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Trade-offs in land allocation for bioenergy production

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Abstract: Biomass as a renewable energy source is scarce and its exploitation must be accurately planned in order to maximize the energy produced, the GHG emissions avoided, and the sustainability of other ecological services. By-products and residues are one of the best sources of biomass since they are readily available at no or at a very low cost. Moreover, in some cases, the use of residues has positive co-benefits. This is the case of manure: typically its disposal constitutes a cost to the farm, whilst its energy use facilitates the disposal, produces energy and decreases GHG emissions. However, the conversion efficiency of manures alone is very low and, therefore, they are often used in combination with energy crops. These provide an important contribution to combustion processes as well. Our aim is thus to assess how much land should be allocated to the production of energy crops destined either to combustion or anaerobic digestion (AD) by formulating and solving a mathematical model that also determines the number, capacity, location and collection basin of each type of plants. The objective is to maximize the net energy produced accounting for energy needed to grow and transport biomass and to dispose of the digestate that results from AD conversion. This closely corresponds to the reduction of local CO₂ emissions. A case study for a farming area is presented. Results show that a careful analysis is needed to determine relevant trade-offs since they strongly depend on local conditions.

Keywords: Energy crops; Bioenergy; Combustion; Anaerobic digestion; Land allocation.

1 INTRODUCTION

Land provides food for an increasing world population (and a population whose food demand will increase), carbon sequestration that mitigates the effects of anthropic emissions and biomass feedstock for energy production. The estimates of global bioenergy potential vary from 350 EJ/yr (Fisher and Schratzenholzer, 2001) up to 1300 EJ/yr (IEA, 2001) and 2900 EJ/yr (Obersteiner et al., 2002). The question is thus how much of this potential can be exploited considering the conflict with food production and environmental impacts. For example, an MIT research (Reilly and Paltsev, 2007) shows that in a scenario of stabilization of greenhouse gases, an amount of land equivalent to the current global crop area is needed to meet the expected global bioenergy production. Furthermore, if only biofuels were considered, the amount of feedstock needed under a stringent US climate policy would turn the USA from a substantial net exporter of agricultural goods (\$20 billion) to a large net importer. This would clearly affect the global agricultural market. The problem is complicated by the concerns on food or energy security, biodiversity conservation and changes in landscapes and rural activities (e.g., Haughton et al., 2009).

The conflicts arising when considering the food vs. energy competition for land affect the whole planet. General equilibrium models of the world economy have been used to study these issues (e.g., Reilly and Paltsev, 2007; Fisher and Schratzenholzer, 2001). However, a large scale perspective forces strong assumptions on land availability and on its suitability for either food or energy crops,

so that the conflict is generally addressed by scenario analysis, i.e. setting a limit to the area that can be devoted to non-food agriculture. On the other hand, data on land cover, soil associations, precipitations and climate allow to better evaluate land availability and suitability. These data are commonly incorporated into local scale studies (Tenerelli and Carver, 2012; Fiorese and Guariso, 2010), that thus allow to evaluate the trade-offs among different land uses.

Furthermore, biomass can be converted into several forms of final energy (e.g., electric or thermal energy, liquid biofuels) with different effects on the local CO₂ emission balance. The choice depends on the available biomass supply, since different sources of biomass are suitable to different conversion routes (McKendry, 2002), and on energy demand. Both issues should be analysed at local scale. For example, thermal energy should be used close to the production sites, since transport or storage are expensive, when not impossible.

In this paper, we analyse one of the conflicts arising in land allocation when optimizing the production of bioenergy at local scale. To this purpose, we study the integrated use of biomass in two energy conversion chains, considering the competing use of land for energy crops, and their consequences on the local carbon budget.

2 ENERGY CONVERSION ROUTES

Two energy routes are considered throughout the paper: the direct combustion in cogeneration plants and the processing of biomass in anaerobic digesters with the use of biogas in traditional engines.

Lignocellulosic biomass is used to produce heat and electricity in cogeneration plants. Specifically, we considered Organic Rankine (ORC) and Rankine cycles, that are more suitable respectively for smaller (in the range 0,3 to 1,5 MWe), and for larger plants (Biomass Energy Report, 2009). These plants can provide district heating to a small municipality and electricity to the national grid. The electrical efficiency increases with the size of the system.

Manures and green biomasses are supplied to AD plants in order to guarantee sufficiently high process efficiencies: manure alone requires larger volumes and also produces lower amounts of biogas with respect to green biomass. We assume that the biogas is used in an internal combustion engine to produce electricity and heat, which are sold to the grid or used on site. The assumed minimum size is 110 kWe. Again, the electrical efficiency is a (nonlinear) function of the size of the plant (Fiorese et al., 2008).

We assume, as it is generally advised (McKendry, 2002), that biomasses with higher moisture are suitable for biochemical conversion processes (AD) and those with less moisture for thermochemical processes (combustion). Therefore, in our analysis, agricultural residues, forest residues and wood by-products are supplied to cogeneration plants, whereas agro-industrial residues and manures are destined to AD processes. There is, however, some biomass that is suitable for both conversion processes, as it is the case for herbaceous energy crops (such as sorghum). Our aim is thus to determine the best distribution of the available herbaceous energy crops between the two conversion routes.

Whatever the path, each step of the energy conversion chain implies a certain emission of GHGs. At the same time, emissions are avoided thanks to the production of energy by biomass instead of fossil fuels.

3 THE DECISION PROBLEM

We developed an optimization model in order to decide the amount of land to devote to the cultivation of herbaceous energy crops for combustion or biogas plants, the number of plants to be built for each technology, their size, location and relative supply basin. The objective function maximizes the net production of energy and, thus, it is formulated in terms of the energy produced and used. As it will be shown later, this objective closely corresponds to the minimization of the net CO_{2eq} emissions.

First, we defined the boundaries of the two conversion routes. Second, we considered all the main activities, sources and technologies that contribute to the creation, processing and distribution of energy and its related products. This is the so-called “supply chain” and it portraits the structure of the energy system, from the procurement of biomass to the distribution of the energy products. Specifically, we describe two supply chains corresponding to the two alternative conversion routes. The two chains are distinct and independent, except for the use of herbaceous energy crops, for which they compete, as shown in Figure 1. The analysed system can therefore be decomposed into the following parts: procurement of residual biomass and cultivation of energy crops; biomass transportation from the production site to the energy conversion site; production of electric power and of thermal energy; disposal of waste products resulting from the energy conversion processes.

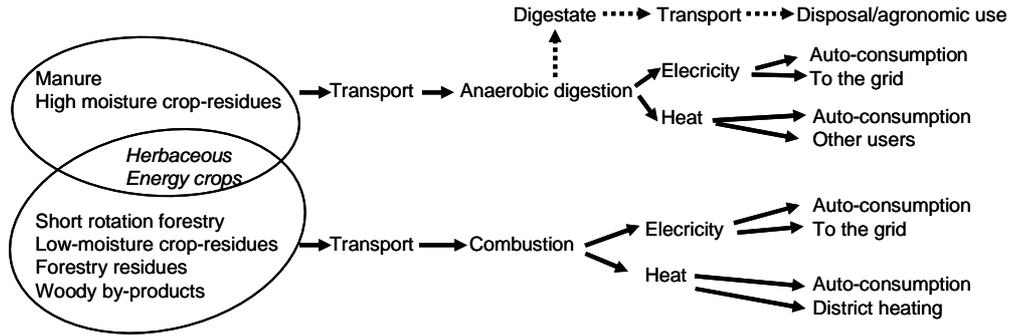


Figure 1. Schematic description of the two conversion routes. Herbaceous energy crops compete for the supply of biomass to either route.

3.1 Decision variables

We formulate the energy optimization problem in discrete terms, i.e. we subdivide the area in a number of parcels, representing biomass supply areas and/or possible location sites for the plants. The decision variables thus represent the overall exploitation of biomass along the two routes and the subdivision of herbaceous energy crops between them. More precisely, they are of three types:

- the amount of dry biomass conferred from each parcel to each cogeneration plant and the amount of wet biomass conferred to each biogas plant;
- the amount of land in each parcel devoted to the cultivation of herbaceous energy crops that is conferred to each combustion plant and that conferred from the parcel to each biogas plant;
- the presence or not of a combustion ($y_j=0,1$) or a biogas ($z_k=0,1$) plant in a given parcel.

3.2 Objective function

The objective function is the maximization of the net energy balance J_{en} . It is given by the algebraic sum of the energy produced ($EN_{combustion}$ and EN_{AD}), the energy used to cultivate and collect energy crops and residual biomass (EN_{dry_biom} and EN_{wet_biom}), the energy used to cultivate and collect herbaceous energy crops ($EN_{herb_en_crop}$), the energy needed to transport the biomass ($EN_{dry_transport}$ and $EN_{wet_transport}$) and the digestate for its final disposal ($EN_{digestate}$). These terms are summed over all the n parcels where a cogeneration plant and the m where a biogas plant can be sited:

$$J_{en} = \sum_{j=1}^n (EN_{combustion} - EN_{dry_biom} - EN_{dry_transport} - EN_{herb_en_crop}) \cdot y_j + \sum_{k=1}^m (EN_{AD} - EN_{wet_biom} - EN_{wet_transport} - EN_{herb_en_crop} - EN_{digestate}) \cdot z_k$$

The methods suggested in Fiorese et al. (2008) and Fiorese and Guariso (2010) were adopted to calculate the value of each term of the objective function and thus to define the set of parameters that describes each conversion alternative. However, here we extend what was already in the literature by considering together different energy routes and including the additional possibility of a crop common to different routes. With regards to biomass procurement, the energy requirement for growing and collecting energy crops is needed. This value includes the energy needed to operate agricultural machineries and to produce and apply fertilizers and other chemicals. The energy to transport the biomass from each parcel to each plant is given by the product of the transportation energy consumption per unit distance per unit biomass, the roundtrip distance and the amount of biomass that is transported. Different transportation energy consumptions have been considered for each type of biomass.

The AD process produces consistent amounts of digestate, a product that should be disposed of. We assume that it is possible to return the digestate to the originating parcel and to use it as a fertilizer. Therefore, the model accounts for this additional transport.

The thermal and electric energy produced in each plant is estimated from the amount of biomass supplied to the plant over the year and the efficiency of the conversion process. We account for economies of scale, so that larger plants have higher conversion efficiencies.

The decision problem is thus represented by a nonlinear mixed integer optimization model for the non-linearity of the relation between the efficiency and the size of the plants.

The solution of such optimization problem can be evaluated also assessing the local net carbon equivalent emissions balance. We assumed that the overall energy produced from biomass replaces the thermal and electric energy produced from fossil fuels (in Italy, mainly natural gas), and accounted for the avoided emissions from improved manure disposal (methane emissions from traditional storage and spreading on agricultural land) and the emissions produced (crop cultivation and transportation of crops, manure, and digested substrates).

3.4 Constraints

A first set of constraints ensures that the biomass conferred to the plants does not exceed the amount that is actually available, for each type of biomass in each parcel. An equivalent set of constraints is imposed on the amount of land that can be used to cultivate herbaceous energy crops and that must not exceed that available for the purpose in each parcel. A third set of constraints imposes a maximum size for each cogeneration and for each biogas plant. Finally, a set of constraints regulates the functioning of AD plants and in particular the mix of manure and green biomass (wet biomass and herbaceous energy crop) that is fed to the digesters.

It is also possible to impose other constraints to adapt the model to each specific case study. For example, a minimum amount of manure to be processed may be imposed, which implies a consequent destination to AD of a fixed minimum fraction of bioenergy crops.

4 DESCRIPTION OF THE CASE STUDY

The optimization problem has been applied to the district of Piacenza, an important Italian farming area in Northern Italy. The district is located between the Po river and the Apennines and it encompasses an area of 2,589 km² divided into 48 municipalities. We assessed the availability of biomass from residual sources (crop residues, forestry by-products, agro-industry by-products) and from animal husbandry (cattle and swine), using the approach described in Angelis-Dimakis et al. (2011). We also suppose that poplars, which are a common crop in Northern Italy, can be grown in short rotation forestry (SRF) plantations on abandoned land (Fiorese and Guariso, 2010) to supply combustion plants. The amount of land that can be dedicated to herbaceous energy crops has been estimated considering how

much suitable land is available; only abandoned land was taken into account so that no land is subtracted to food crops (Fiorese and Guariso, 2010). Sweet sorghum is assumed as the typical herbaceous energy crop for its interesting average yield of 24 dry ton per year (Bonari et al., 2004). The amount of biomass potentially available in the district is shown in Table 1.

Finally, among all the 48 municipalities, we select as potential plant sites only those that have enough demand for thermal energy. We use as a proxy of this demand the number and density of inhabitants (municipalities with more than 5000 inhabitants and a density above 100 inhabitants per km²). As for biogas plants, we assume that the heat produced by the plant can be used on farm; this is realistic since the amount of heat remaining after auto-consumption is small.

Table 1. Potential availability of biomass in the district of Piacenza.

Conversion route	Sources of biomass	Availability
Combustion	Residuals	66 10 ³ dry t/year
	Poplar SRF	11 10 ³ dry t/year
Biogas	Bovine manure	109 10 ³ om t/year
	Swine manure	20 10 ³ om t/year
	Agro-industry (tomato)	41 10 ³ om t/year
Both	Sorghum	max 64 10 ³ dm t/year

5 RESULTS

For the size of Piacenza district (less than 100 parcels), the nonlinear optimization problem can be solved by a commercial software package without significant computational burden. We solved the problem considering two alternative energy plans: the first, more distributed, involves smaller plants (maximum 1.5 MWe for cogeneration and 0.65 MWe for biogas) and the second entails a more concentrated use with larger plants (maximum 5 MWe for cogeneration and 1.5 MWe for biogas). Given the biomass characteristics, a distributed resource, we expect from the first plan low energy requirements for biomass transportation, but also a lower efficiency. Larger plants can in fact benefit from economies of scale for the conversion efficiency, but on the other hand the transport of biomass to fewer locations will require more energy.

5.1 Alternative 1 (Small plants)

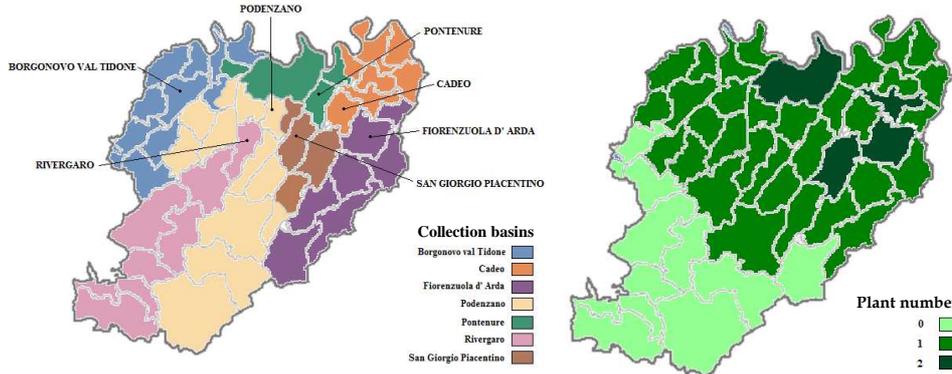
The solution of the decision problem suggests that 7 cogeneration plants (overall 10 MWe power) and 40 biogas plants (overall 25 MWe power) can be sited in the district. Six combustion plants reach their maximum size of 1.5 MWe, while the seventh has a lower power (750 kWe). Of the 40 biogas plants, as many as 37 have an electrical output of 650 kWe corresponding to the assigned limit. Figure 2 shows, on the left, the allocation basins of the combustion plants and, on the right, the number of biogas plants in each municipality of the district.

The optimal value of net energy production is 1.8 10⁹ MJ per year, corresponding to 44.3 Gtoe/year. The energy benefits are two orders of magnitude bigger than the energy costs (growing of energy crops and transportation), as it emerges from the values of the components of the objective function in Table 2. Similarly, GHG emissions due to agricultural activities and biomass transportation are small fractions of those of fossil fuels replaced. Therefore, the maximization of the production of energy is a proxy for the maximization of the net GHG avoided in the system (Table 2).

The share of available herbaceous energy crop that is devoted to biogas is 53% while the remaining 47% goes to combustion plants. Note, however, that due to the additional constraint imposed (the digestion of at least half of the available manure), about half of the total is already bound to be used for biogas.

Table 2. Results of the optimization model in the district of Piacenza.

		Alternative 1	Alternative 2
Energy objective	10^6 MJ/yr	1853	2078
Energy requirements			
<i>Energy crops</i>	10^6 MJ/yr	80	80
<i>Transportation</i>	10^6 MJ/yr	2.8	4.6
Energy produced			
<i>Electric</i>	10^6 MJ/yr	903	1036
<i>Thermal</i>	10^6 MJ/yr	1033	1127
Avoided GHG emissions	10^3 ton CO _{2eq} /yr	101	112

**Figure 2.** Optimal sites and allocation basins for the cogeneration plants (left) and for biogas plants (right) for Alternative 1.

5.2 Alternative 2 (Larger plants)

With respect to Alternative 1, the result of the optimization model proposes a lower number of cogeneration plants (2 plants, each with a size close to 5 MWe) and 38 biogas plants (with an average size of 800 kWe). In this latter case, even though larger scale biogas plants can be chosen, the optimization model favors again a high number of small scale plants. The localization of the biogas plants resembles the one pictured in Figure 2.

The optimal value of the energy objective is $2.1 \cdot 10^9$ MJ per year and also the value of GHG emissions improves as shown in Table 2. From the terms of the energy objective in the same table, it is possible to observe that the energy needed to transport the biomass increases with respect to the distributed energy system. This is because the biomass devoted to combustion is allocated to fewer and larger plants, therefore increasing the hauling distances. However, transportation impacts by only 0.2% of the overall energy objective.

Finally, the available share of herbaceous energy crop that is devoted to biogas is 93%, while the remaining 7% goes to combustion.

The increase of scale of the plants favours the energy production from biogas plants, at the expense of combustion ones. This can be explained by the different shapes of the functions that describe the efficiency for the two conversion routes: that related to biogas grows faster than that for combustion.

6 DISCUSSION

Observing the results on the distribution of sorghum between combustion and biogas (Table 3), it clearly appears that its use in biogas plants is more advantageous as confirmed by the calculation of the marginal energy benefit of a ton of sorghum at the scale of the average plant.

However, this conclusion is only local around the current solutions. If a larger amount of land is available for growing herbaceous energy crops the marginal

value may rotate in favour of combustion. In the Piacenza district, there is in fact a significant amount of land (700 ha) previously grown with sugar beet recently dismissed (to comply with the EU agricultural policy; EC, 2006). In this new situation, the share of energy crops that goes to cogeneration plants is 53% and that of biogas plants decreases to 47%.

In all cases, the maximum size of biogas plants allowed by the decision problem is never reached. They are just the size suitable for a single farm or by an aggregation of few farms. This means that the cost of extended transportation of manure to the plant and the digestate back to the field is too high to be compensated by the increased efficiency of larger plants. On the contrary, the size of cogeneration plants increases when it is allowed to do so by modifying the constraints in the model. This increase is conditioned, as previously pointed out, by the different shape of the function that relate efficiency and size for the two conversion routes.

Table 3. Performance of the system under different assumptions on plants' maximum size.

		Alternative 1	Alternative 2
Maximum plant size (MWe)	Cogen.	1.5	5
	Biogas	0.65	1.5
Number of plants (and average size in MWe)	Cogen.	7 (1.4)	2 (4.5)
	Biogas	40 (0.6)	38 (0.8)
Share of land to conversion route (%)	Cogen.	47	7
	Biogas	53	93

7 CONCLUSIONS

On average in the past ten years, about $422 \cdot 10^3$ ha have been used in the district of Piacenza to grow food crops such as wheat, maize and other cereals (Regione Emilia-Romagna, 2011). The area that we assume to use for herbaceous energy crops amounts to 2675 ha, or 0.6% of the area devoted to cereals. However, if we sum the amount of energy crops produced on this small share of land to all the residual biomass potentially available in the district, the overall contribution to the energy mix and to a carbon mitigation policy becomes significant. According to the different alternatives, biomass can supply around 10% of the total demand of electricity in the district of Piacenza (2,800 GWh in 2009). Furthermore, if we compare the electricity that can be produced in biogas plants and the demand in the agricultural sector, biogas plants can by far satisfy the whole demand (the production is 260-360% of the demand). Moreover, the bioenergy sector may contribute to about one fourth of the total carbon emission reduction required to meet the target sets in the Kyoto protocol (about 480 kt CO_{2,eq}; Regione Emilia-Romagna, 2009) if the plans outlined here are implemented.

Results for small plant sizes show that the use of herbaceous energy crops is more convenient in biogas plants: a highest share of the crop competing between the two conversion routes goes to biogas plants in most cases. The problem that we solved for the district of Piacenza sheds interesting insights over the policies that the local administration can undertake to mitigate global climate change and to promote renewable sources of energies. Only a detailed analysis performed at local scale can in fact take into account all the specific features of the system. In our case, for instance, the presence of a significant amount of manure drives the results towards a more intensive use of biomass in biogas plants and this conversion route should certainly be promoted by the local administration since it has several co-benefits, such as avoiding the methane emissions of the traditional disposal of manure, and has positive economic returns.

The proposed model can however be applied to other case studies to inform energy and carbon mitigation plans because the approach is based on readily available data and some conclusions, such as the large predominance of the avoided emission term in the carbon balance, are very general.

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