not assess optimization options for existing biogas plants feeding. This paper developed a bio-economic model for the optimization of agricultural biogas supply chains using artichoke byproducts in existing plants. A multiple goal linear programming approach was adopted, using two objective functions, calculating respectively net present value and land use from energy crops, associated to a regional biogas network. Three scenarios were defined using primary and secondary data on the residues of a specific artichoke variety - globe - and an Italian region - Sardinia. In the Business As Usual scenario, net present value is about 7 million € with a land use of about 2720 ha. When using artichoke residues, the economic impact increases by 28% and land use is reduced by 83% if net present value is optimized. When land use is optimized, the economic impact still grows by 25% and land use is reduced by 100%. Results from this study confirm that, under certain conditions, locally available residual biomasses can replace energy crops in existing biogas networks, coupling viability and sustainability.

1. Introduction

European production of bioelectricity from biogas has rapidly increased over the course of the last decade, reaching 57 TWh in 2014. More than half was generated in Germany, while Italy represented the second major producer, with more than 8 TWh (Eurobserv'Er, 2015). In both countries, agricultural biogas is particularly important (Eurobserv'Er, 2014) and was targeted by dedicated supporting schemes (Britz and Delzeit, 2013). In Italy, only in the 2010–2012 period, about 1200 new plants were authorized, and in 2016, almost 1500 plants were operating (Gestore Servizi Energetici, 2017). Most of this growth was achieved due to the introduction of the Law 99/23 July 2009, which granted a 280€ MWh^{-1} feed-in tariff to facilities fed with biomass from livestock and agricultural activities, beside the existing tradable green certificates (Chinese et al., 2014; Gestore Servizi Energetici, 2015).

The use of dedicated crops for energy and fuel production was increasingly blamed for the accrued competition for resources in the so called food-energy nexus (Ciaian and Kancs, 2011; Czekała, 2018; Harvey and Pilgrim, 2011; Jacobs et al., 2017; Molari et al., 2014; Murphy et al., 2011; Tilman et al., 2009). In the case of biogas, this resulted in both global - as for the influence of German sector on European and international prices and land use change (Britz and Delzeit, 2013) - and local effects - as for the increased consumption of animal feed or the cultivation of marginal land to substitute maize directed towards energy production (Styles et al., 2015). In addition, anaerobic digestion (AD) of energy crops does not always represent a burden-free renewable energy, since fossil energy and derived products still need to be used to produce its feedstock (Dressler et al., 2012; Huttunen et al., 2014; Lijó et al., 2015).

In response to these undesirable impacts, the European and National policy frameworks were soon adjusted to balance the multiple goals of supporting renewable energy without causing negative social and environmental outcomes. In the Energy Roadmap to 2050, the European Commission underlined the need for bioenergy systems able to reduce the related land use, while achieving significant emission savings (European Commission, 2011). In the recently published Policy framework for climate and energy to 2030, it was also emphasized that the

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future development of renewable energies should be largely market-based reducing public expenditures (European Commission, 2014).

The use of residual biomasses for biogas production was prioritized because of its several positive outcomes in terms of land use (Börjesson and Berglund, 2007; Carnevale et al., 2017; Jury et al., 2010), competition with food and feed (Styles et al., 2015), environmental impacts (Bacenetti et al., 2016; Lijó et al., 2015; Pagani et al., 2017; Segré, 2014), and feedstock supply costs (Schievano et al., 2015). In 2012 the Italian government started to decrease feed-in tariffs for electricity generated from biogas and to differentiate them by plant size and feedstock typology (Italian Ministry of Economic Development, 2012). This trend was further confirmed by the most recent revision of the incentive scheme (Italian Ministry of Economic Development, 2016).

Given the need to diversify feedstocks, various studies explored the biogas generation potential of residues from several crops, as tomato processing waste (Calabrò et al., 2015), potato peels (Schievano et al., 2009), beet pulp (Kryvoruchko et al., 2009), citrus peels (Lanuzza et al., 2014), artichoke residues (De Menna et al., 2016). Some of these crops share similar characteristics with maize in terms of geographical and climatic conditions, whereas others may be limited to certain areas and seasons. However, the real degree of substitution of energy crops in existing biogas plants is not only dependent on the local availability of residues and their biomethane potential (BMP), but also on the economic and logistical feasibility of the supply.

The territorial optimization of biomass supply chains represented the focus of several studies. In a recent paper, reviewed and classified different typologies of optimization and evaluation models. In case of multi-objective models, several authors used Pareto-optimality to derive a portfolio of policy options (Čuček et al., 2012; Santibañez-Aguilar et al., 2011; You and Wang, 2011), while few adopted for example the goal programming method (Pomerol and Barba-Romero, 2000). Ba et al. (Ba et al., 2016) underlined how optimization models allow a simplified representation of the problem and provide strategic information for the identification of the best alternative. However, since biomass supply chains are dependent on numerous local and national variables, they are usually lacking in generality and scalability (Ba et al., 2016).

In the case of biogas supply chains, literature presents optimization models usually focused on the assessment of the optimal size and maximum number of new plants per area, basing on feedstock availability (Amiri et al., 2013; Balaman and Selim, 2014; Chinese et al., 2014; Fiorese and Guariso, 2012; Karmakar et al., 2010; Pantaleo et al., 2013; Patrizio and Chinese, 2016). Biomass supply is either estimated or based on current yields and productions. However, these studies are not modelling existing biogas networks and plants, i.e. optimizing actual feedstock supply or assessing alternative scenarios. When by-products are considered, a detailed description of the origin with the related logistic modelling is usually missing. Finally, they aim at economic optimization, only with an assessment of the related impacts, not with a multiple-goal optimization (Amiri et al., 2013; Balaman and Selim, 2014; Chinese et al., 2014; Fiorese and Guariso, 2012; Karmakar et al., 2010; Pantaleo et al., 2013; Patrizio and Chinese, 2016).

Thus, this paper aimed to develop and test an analytical model for the economic optimization and land use minimization of an existing biogas regional network, using local crop residues. The model provides a detailed representation of a real territorial context while using a multiproduct and multiobjective approach that could be scaled and applied also to other bioenergy systems and regions Table 1.

2. Materials and methods

2.1. Area of investigation

Cultivation residues from a specific crop variety - globe artichoke - and an area of investigation - Sardinia - were identified to test the optimization model. Globe artichoke is a thistle cultivated for its flower buds and most of the aboveground biomass is usually underutilized (Pandino et al., 2013; Raccuia et al., 2013). However, it could represent a promising biomass feedstock for the Sardinia Region and the regional supply chains for anaerobic digestion (Cravero et al., 2012; Foti et al., 1999; Ierna et al., 2012; Ierna and Mauromicale, 2010; Ledda et al., 2013; Scano et al., 2013). In another recent study focusing on Sardinia, De Menna et al. (2016) tested the BMP of globe artichoke (*Cynara cardunculus* L. var. *scolymus*) residues and their regional availability. Results suggested the potentiality of such crop residues for the local biogas sector, without assessing the related economic impact, especially in terms of energy crop substitution and supply chain optimization.

2.1.1. Artichoke potential and regional availability

Artichoke cultivars under cultivation in Sardinia include C3, Madrigal, Spinoso sardo, Tema and Violetto. Table 2 shows the BMP of artichoke residues from these varieties, while Table 3 shows the cultivated area and the biomethane potential in the 5 districts identified in the region, calculated basing on the local mix of varieties in De Menna et al. (2016).

2.1.2. Regional biogas sector

In 2015, the biogas plants under operation in Sardinia were 16 (Gestore Servizi Energetici, 2015). Primary data on authorized biogas plant feeding mix, actual diets, financial information, and energy crops prices were collected through interviews with plant owners, in order to select only operating agricultural digesters, fed at least partially with energy crops (namely maize and triticale). Table 4 shows the selected AD plants, while Fig. 1 shows their geographical distribution with respect to artichoke districts.

As the majority of Italian biogas plants, all these digesters were authorized and entered into service in 2012, with the exception of a_1 that started operating in 2013. All of them have a nominal power of 999 kW and they are receiving a feed-in tariff of 280 € MWh^{-1} produced, as foreseen by Law 99/23 July 2009 (Italian Parliament, 2009) for plants of this size. Secondary data were used to estimate crop yield and feedstock BMP: Fabbri and Pacchioli (2015) for maize and triticale, Bordoni et al. (2013) for ovine slurry and whey, and Soldano et al. (2011) for olive pomace.

2.2. Model development

Given the objectives of the study, a bioeconomic model was developed using multiple goal linear programming (MGLP) in GAMS® (Eiselt and Sandbolm, 2007). Fig. 2 shows the running framework of the Bioeconomic Byproducts Optimization (BioBO) model.

Note: Arrows indicate relations between modules of the model: black arrows refer to money flows (including investment); light grey arrows refer to mass flows; dark grey arrow refers to land use flow; dotted arrow refer to the utility function.

2.2.1. Utility function and objective functions

In BioBO, two scalar objective functions were defined on yearly basis for the regional agricultural biogas supply chain: the first calculates the overall land use (Eq. 1), deriving from cultivation of energy crops (maize and triticale) used in all biogas plants; the second computes the net present value (NPV) of the whole biogas network (Eq. 2).

$$A = \sum_{j}\sum_{ye} A_{j,ye} \tag{1}$$

$$Z = \sum_{j} (rev_j - C_j^{tot}) \tag{2}$$

Then, a dimensionless utility function (UF) was defined as a linear weighted combination of the two objective functions (Eq. 3), basing on Pomerol and Barba-Romero (2000):