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Decision Support System for Anaerobic Digestion Optimal Feeding and Localization

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In Italy, the extension and widespread cultural diversification find a strong ally in the energy of agricultural, zootechnical, and agro-industrial matrices through Anaerobic Digestion and in particular in "Co-digestion", a technique based on the joint use of different biomass which allows achieving higher energy yields respect to the simple digestion. To date, this technology is exploited to treat mainly zootechnical waste and energy crops, and in many agricultural cases this is an obligatory choice, as the availability of residual biomass is modest and it is composed almost exclusively by wastewater; therefore a not negligible extension of the company / extra-company Utilised Agricultural Area (UAA) for dedicated cultivation is often needed to improve yield and make the digestion economically sustainable.
In this context, the use of agro-industrial residues available in primary processing industries operating at "zero km" to the digestion plant would help the entire supply chain both from an economic, energetic and environmental point of view, as the energy content of by-products is often comparable or higher to that of energy crops.
The objective of this work is focused on the development of a decision support tool aimed at technical assistance for the installation of small, medium, and large-scale biogas plants. Efficient sizing, logistics, and operation of waste recovery plants require continuous and consistent waste feedstock supply. For this purpose, the strategic choice of the feed is provided through an optimization analysis based on the availability of residual biomass on a selectable territory; this allows to size the plant and locates it geographically exploiting a "Facility Location Problem " approach and GIS technologies. The economic assessment of the technical optimal solution is made available to the user through the forecast of cash flows, taking into account both CapEx and Opex of the process. This analysis is then supported by the evaluation of Pay Back Time (PBT), Net Present Value (NPV), and other economic parameters. Moreover, national incentives have been taken into account in the evaluation.

1. Introduction

In Italy, biomass is a form of energy praised as much as criticized. To date, various agro-industrial sectors produce large quantities of waste, which causes significant problems in their management as their energy use, in some areas, is limited due to inadequate technological development concerning the demand. Costs, doubts related to the regulatory system, as well as a restricted vision to only owned resources, are the main causes that stop entrepreneurs from investing in plants that exploit this kind of fuel (such as anaerobic digestion plants).
Several researchers faced the problem of biomass plant location from different points of view (D. Chinese and A. Meneghetti, 2005, H. Woo, et al., 2018, S. Ouyang, et al., 2019, L. Jayarathna et al., 2020), by using optimization tools also coupled with Geographical Information Systems (GIS).
In this work, is presented a "Decision Support System" that has been developed to provide technical assistance for the installation of biogas plants, with a size ranging between 1kW and 999kW, and its supply chain, everything in compliance with the Ministerial Decree of 4 July 2019 (relating to the incentive of electricity from

renewable sources other than photovoltaics). The software relies on an updatable database including the over 8.000 Italian municipalities that host at least one of the agro-industrial chains responsible for the production of several types of residual biomass, such as legume waste, potato scraps, grape pomace, tomato peels, citrus pastazzo, apple and pear production residues, rice husk, solid and liquid wastewater from bovine, pig and sheep, pig blood, hatchery waste, and whey. The respective quantities were estimated starting from the data provided by ISTAT in the "Sixth Census of Agriculture" regarding the extension of crops and livestock, to which yield, production, and waste coefficients proposed by ISPRA were applied to obtain the quantity of biomass, located on a municipal basis.

The estimated data is then made available to a mixed-integer linear programming optimization model (MILP) capable of choosing the optimal feedstock and size, to find the CapEx and OpEx costs of a digestion plant that can be installed in a territory pre-selected by the user.

A second MILP model, consisting of a Facility Location Problem, is used to find the location of the plant within the chosen area. This second optimization step applies to a set of suitable points, extrapolated through a pre-selected territory processing conducted through the QGIS application. To assess which of the proposed points constitutes the best option in minimizing costs, the regional PGPR regulations relating to environmental protection are exploited, jointly with geological and technical constraints in compliance with the localization regulations of plants. The digester's impact location on population is also taken into account.

The entire business plan of the project is provided as output, including both the CapEx and OpEx costs, the supply and transport of biomass, and the revenues related to the electricity incentive. This is coupled with data relating to the sizing of the system, the type of recommended process, and the profitability analysis, which can be viewed through a cashflow chart and the calculation of some economic parameters. To contextualize the results, the tool was applied to a case study in the province of Messina (Sicily, Italy).

By analyzing the quantity of citrus pulp, bovine slurry, and sheep manure (biomass deriving from the main activities of the territory), a 999kW plant can be easily installed nearby Messina, away from areas protected by environmental and/or other legislative constraints, accessible from both primary and secondary roads and in a position that preserves the residential area from any odor impacts. In the study, it was found that its electrical and thermal energy production would be continuous over the year, except for the summer period, during which the production drops to values around 89% compared to that of the rest of the year. This trend allows obtaining a PBT equal to three years with a NPV of 1'500'000 evaluated at the 20th year of the plant life.

2. Methodology

2.1 Available biomass quantification

Particular attention was paid to the production sectors that generate significant quantities of waste and by-products with organic matter capable of satisfying the energy demand of the biogas chain with seasonal regularity. In this work, the Italian territory has been divided into many sub-areas as are the municipalities, for each of these, the extension of different types of crops and farms on the Italian territory was collected through the information reported in the 6th agricultural census drawn up by ISTAT. Then 17 different types of biomass have been selected following the directives listed in the ministerial decrees relating to the production of electricity from renewable sources. The final result consists of a database which contains annual quantities of biomass produced, for each Italian municipality, evaluated exploiting specific production and agro-industrial waste coefficients estimated in ISPRA, "Studio sull'utilizzo di biomasse combustibili e biomasse rifiuto per la produzione di energia.", 2010.

2.2 Spatial data analysis

After the selection of a portion of territory composed of up to 20 municipalities, using QGIS application (v.3.4.12), the centroid for each of these sub-areas has been identified in good approximation as a representative point of each municipal limit for the location of the companies that produce biomass present in that area.

The second step consisted of identifying all the places capable of hosting an anaerobic digestion plant within the entire portion of the selected territory. This was done by eliminating from a set of points equidistant 2 km from each other all the places that fell within limited areas not suitable for hosting a digestion system, appropriately identified through the QGIS QuickOSM plugin, following criteria reported in "Linee guida per una nuova filiera del biorifiuto", 2015. This allowed obtaining a very good precision in the localization of the plant, pointing to the exact place where the system will be installed and not a generic area.

The results of this operation are *N* origin points and *K* destination points; for each pair belonging to these two sets, with the help of the QGIS QNEAT3 plugin, the distance on the road that can be traveled using transport of biomass was evaluated. This involved the production of a road graph and an origin-destination matrix, exploited in the optimization analysis described in paragraph 2.4.

2.3 Feed optimization and sizing

For a given set of biomass and its respective available quantity on the entire selected area, this study aims to design the economic optimal strategies for power installation, logistics, and resource flows of a new anaerobic digestion plant. Two mixed-integer linear programmings (MILP) models were developed to solve the optimization problems. The whole problem was split into two parts: the first one is illustrated in this paragraph; it identifies the optimal diet, the total inlet biomass flow, the annualized profit, and an estimate of capital and operative costs (CapEx and OpEx).

The objective function Eq(1) is to maximize the profit J, which is determined by the revenue (REV), savings due to thermal and electrical self-production (STS and SES), and the total costs including external supply costs (SC), the capital costs ($CapEx$) and operational costs ($OpEx$).

$$J = REV - SC - CapEx - (OpEx - STS - SES) \quad (1)$$

The revenue REV is defined as Eq(2) where the total annual electricity produced EE_{TOT} net of the annual self-consumption ESC_{TOT} is multiplied by the incentive rate I_{EE}.

$$REV = (EE_{TOT} - ESC_{TOT}) \times I_{EE} \quad (2)$$

The total annual produced electricity (EE_{TOT}) is obtained in Eq(3) by adding the electricity produced in each month m, EE_m, which is considered constant during the month. The annual self-consumed electricity ESC_{TOT} is obtained as a percentage (11%) of the produced amount, as reported in Eq(4).

$$EE_{TOT} = \sum_m EE_m \qquad m = 1,2 \ldots 12 \quad (3)$$

$$ESC_{TOT} = EE_{TOT} \times 11\% \quad (4)$$

The saving due to electrical self-production SES is defined in Eq(5) by the amount of annual self-consumed electrical energy $SCEE_{TOT}$ and the national area price of electrical energy $€_{EE}$.

$$SES = SCE_{TOT} \times €_{EE} \quad (5)$$

In the same way, the saving due to thermal self-production STS, defined in Eq(6), is evaluated by the amount of annual self-consumed thermal energy $SCTE_{TOT}$, the methane's lower heating value LHV_{CH4} and its national cost $€_{CH4}$; $SCTE_{TOT}$ is defined in Eq(7), where $SCTE_m$ is the self-consumed thermal energy in the month m, which is evaluated with the energy balance in Eq(8).

$$STS = SCTE_{TOT} \times LHV_{CH4} \times €_{CH4} \quad (6)$$

$$SCTETOT = \Sigma m\ SCTEm \qquad m = 1,2 \ldots 12 \quad (7)$$

$$SCTEm = m \times cpmix \times (T - Tm) \times (1 + kt) \qquad m = 1,2 \ldots 12 \quad (8)$$

In this equation, the term "m" is the total amount of biomass fed to the digestor in the month m, Cp_{MIX} is the specific heat of the mixture, T is the temperature corresponding to the desired type of digestion, T_m is the average temperature of the selected area in the month m and k_t is a thermal loss coefficient.
External annual supply costs SC are evaluated in Eq(9) in which the external supply cost of the biomass i $€ES_i$ is multiplied by the difference between the quantity of biomass i fed to the reactor m_i and the quantity of biomass i declared available by the owner am_i.

$$SC_{TOT} = \sum_I [€ES_i \times (m_i - am_i) \qquad i = 1,2, \ldots NB \quad (9)$$

In this equation, the term "NB" indicates the number of biomasses included in the digestor diet. The annual installment due to capital costs $CapEx$ is defined through a step-wise function implemented in the model but not described in the following which allows defining an annual payment from an estimated capital cost associated with the installed power of the new plant P, which is defined in Eq(10) as the maximum produced hourly-quantity of biomethane corresponding to the months of maximum production BM^{MAX}, multiplied by the lower heating value of methane and by the electrical efficiency η_{EE} of the CHP group.
As $CapEx$, operative costs $OpEx$ are evaluated through a step-wise function and they are dependent on the independent variable of the problem power of the plant P.

$$P = BM^{MAX} \times LHV_{CH4} \times \eta_{EE} \quad (10)$$

A range of constraints has been introduced in the developed MILP model to bound the selection of biomass included in the diet, size, and process parameters.
The quantity of biomass i fed to the reactor m_i is bound to be lower than that available in the selected area aam_i multiplied by the decision variable xi associated to the biomass i, in Eq(12):

$$m_i \leq aam_i \times x_i \qquad i = 1,2, \dots NB \qquad (12)$$

In each month of the year, in which the diet may vary due to the availability of raw material, the quantity of Total Solids TS_m introduced into the digester must fall within the industrial ranges: a lower limit of 4% of the total quantity TS_{min}, corresponding to the minimum content allowed in wet digestion, and the maximum value of 35% of dry digestion TS_{max} have been selected; Eq(13) bounds the TS content and allows to predict the type of digestion, as suggested in M. Fiala "Energia da biomasse agricole", Impresaagr., 2012:

$$TS_{min} \leq \mathrm{TS} \leq \mathrm{TS}_{\mathrm{max}} \qquad m = 1,2 \dots 12 \qquad (13)$$

Due to the ammonia inhibition caused by an excess of nitrogen present in the biomass, in each month m of operation of the plant, the Carbon-Nitrogen ratio of the biomass C/N_m must be adjusted so that it remains within the industrially used limits CN_{min} and CN_{max}, as described by the Eq(14):

$$C/N_{min} \leq C/N_m \leq C/N_{max} \qquad m = 1,2 \dots 12 \qquad (14)$$

Eq(15) expresses the need to work within a continuity regime throughout the year: in each month the methane yield BM_m of the plant will vary according to the type of biomass available; the trend is therefore linked to the month of maximum productivity BM_{PEAK} according to a percentage index R chosen a priori (usually 75 – 80 %):

$$BM_m \geq R \times BM_{PEAK} \qquad m = 1,2 \dots 12 \qquad (15)$$

Following the current Italian legislation on incentives for the production of electricity from renewable sources, in Eq(16) the nominal power of the plant P, evaluated in the month of maximum production, is bound to fall within the range of 1kW - 1MW:

$$1\ kW \leq P \leq 1MW \qquad (16)$$

This calculated value acts as an independent variable for the calculation of CapEx and OpEx through a step-wise function. Eq(17) bounds the amount of biomass fed to the reactor m_i to be greater than a certain amount m_i* (which is supposed to be owned by the user) so that the entire residual amount available to the user can be included in the diet:

$$m_i \geq m_i^* \qquad i = 1,2, \dots NB \qquad (17)$$

Eq(18) and Eq(19) bound the decision variable x_i to be Boolean:

$$x_i \geq 0 \qquad i = 1,2, \dots NB \qquad (18)$$

$$x_i \ integer \qquad i = 1,2, \dots NB \qquad (19)$$

2.4 Plant localization

In this second MILP model, the aim is to identify which between the K destination points present in the ODM, obtained during the spatial data analysis, is the one that minimizes the transportation cost of the biomass; in the same way, the origin points are selected to reach the minimum transport cost satisfying the supply-demand estimated by the previous model. This type of problem was tackled by exploiting the typical approach of Facility Location Problems (FLP). The objective function, reported in Eq(20), is to minimize total daily transportation cost TC_{TOT}, which is determined by the sum of the daily transport cost TC_j of the (unique) open plant j ∈ K, localized in one of the k ∈ K destination points. Since j = 1, TC_{TOT} will correspond to the transportation cost of the unique open plant j; for k ≠ j, $TC_m = 0$.

$$TC_{TOT} = \Sigma_k \ TC_k \qquad (20)$$

The daily transport cost of the open plant localized in TC_k is evaluated in Eq (21), where md_i is the total daily quantity of biomass i transferred from all the C ⊂ N origin points selected to the destination point k, ρi is the density of the biomass i, $CPCT$ is the capacity of the transport vehicle, SC_i is transport cost of the biomass i per kilometer and D_{nk} is the distance between the origin point n and the site k. This value is then approximated to the higher integer to take into account each road section traveled between the origin points and selected destination point even with an unsaturated load.

$$TC_k = \sum_i^{NB} \sum_c^{C} \left(\frac{md_i}{\rho_i \times CPCT} \times SC_i \times D_{nk} \right) \qquad k = 1,2, \dots, K \qquad (21)$$

A range of constraints has been introduced in the developed MILP model to bound the selection of the site j.

In Eq(22) the total quantity of biomass i transferred to the plant j mg_i is bound to be equal to the supply quantity established from the previous model, here defined as md_t^{TARGET}:

$$md_i = md_i^{TARGET} \qquad i = 1,2, \ldots NB \qquad (22)$$

This equation assumes that in each origin point the biomass production is constant in time during all the month. The quantity mg_i is evaluated for each biomass i as the sum of the daily transferred quantities from each selected origin point c to the open plant j.
The number of open plants is bounded to be equal to one, where x_k is a decision variable so that the open plant is unique:

$$\sum_k^K x_k = 1 \qquad (23)$$

The daily quantity of biomass i transferred from each selected origin point c md_i^c is fixed to be less than the daily available quantity of biomass i in each origin point c mda_i^c:

$$md_i^c \le mda_i^c \qquad i = 1,2, \ldots NB \qquad (24)$$

The quantity md_i^c is defined as the sum of the quantities daily transferred from all the selected origin points C to the open plant j, while md_i^c corresponds to the daily-basis quantity found in the steps described in "paragraph 2.1.
Eq(25) bounds the quantity transferred from a particular selected origin point c* ϵ C mdc^*_i (which is the one in which the user declares its owned amount of biomass is localized in) to be greater than the quantity declared md_i^* (daily-basis of m_i^*):

$$mdc^*_i \ge md_i^* \qquad i = 1,2, \ldots NB \qquad (25)$$

The operating capacity requested of the plant localized in k C_k is imposed to be less than that available on the site k CA_k:

$$C_k \le CA_k \times x_k \qquad k = 1,2, \ldots K \qquad (26)$$

Here C_k is evaluated as the sum of the ratio between the quantity of each daily transferred biomass i from all selected origin points and the density of the biomass i, while CA_k is evaluated as the sum of the ratio between md_t^{TARGET} and the density of the biomass i. The decision variable x_k to be Boolean (see eq.18 and 19).

3. Conclusions

3.1 Available biomass quantification

The two optimization models were then applied to the case study of the province of Messina, Italy. In this region, the agro-industrial activity is mainly linked to the fruit juice sector and the breeding of cattle and sheep. Then, the correspondent biomass produced: citrus pastazzo, cattle sewage, and sheep manure have been selected to be analyzed in 20 municipalities in the Messina area, namely those in the immediate circumstances of San Pier Niceto (ME); in this municipality annual quantities of citrus fruit pulp, cattle sewage and sheep manure were calculated to equal to 961 tons/y, 1875 tons/y, and 380 tons/y, respectively. For each of the procurement and transport costs have been established, assuming that pastazzo is the only biomass whose value results in a cost for the buyer (3 €/ton), while for the other two the disposal realizes in a profit (2.5 €/ton). Finally, the distribution of the quantity of the three biomasses on the whole area has been found.

3.2 Spatial data analysis

A set of points equidistant 2 km from each other has been selected (Figure 2a). Then, through the QGIS application, a series of exclusive layers were superimposed (Figure 2b).

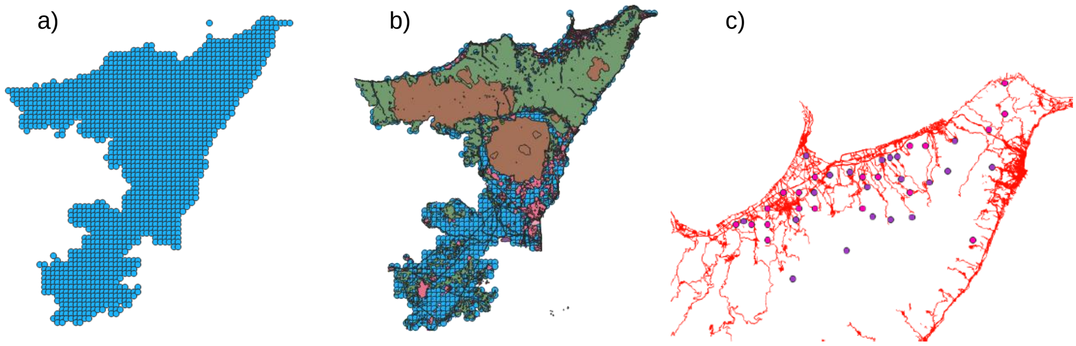

Figure 1 – (a) Set of equidistant points; (b) Super-imposed exclusive layers; (c) Final sets of origin and destination points with road graph within the selected area

The initial set of points was filtered, allowing to obtain a set of K destination points geolocated on the map. As the last step, after identifying the road graph of the area considered, for each pair of origin (centroids of municipal areas) and destination points, the ODM has been obtained (Figure 2c).

3.3 Feed optimization and sizing

The potential of the area was then evaluated. The model predicts an optimum plant of 999 kW, fed with 52,773 tons/y of sheep manure, 16,348 tons/y of bovine slurry, and 1,838 tons/y of citrus pulp.
By choosing the type of digestion (mesophilic) it is possible to trace a first parametric sizing of the pre-mixing tank (151 m^3), of the digester (3,152 m^3 with an HRT of 20 days), a digestate storage tank (24,121 m^3 with 18 days of retention time) and a gasometer (1',406 m^3). The production is constant during the whole year with exception of the summer period in which citrus is not available. The economic evaluation of the plant was realized in a PBT of about 3 years and an NPV valued at 20 years of 1.5 million euros.

3.4 Plant localization

The location of the plant is foreseen in an unprotected wooded area, sufficiently far from city centers, easily reachable through long-distance roads or suburban roads which if crossed by trucks do not affect city traffic (Figure 3).

Figure 2 – Plant localization

This study allows us to evaluate the potentiality of an area in terms of the production of electricity from anaerobic digestion, evaluating both its geographical and economic aspects. The accuracy in positioning is almost unlimited and depends on the number of constraints that the user chooses to impose on the area. The technical aspects of sizing and optimization have been treated so that they can be implemented in forecasting systems that are efficient enough to obtain a good prediction of the seasonal trend of production and plant yield concerning a specific geographical area.

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