# Optimizing biogas production: an application to an Italian farming district

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# Optimizing biogas production: an application to an Italian farming district

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**Abstract:** Biogas can be extracted from animal manure through anaerobic digestion (AD) and can afterwards be used to produce energy. Moreover, this process reduces completely methane emissions and stabilizes the manure before its agronomic use. AD plants can be built in a wide range of capacities: as capacity increases, economies of scale in capital equipment are realized, but transportation costs increase as manure and the digested substrates must be conveyed over longer distances. It is thus a key issue to assess the tradeoffs between biomass' transportation and plants' capacity. We propose a method to evaluate the AD plants' convenience on a given territory by an economic, energy and emissive point of view. A mathematical model is formulated in order to optimize biomass use by finding the optimal AD plants' number, capacity, location, and the corresponding biomass collection basin. The method is applied to the district of Cremona, one of the most important Italian farming areas. The optimal solution is achieved by widespread AD plants over the territory in order to exploit biomass locally. Biomass transportation is minimized for its high costs are not balanced by economies of scale. AD plants in Cremona yield positive returns in economic terms, as energy produced and GHG emissions avoided (7% reduction with respect to 2003). The robustness of this result has been confirmed by sensitivity analysis of the plant and transportation costs. The final result is crucial for local planning of biomass exploitation: local governments can encourage the development of conversion plants at municipal level without the need for centralized decisions.

***Keywords:*** anaerobic digestion; biogas; plant location; GHG emissions.

## 1. INTRODUCTION

Anaerobic Digestion (AD) is a biological process in which microorganisms break down biodegradable material producing biogas suitable for energy conversion, thus helping replace fossil fuels. Biogas can in fact be burned and converted into heat and power in cogeneration plants. Moreover, the nutrient-rich solids left after digestion can be used as fertiliser. In recent years, this bio-energy conversion technology has been developing as one of the most attractive renewable energy resources especially in Northern Europe (Germany, UK and Denmark) [Dagnall and Wooley, 2008]. The agricultural-zoothecnical sector represents a great source for the production of substrates for anaerobic digestion, e.g. agricultural residues, animal manure and energy crops.

In Italy, one of the main problems concerning farming areas is animal manure management, mainly because of methane and malodorous atmospheric emissions produced by manure, as well as excessive nitrogen load on soils. Currently only a storage period in tanks is imposed by law for this kind of waste before spreading on the agricultural land, but this system turns out to be ineffective with reference to the emissions issue. In this context, AD of manure represents a valid solution that offers at the same time the possibility to produce energy and to completely reduce $CH_4$ emissions, making the manure stable before its agronomic use.

AD plants can be built in a wide range of capacities. As capacity increases, economies of scale in capital equipment are realized, but transportations costs increase as manure and other substrates must be conveyed over longer distances to the plant site [Marrison e Larson, 1995]. As a result, estimating the convenience of biomasses transportation in realizing central plants turns out to be a key issue. This is particularly important for manure because of its low energy content. For these reasons, we propose a methodology to define the AD energy system configuration that optimizes plants' size and location, accounting for economic, energy and emissive performances. The optimization problem formulated for this purpose derives from the standard approach described in the literature [e.g., Drezner and Hamacher, 2001]. As a case study, the method is applied to the district of Cremona in Northern Italy.

## 2. BIOGAS ENERGY CONVERSION TECNOLOGY

Many different feedstocks can be fed to AD plants: agricultural residues, dedicated energy crops, animal manure [e.g., Borjesson and Berglund, 2007]. We assume in the following to feed only bovine and pig manure to AD plants. In order to reach a uniform organic matter content, row materials are mixed together before being fed to the digesters; these are continuously stirred tank reactors and operate with a maximum temperature of 55°C (thermophilic conditions). The digested effluent is stocked in one or more storage tanks. The gas produced in the digester is flushed through a condenser and a sulphide scrubber and collected in a gas storage tank. We assume that the biogas losses in the process are negligible.

The biogas produced is then used in a co-generation system to produce heat, with a constant efficiency ($\eta_{heat}$), and electricity, with an efficiency ($\eta_{el}$) function of the nominal plant capacity (*Pe*) as in Figure 1. The generator is connected to the plant circuits consisting of a mixer, pumps and gas blower and supplies the needed electricity. The heating of the digester and of the manure before being added to the digester is achieved by the hot water circuits. Capital costs for the construction of this type of AD plants are function of the plant nominal capacity, according to a moderate scale economy as pictured in Figure 2.

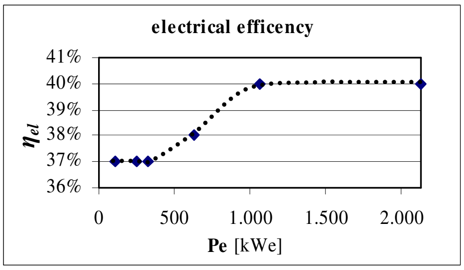


**Figure 1.** Electrical efficiency ($\eta_{el}$) as a function of AD plant nominal capacity [UTS, 2007].

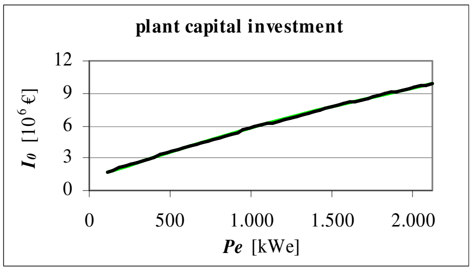


**Figure 2:** Capital investment ($I_0$) as a function of AD plant nominal capacity [UTS, 2007].

## 3. THE DECISION PROBLEM

A decision problem is formulated in order to optimize the biomass energy use by finding the optimal AD plants number, location, capacity, and the corresponding collection basin on a given territory. Similar models have been used to design the optimal use of ligno-cellulosic biomass in co-generation plants [Fiorese *et al.*, 2006; Freppaz *et al.*, 2004]. The studied area is divided into *N* parcels, each with its own biomass availability that is assumed to be concentrated in the centre of the parcel. Though not strictly necessary, we assume in the following that only one AD plant can be assigned to each parcel and the all biomass must be treated. As shown in Figure 3, the model comprises the following terms:

- The cost of bovine and pig manure transport from the *i*-th origin parcel to the *j*-th destination plant in special trucks with 30 ton capacity [Ghafoori *et al.*, 2007];

- The cost of digested biomass transport from the *j*-th plant back to its *i*-th parcel of origin where it is finally used as a fertiliser;
- The cost of building and operating each *j*-th AD plant;
- The revenues from the heat and the electricity sold, accounting for auto-consumption, and from the national incentives for renewable energy.

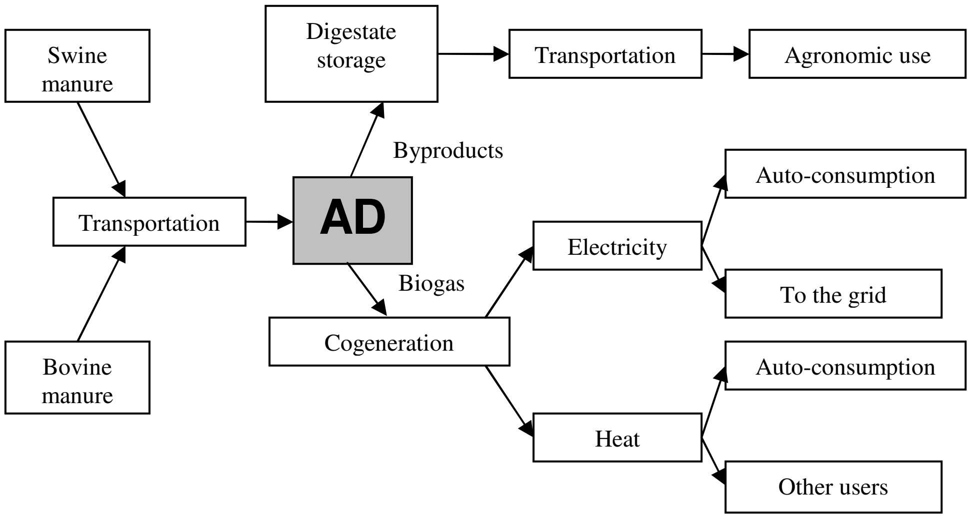


**Figure 3.** Bio-energy supply chain.

### 3.1 Decision variables

The decision variables ($x_{ij}$) are the fractions of biomass in the *i*-th parcel conferred to the *j*-th plant. Two auxiliary variables can be derived once the optimal values are determined. The first is the nominal plant capacity, $Pe_j$, of the *j*-th plant which is a linear function of biomass supply calibrated from experimental data of cogenerative plants currently acquirable in the area (capacities in the range 100 to 2100 kW):

$$Pe_j = -26{,}31 + 0{,}0003 \cdot \sum_{i=1}^{N} \sum_{s} (a_{i,s} \cdot f_{b,s} \cdot b_s) \cdot x_{ij} \qquad (1)$$

The second, $y_i$, simply accounts for the presence or absence of a plant in the *j*-th parcel:

$$y_j = 1 \ \ if \ \ \sum_{i=1}^{N} x_{ij} > 0, \qquad y_j = 0 \ \ otherwise \qquad (2)$$

### 3.2 Objective function

The decision variables value is assigned by maximizing the economic return from energy production that represents the objective function ($J_{EC}$) of the decision problem. The economic return is formulated through the net present value (*NPV*) method:

$$J_{EC} = \sum_{j=1}^{N} NPV_j = \sum_{j=1}^{N} \left( -\frac{I_{0,j}}{(1+r)^{-1}} + \sum_{t=0}^{19} \frac{F_{j,t}}{(1+r)^t} \right)_j \qquad (3)$$

where *NPV* is calculated considering the discount rate *r*, assumed constant, the cash flow ($F_{j,t}$) for the *j*-th plant in year *t* and the capital investment ($I_{0,}$ Figure 2); a 20 years life period is assumed for AD plants, plus one year for plant construction. The annual cash flow is given by:

$$F_{j,t} = EC_{energy\ j,t} - \left( EC_{main,j} + EC_{oper,j} + EC_{transp,j} \right) \qquad (4)$$

where $EC_{energy}$ represents the expected benefits from energy production, $EC_{main}$ and $EC_{oper}$ represent plant maintenance and operation costs and $EC_{transp}$ represents biomass transportation costs.

All the parameters used in the model are listed in Tables 1 and 2 (for details refer to Polimeni, 2007).

**Table 1.** Parcel dependent parameters in the objective function.

| Symbol | Description | Unit of measure |
|---|---|---|
| $d_{ij}$ | Distance between the *i*-th parcel and the *j*-th plant | km |
| $a_{i,s}$ | Biomass available in the *i*-th parcel, *s*=1 for bovine manure and *s*=2 pig manure | t |
| $f_{b,s}$ | Organic fraction in the *s*-th biomass | - |

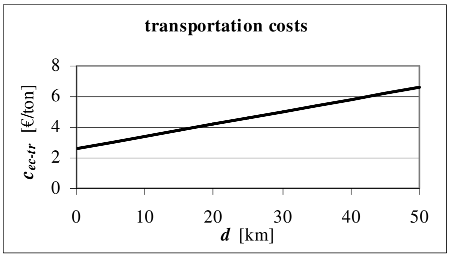


**Figure 4.** Transportation costs as a function of distance.

**Table 2.** Parameters used in the objective function and in the calculation of the emissive and energy indicators.

| Symbol | Description | Value | Unit of measure |
|---|---|---|---|
| $b_s$ | Biogas yield for biomass *s* | 420 – 460 [(a)] | $m^3_{biogas}/t_{om}$ |
| $LHV_{biogas}$ | Biogas low heating value | 19,4 [(a)] | $MJ/m^3_{biogas}$ |
| $fd_s$ | Digestate fraction for biomass *s* | 0,96 – 0,98 [(b)] | - |
| $OH$ | Hours of operation | 7468 [(a)] | hours/year |
| $\eta_{heat}$ | Plant heat efficiency | 0,44 [(a)] | - |
| $f_{el}$ | Electrical auto-consumption fraction | 0,095 [(a)] | - |
| $f_{heat}$ | Heat auto-consumption fraction | 0,85 [(a)] | - |
| $fc_{ec\text{-}tr}$ | Fixed economic transportation cost | 2,6 [(c)] | €/t |
| $vc_{ec\text{-}tr}$ | Variable transportation cost | 0,08 [(c)] | €/km/t |
| $c_{en\text{-}tr}$ | Energy for transportation | 0,984 [(d)] | MJ/km/t |
| $c_{em\text{-}tr}$ | Transportation emission | 0,076 [(d)] | kg $CO_{2\,eq}$/km/t |
| $ef_{cogen}$ | Cogeneration emission factor | 0,147 [(e)] | kg $CO_{2\,eq}/m^3_{biogas}$ |
| $ef_{ng,el}$ | Natural gas electrical emission factor | 0,098 [(d)] | kg $CO_{2\,eq}$/MJ |
| $ef_{gn,term}$ | Natural gas heat emission factor | 0,07 [(d)] | kg $CO_{2\,eq}$/MJ |
| $p_{el}$ | Electrical energy price | 0,074 [(f)] | €/kWh |
| $p_{gc}$ | Green certificates price | 0,125 [(f)] | €/kWh |
| $p_{heat}$ | Heat price | 0,08 [(g)] | €/kWh |
| $c_{main}$ | Plant maintenance costs | 0,03 [(a)] | €/kWh |
| $T$ | Plant lifetime | 20 | years |
| $t_{gc}$ | Green certificate duration | 12 | years |
| $r$ | Annual discount rate | 3 | % |
| $C$ | Maximum plant nominal capacity | 2127 | kWe |

[(a)] UTS, 2007; [(b)] Provolo, 2004; [(c)] adapted from Ghafoori et al., 2007; [(d)] Spiellman et al., 2004; [(e)] NERI, 2001; [(f)] GRTN, 2007.

### 3.3 Economic benefits and costs calculation

Economic benefits from energy production are given by revenues from selling the heat and the electricity produced (excluding the fraction, $f_{el}$, needed for auto-consumption), and the associated green certificates, which are an Italian incentive for the development of renewable energy resources:

$$EC_{energy,j} = (p_{el} + p_{gc}) \cdot EN_{out-el,j} + p_{heat} \cdot EN_{out-heat,j} \tag{5}$$

The electricity $EN_{out\text{-}el}$ and the heat $EN_{out\text{-}heat}$ produced are calculated as follows:

$$EN_{out-el,j} = \frac{1}{3{,}6} \cdot (1 - f_{el}) \cdot \eta_{el,j} \cdot LHV_{biogas} \cdot \sum_{i=1}^{N} \sum_{s} (a_{i,s} \cdot f_{b,s} \cdot b_s) \cdot x_{ij} \tag{6}$$

$$EN_{out-heat,j} = \frac{1}{3{,}6} \cdot (1 - f_{heat}) \cdot \eta_{heat} \cdot LHV_{biogas} \cdot \sum_{i=1}^{N} \sum_{s} (a_{i,s} \cdot f_{b,s} \cdot b_s) \cdot x_{ij} \tag{7}$$

where $\eta_{el,j}$ is a function of $j$-th plant capacity as in Figure 1. Plant maintenance costs ($EC_{main}$) are calculated as a fraction $c_{main}$ of gross energy output, whilst operation costs ($EC_{oper}$) are calculated as a function of the plant nominal capacity.
Finally, transportation costs ($EC_{transp}$) are the sum of manure ($EC_{tr\text{-}manure}$) and digestate ($EC_{tr\text{-}digested}$) round-trip transportation costs. They comprise both fixed costs ($fc_{ec\text{-}tr}$) representing loading and unloading operations, and variable costs ($vc_{ec\text{-}tr}$), function of the distance as shown in Figure 4 (adapted from Ghafoori *et al.*, 2007 to the current regional situation):

$$EC_{tr-manure,j} = \sum_{i=1}^{N} \sum_{s} \left[ \left( vc_{ec-tr} \cdot d_{ij} + fc_{ec-tr} \right) \cdot a_{i,s} \cdot x_{ij} \right] \tag{8}$$

$$EC_{tr-digestate,j} = \sum_{i=1}^{N} \sum_{s} \left[ \left( vc_{ec-tr} \cdot d_{ij} + fc_{ec-tr} \right) \cdot a_{i,s} \cdot fd_s \cdot x_{ij} \right] \tag{9}$$

### 3.4 Constraints

Two types of constraints have been defined. The first imposes that, in each $i$-th parcel, all the available biomass is carried to AD plants, because of the necessity of stabilizing manure:

$$\sum_{j=1}^{N} x_{ij} = 1 \qquad \forall i \tag{10}$$

and the second imposes that the nominal capacity of each $j$-th plants is limited to a maximum value $C$ (due to the technology of the plant itself):

$$Pe_j \le C \qquad \forall j \tag{11}$$

To avoid very small plant sizes, a penalty has been established on low capacities.

## 4. THE ENERGY AND ENVIROMENTAL INDICATORS

An energy indicator ($I_{EN}$) and an emissive indicator ($I_{EM}$) are defined to evaluate the solution of the optimization problem. $I_{EN}$ estimates the system net energy production (MJ/yr) from the heat and electricity ($EN_{out}$) minus the energy needed for the transportation of biomass, both of manure from the parcel to the plant and of the digestate the way back ($EN_{transp}$):

$$I_{EN} = \sum_{j=1}^{N} \left( EN_{out,j} - EN_{transp,j} \right) \tag{12}$$

$I_{EM}$ assesses the system GHG mitigation potential (t $CO_{2,eq}$/yr): it comprises the avoided emissions (methane emissions from traditional storage, $EM_{storage}$; emissions from fossil fuels combustion for an equivalent amount of energy, $EM_{fossil}$) and the emissions produced (cogeneration emissions, $EM_{cogen}$; emissions for the transportation of both manure and digested substrates, $EM_{transp}$):

$$I_{EM} = \sum_{j=1}^{N} \left( EM_{storage,j} + EM_{fossil,j} - EM_{cogen,j} - EM_{transp,j} \right) \tag{13}$$

## 5. DESCRIPTION OF THE CASE OF STUDY

The optimization problem presented above has been applied to the district of Cremona, one of the most important Italian farming areas in Northern Italy. The district is located in the plain of the Po valley and it encompasses an area of 1.770 km$^2$ divided in 115 municipalities. The agro-industrial sector is of major importance in the economy of the district. Particularly, the area is characterized by a large number of feedlots: official data of year 2000 indicated an animal density of 157,2 bovines and 363,5 swine per km$^2$, whereas these figures are respectively 20,7 and 28,7 for Italy [ISTAT, 2000].
The amount of animal manure available in the district of Cremona is estimated from the number of bovines and pigs in the area [ISTAT, 2000]. The parameters used to derive the potential biomass supply and its organic content (the fraction important for the anaerobic digestion process) from the animal number are listed in Table 3, while the numbers of animals and potential biomass supply for the district are listed in Table 4. We estimate a total production of 190 million m$^3$ of biogas per year.
Because biomass is largely distributed over the area of study, we perform the analysis at the finer spatial scale allowed by the available data. This means we have used the municipalities as parcels, except for those whose biomass could supply more than one plant, which were split into two parts. Therefore, in the optimization model the number of parcels considered is equal to 124 (average size of 14 km$^2$).

**Table 3.** Parameter used to assess the availability of biomass.

| Parameter | Bovines | Swine |
|---|---|---|
| Manure production (t/unit/day) [(a)] | 0,05 | 0,01 |
| Dry matter content (%) [(b)] | 8 | 4,5 |
| Organic matter content in dry matter (%) [(b)] | 86 | 90 |
| Organic matter content in manure (%) [(b)] | 6,9 | 4,1 |

[(a)] Ab Energy [2007]; [(b)] UTS [2007].

**Table 4.** Number of animals in the district of Cremona, relative biomass supply and potential biogas production.

| | Bovines | Swine |
|---|---|---|
| Animal units [(a)] | 278.270 | 643.656 |
| Manure production (10$^3$ t/year) | 5.078 | 2.349 |
| Organic matter production (10$^3$ t /year) | 349 | 95 |
| Biogas production (10$^6$ m$^3$/year) | 147 | 43 |

[(a)] ISTAT [2000].

## 6. RESULTS

The overall non linear optimization problem can be solved by a commercial software package without significant computational problems. Its solution entails AD plants distributed over the territory in order to exploit locally produced biomass. For the whole district, the optimal solution foresees the realization of 105 plants of small-medium capacities (Figure 5). Only a few parcels (in white in Figure 5) do not have enough biomass on their territory and, therefore, do not host any plant. Three plants have a capacity over 1 MWe (the two largest plants have a capacity of 1,7 MWe), all other plants are smaller. This means that biomass transportation is minimized. Its high costs are not balanced by savings achievable exploiting the economy of scale of centralized plants and thus the upper capacity constraint is not active in the optimal solution.
The solution shows that biomass exploitation in AD plants yields positive returns in economic terms (the NPV exceeds 300 M€, but is slightly overestimated because the collection costs within each municipality have been disregarded), energy produced (1.500 TJ/yr) and $CO_{2,eq}$ emissions avoided (300 Gg $CO_{2,eq}$/yr). Economic return is strongly influenced by the presence of public incentives for power production from renewable sources: when the green certificates price ($p_{gc}$) is set to zero, the objective function may

become negative. However, in a carbon constrained world with a carbon market, the $CO_{2eq}$ avoided emissions may also be evaluated in economic terms. Assuming a value of 19 €/t $CO_{2,eq}$ (ExternE, 2007), the objective increases of 26% and the overall plan may still be balanced even without incentives.

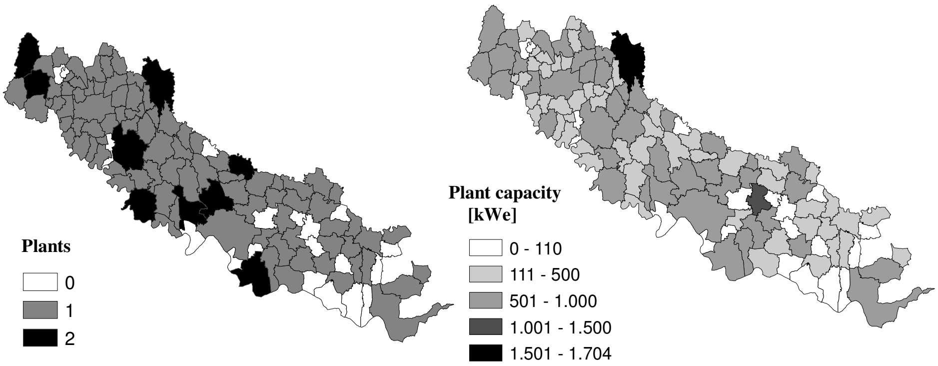


**Figure 5.** Optimal plant distribution in terms of number (left) and size (right).

An extensive sensitivity analysis was carried out to check the robustness of results obtained. Varying the plant cost curve shows that economies of scale cannot compensate transportation costs over a wide range of plant capacities. The optimal solution changes only when transportation costs are drastically reduced: if fixed transportation costs are set to zero, the optimal solution is characterized by 27 centralized plants. Moreover, even annulling fixed transportation costs, if the variable transportation costs increase, as it is quite probable in the near future, the optimal solution rapidly goes back to a more decentralized one, with a decrease of the economic performances of about 20% for a tenfold transportation cost, as shown in Figure 6 and Figure 7.

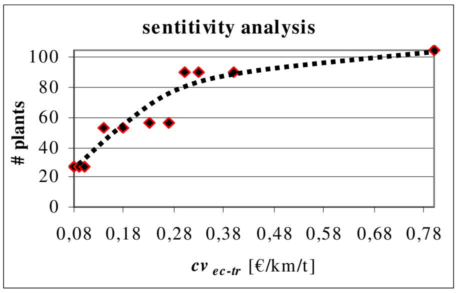


**Figure 6.** Optimal number of plants as a function of variable transport costs

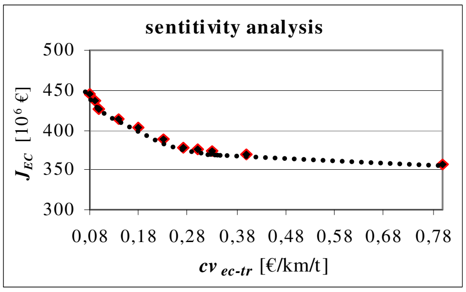


**Figure 7.** Optimal economic objective as a function of variable transport costs

## 7. CONCLUSIONS

The implementation of the proposed methodology led to an optimal solution in which the low energy content and the high manure transportation costs suggest the construction of small-medium AD plants distributed all over the studied area. Sensitivity analysis confirms that this solution is robust for a wide variation of plant investment and manure transportation costs. Thus local governments can encourage the construction of conversion plants at municipal level without the need for central planning, exploiting locally produced biomass. To implement this plan, the model solution should be integrated with GIS tools to define actual plant location taking into account the existing infrastructures, protected areas and other local constraints, as suggested by Ma *et al.* [2005].
The distributed solution in the district of Cremona leads to positive returns in economic terms (4 years for investment payback), energy produced (13% of the district power

consumption in 2005) and, most of all, avoided $CO_{2eq}$ emissions (7% reduction with respect to 2003). The proposed plan allows the district of Cremona to effectively contribute to national $CO_2$ balance: the Kyoto Protocol set the Italian reduction target to 6,5% with respect to 1990.

## ACKNOWLEDGEMENTS

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