Energy recovery of the biomass from livestock farms in Italy: the case of Modena Province

L. Montorsi*
Department of Sciences and Methods for Engineering
University of Modena and Reggio Emilia, Reggio Emilia, Italy
e-mail: luca.montorsi@unimore.it

A. Bassi, M. Francia, M. Milani, M. Stefani, S. Terzi
Department of Sciences and Methods for Engineering
University of Modena and Reggio Emilia, Reggio Emilia, Italy

ABSTRACT

The energy recovery from manure of different Italian livestock farms is analysed by means of numerical simulation using an in-house developed code. In particular, the animal farming in the province of Modena is taken into account and biomass is exploited in an integrated system including different waste to energy technologies. In the considered system, the manure of a number of types of animals is fed into an anaerobic digester, while the digested sludge is separated into the solid and liquid fractions. The former is employed as a fuel in a downdraft gasifier, while the latter is purified by means of both forward and inverse osmosis. Finally, the obtained bio-gas and syngas are used in a cogeneration system based on a spark ignition internal combustion engine to produce electric and thermal power.

The potential power production of the considered territory is estimated and compared with the energy requirements of the animal farms. Different strategies for the distributed exploitation of the manure versus a centralized solution are investigated and the relating plant size and production of electric energy and thermal energy are evaluated.

KEYWORDS

Biomass, waste to energy, anaerobic digestion, gasification, water purification, simulation

INTRODUCTION

Due to the increasing awareness of the drawbacks regarding the use of fossil fuels, the attention towards the renewable energy sources has increased substantially in the recent years and particularly the viewpoint of the waste management has changed from disposal to a possible energy resource [1]. Furthermore, the organic fraction of wastes in the form of municipal solid waste, sewage sludge, poultry litter, cattle manure and industrial effluents has been widely analyzed for its use as renewable sources for energy [2 - 6]. Benefits from the waste to energy technologies for the organic fraction can be derived not only in terms of power production, but also in terms of Greenhouse Gases (GHG) reduction [2, 7] and the positive effects on the emission mitigation can be proved also when comparing the energy exploitation of manure with the land application [8]. In addition, the use of animal manure as a bioenergy source determines advantages for the rural communities, that can diversify the incomes, moderating the impacts of commodity prices, and securing the local energy demands [9].

Despite the benefits that waste to energy technologies can offer both in terms of power production and emissions reduction, the application of bioenergy systems encounters many barriers due to the amount and complexity of information relating to the development of such

systems [10, 11]. At the level of technology design assessment, the access to information about the bioenergy systems and best practices for biomass production, harvesting and conversion appears to be complex as well as the manipulation of the data and specifications of the different systems for the decision of the best technology for the local biomass exploitation.
Simulation programs are a possible solution for supporting the decision making, creating strategies and procedures and forming policy. This paper focuses on the development of a numerical tool for the comparison of different waste to energy technologies and thus supporting the selection of the best exploitation methodology when a specific number of biomasses is available. In particular, the proposed tool focuses on three processes for the bioenergy systems: anaerobic digestion, gasification and incineration. The performance of the considered processes is calculated on the bases of the numerical models described in [12, 13], while a Java GUI is developed in order to create a user friendly interface that can be employed by people with no expertise in coding or software creation.
The in-house developed code is used to analyse the energy recovery from manure of the Italian livestock farms located in the province of Modena. Anaerobic digestion and gasification are accounted for as well as the manure from different types of animals is considered. The reference bioenergy system includes an anaerobic digester, a downdraft gasifier and water treatment for the liquid part of the digested sludge. The obtained bio-gas and syngas are used in a cogeneration system based on an internal combustion engine to produce electric and thermal power.
The potential electric power production of the considered territory is calculated for a number of different scenarios. In particular, the distributed exploitation of the manure versus a centralized solution is investigated in terms of plant size and electric and thermal energy production.

MODELLING

An in-house code is developed in order to include the prediction capabilities of detailed numerical models for anaerobic digestion, gasification and combustion of biomasses in an easy to use Graphical User Interface (GUI). The aim of the code is to create a platform for the simulation of different scenarios of waste to energy technologies for the exploitation of a given biomass composition. The numerical models for the simulation of the performance of the considered biomass conversion processes are described in [12, 13]. In the following, the focus is devoted to the interface created for enabling a flexible and user friendly utilization of these numerical models. In fact, the developed Biomass Management Tool (BMT) is intended not only for experts in the numerical modelling, but for supporting the decision making, creating strategies and procedures and forming policy. Thus, the aim of the work is bridging the gap between the amount of information needed for the evaluation of the bioenergy systems and the performance prediction of each system.
The adopted coding language is Java [14], due to its capabilities in handling GUI elements and the possibility of creating routines with the mathematical models of the biomass conversion processes accounted for in the analysis.
Figure 1 shows the main page of the software and along with the usual tools for files and windows handling, the different sections of the current project can be accessed on the panel at the left hand side. The sections include the setting of the “Scenario” conditions, such as the biomass input, the preliminary screening of the energy conversion efficiency of the modelled WTE technologies applied to the input biomass, and the “Engineering” results detailing the performance of the bioenergy systems that the user intends to investigate. Future work will be devoted to implement an “Economics” and “Management” sections to include in the analysis

parameters for the evaluation of the investment and constraints relating the logistics of the energy systems, such as the maximum distance of the biomass supply chain as well as the maximum area occupied by the plant. Figure 2 depicts the panel for the biomass input and as an example the animal wastes are in foreground, but vegetable wastes and the desired composition of the Municipal Solid Wastes (MSW) can be evaluated in the analysis as well. Each biomass amount can be set either in terms of percentage of the overall total or in terms of tons per years available. When applicable, the number of heads of the selected animals can be also used as an input and the corresponding annual manure production is calculated. Furthermore, a summary of all the biomasses employed in the simulation is provided in order

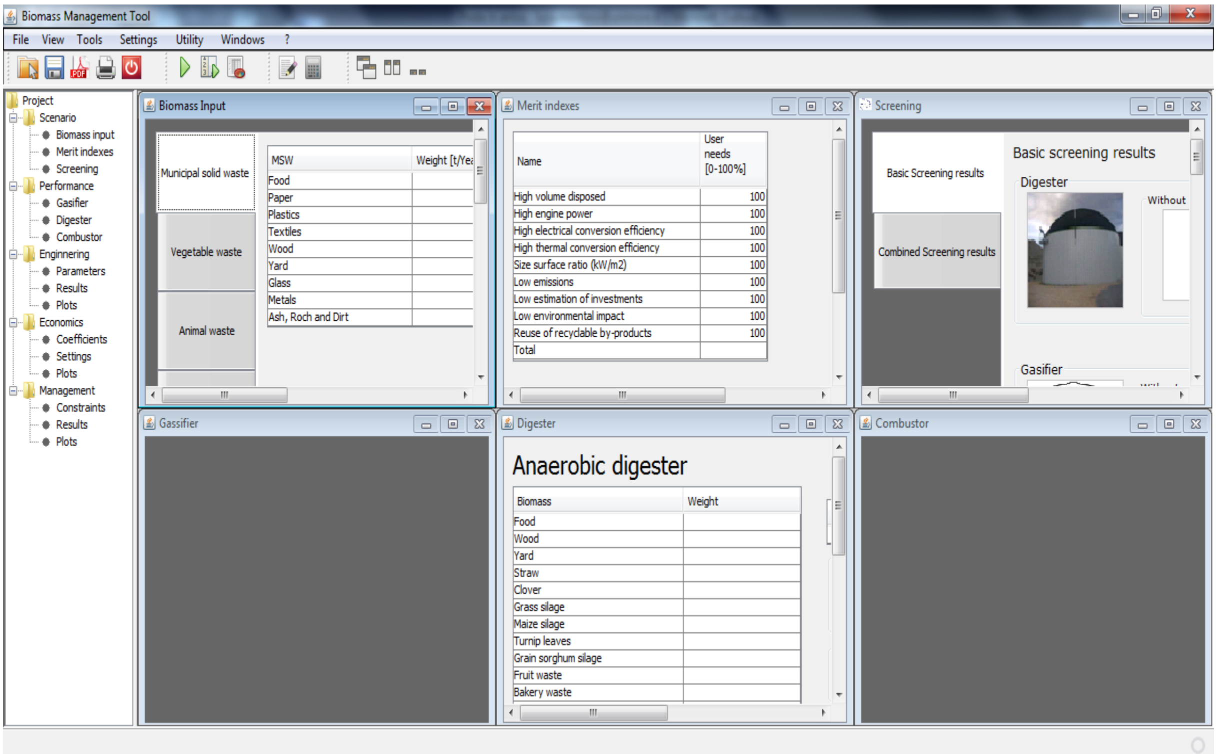

Figure 1. Main screen of the BMT software

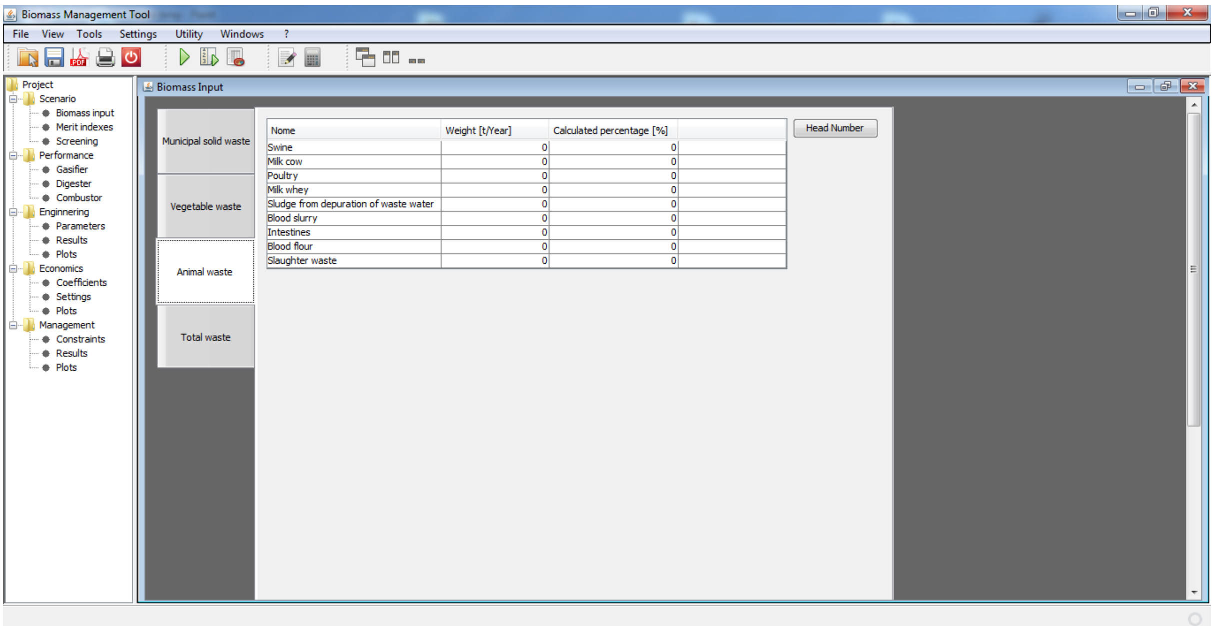

Figure 2. Main screen of the BMT software: focus on the input biomass for animal wastes.

to have a complete overview of the input conditions and eventually modify them. In the BMT code 42 species of biomasses are considered.

First data processing is the preliminary screening of the main WTE technologies in order to address the overall efficiency of the different processes for the exploitation of the input biomasses, see Figure 3. The preliminary screening is the result of a rough estimation of the efficiency of the anaerobic digestion, gasification and combustion when using the selected biomasses as an input. The suitability of each process is visualized using three symbols that at a glance show if the three considered bioenergy systems could be effectively adopted for the energy conversion of the input biomass composition. Eventually the use of a biomass pretreatment is also accounted for and a suitability evaluation is also given in the case of a preprocessing treatment of the biomasses. The preliminary screening section includes also a second panel that can be used for detailing slightly further the basic suitability analysis, see Figure 4. Using this option, the screening is subdivided for each considered process, and the input biomasses can be directed to the different waste to energy technologies by selecting the proper fraction for each energy conversion system. If a biomass is clearly not suitable for the

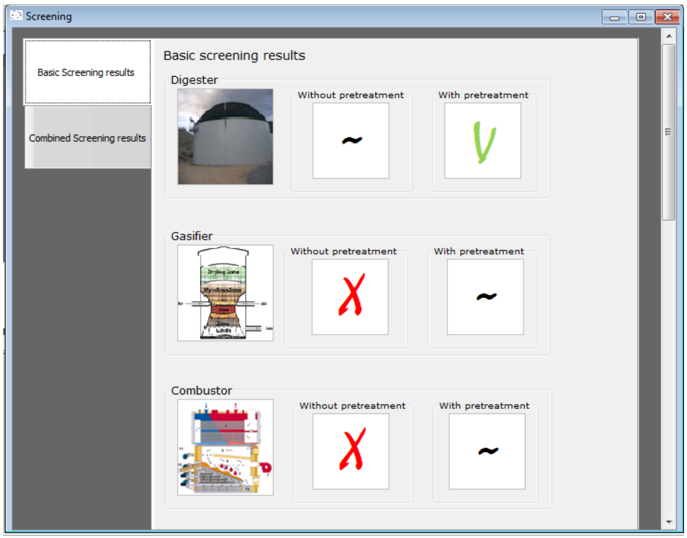

Figure 3. Panel for a preliminary screening of the results from the considered WTE technologies.

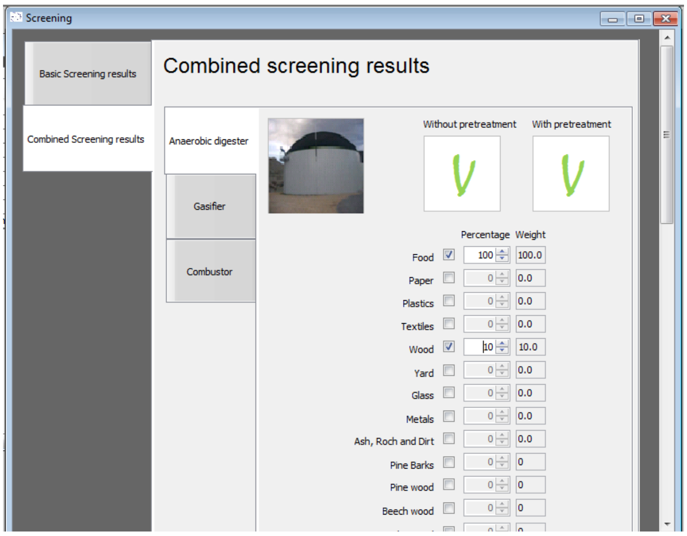

Figure 4. Panel for selecting a fraction of the input biomasses for the preliminary screening of the results from the different WTE technologies (Case of the anaerobic digester).

analyzed process, its fraction can be set to null and thus that biomass will be disregarded in the preliminary efficiency evaluation of that system for the exploitation of the input biomasses.
In addition, the preliminary screening of the main WTE processes can be influenced by means of a set of merit indexes implemented in the code. Figure 5 lists the considered merit indexes and the default value is set to 100% for all of them. If one or more indexes correspond to particularly important constraints for the analysed case study, the merit values can be modified accordingly and their weight in the calculation of the suitability of the selected processes will be different affecting the symbols displayed in the panels of Figures 3 and 4.
Finally, the performance results of each WTE technology are plotted in a separate window, see Figure 6. In the results panel, the biomasses exploited in the considered energy system are reported along with the daily and annual production of biofuel (i.e. biogas or syngas) and the electric energy production (i.e. electric power and energy produced per year). An important parameter that can be set in this panel is the annual operating time; the value can be different for the three considered bioenergy systems and it influences the size of the plant that can process the input biomass rate.

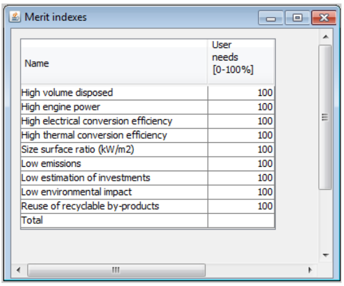

Figure 5. Considered merit indexes for the preliminary screening.

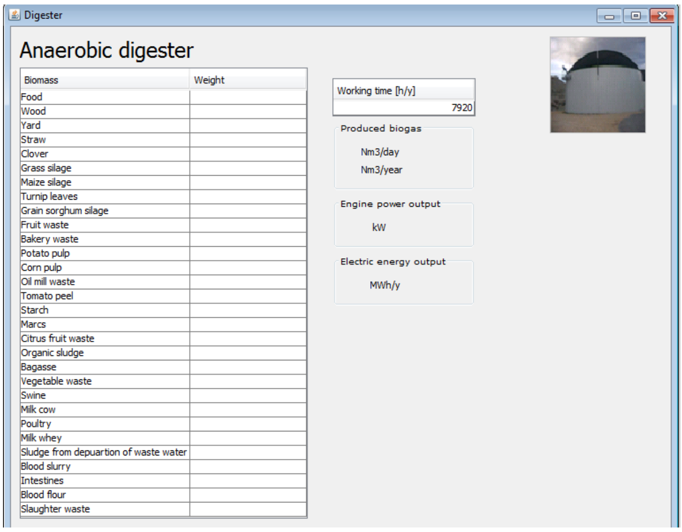

Figure 6. Panel with the report of the main performance parameters of each WTE technology (Case of the anaerobic digester).

CASE STUDY

The in-house code described in the previous section is used to evaluate the potential application of an integrated waste to energy system to the manure available from the animal farming in the province of Modena in Italy. According to the Italian regulation, the manure from livestock farms is considered as a waste that must be disposed of in the proper way, i.e. either as a

fertilizer or in landfill. The province is subdivided into 47 municipalities, see Figure 7, where animal farming plays an important role on the local economy. The farms focus mainly on the families listed in Table 1 and the total number of heads is significant, particularly for pigs and cows. The relating amount of manure is therefore remarkable and it is usually employed as fertilizer in agriculture or disposed in landfill when it exceeds the limit to be spread on the soil. Anaerobic digestion is likely one of the most promising waste to energy technology for exploiting the manure from the different animal farms. In order to evaluated the electric energy that could be produced by the biogas from the manure of the province of Modena the annual manure production is adopted as an input in the BMT code.
In order to minimize the final wastes remaining, an integrated approach for the exploitation of the initial biomass is analysed; the plant includes the following processes: anaerobic digestion, gasification and water treatment. The employment of the three processes enables to maximize the exploitation of the biomass and to reduce the remaining amount of waste; thus it is possible to improve the total energy conversion efficiency of the system calculated on the basis of the initial energy content of the adopted biomasses. Figure 8 shows the layout of the proposed integrated plant. First, the manure from the considered animals is converted into biogas using an anaerobic digester; then, after the time period necessary for the bacterial reactions to take

Figure 7. Map of the Province of Modena showing the subdivision in its municipalities.

Table 1. Total number of heads for each considered animal family in the Province of Modena (data at the end of 2011)

Family	Total heads	%
Swine	295,623	68.3
Ovine	5,489	1.3
Poultry	33,250	7.7
Horse	4,742	1.1
Bovine	94,012	21.7

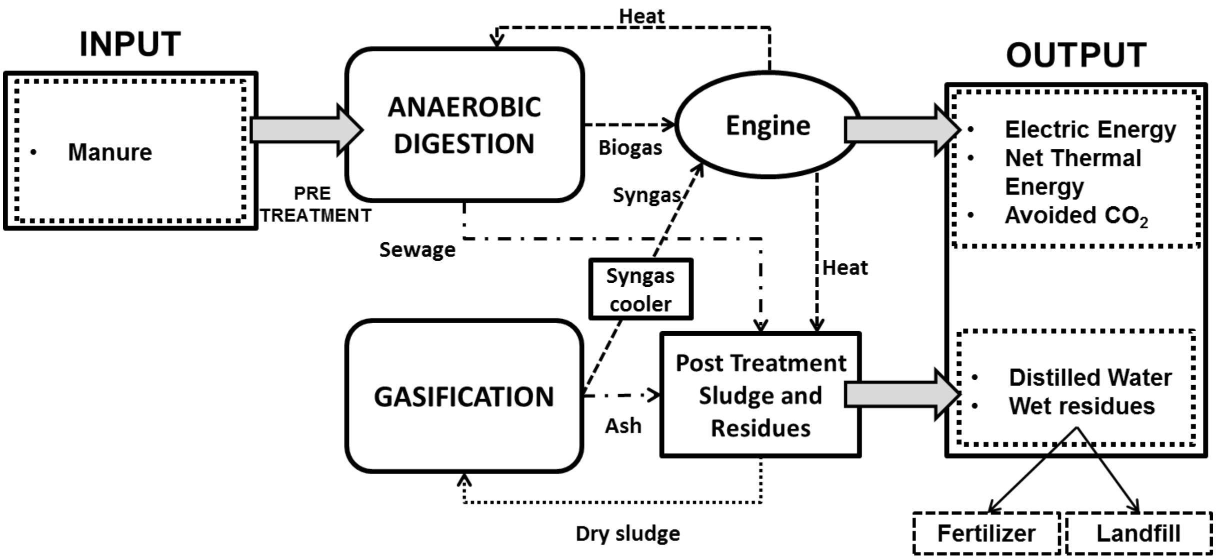

Figure 8: Layout of the considered integrated plant

place, the biological sludge is dehydrated and successively dried. The dried part of the sludge is loaded in the gasifier, while the liquid part is treated in the water purification process. Before storing the syngas and the biogas in the tank, a gas treatment system is adopted. including filtration, cooling and desulfurization. The purified gas is then used as fuel in a spark ignition internal combustion engine ICE. An alternator connected with the ICE produces electrical energy while the heat exchanged at high and low temperature is used for self-sustenance operations of the plant such as the heating of the anaerobic digester or the biological sludge drying. The liquid fraction of the biological sludge is finally converted in distilled water and in an ammonia solution after micro, ultra and nano-filtration and finally forward/reverse osmosis treatments.

Gasifier humid slag and the solid part of the filtration can be used as fertilizer or disposed in a landfill in accordance with the local regulation.

RESULTS AND DISCUSSION

In the following, the main results that can be obtained by means of the BMT code are presented and the potential of the exploitation of the manure from the animal farming in the province of Modena in Italy is discussed.

First scenario that is taken into account considers each municipality of province separately and the performance of a single integrated plant exploiting all the manure from that district is analysed. This scenario represents a distributed case of energy production from the manure of the provincial area. Figure 9 plots the electric power generation from the supposed 47 plants and the contribution of the biogas and syngas to the total production. It can be noticed that in several municipalities the size of the potential integrated plant is remarkable and 8 systems result larger than 1 MW. On the other hand, many bioenergy systems are characterized by very small sizes and 10 plants have an electric power output close to or smaller than 100 kW.

The effectiveness of the integrated anaerobic digestion and gasification conversion system is outlined in Figure 10. In fact, the exploitation of the solid part of the digested manure in the gasifier contributes for approximately the 20% of the total power production. The differences in the biogas and syngas contribution to the electric energy produced is due to the different

input composition of the integrated plant as a consequence of the number of heads of swine, bovine, horse, ovine and poultry of the considered municipality.
For the calculation of the annual production of electric energy a working period of the plant

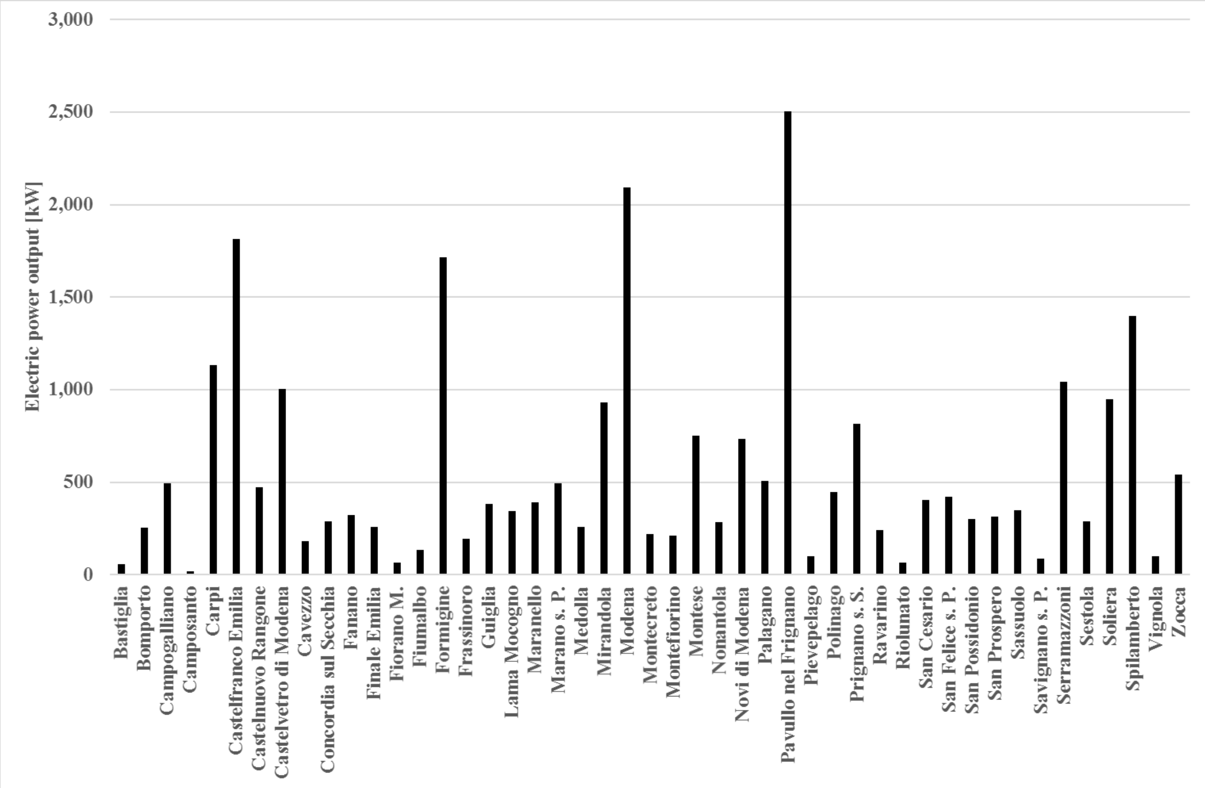

Figure 9. Electric power output of the integrated plants exploiting the manure from all the considered animal families for each municipality.

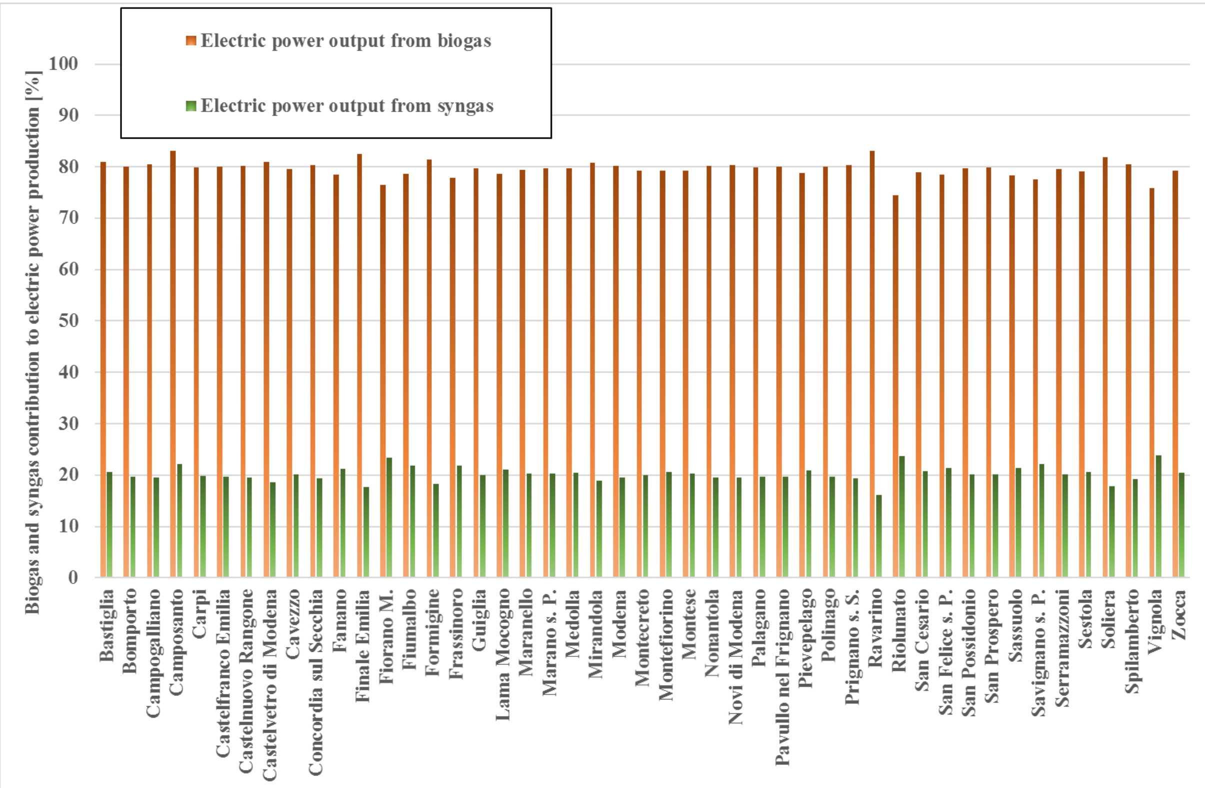

Figure 10. Biogas and syngas contribution to the total electric power production for the integrated plants exploiting the manure from all the considered animal families for each municipality.

equal to 7200 hours is considered. By summing the electric power production of all plants, an annual electric energy amount of approximately 190.04 GWh is predicted. This value is remarkable, in particular when compared to the energy requirement per year of the whole agricultural sector of the province of Modena, see Figure 11. In fact, by exploiting the manure of the provincial animal farming, the resulting electric energy production exceeds largely the needs of the agricultural industry (i.e. 195.7 %).
The BMT code takes also the thermal power production into account. Figure 12 depicts the total thermal production of the 47 integrated plants and compares it to the net thermal power output of the systems. The latter values are calculated by subtracting from the total thermal power available at the internal combustion engine co-generation system the amount needed both for heating the anaerobic digestion reactor and for the drying process of the separated solid part of the digester sludge. In fact, these two contributions are not negligible and indeed amount to a large part of the heat recovered from the engine. In a few districts characterized by very small size plants the heat by the CHP system is very close to the amount required to sustain the digester temperature and the sludge drying process.
Figure 13 highlights two important features of the bioenergy system such as the avoided emission of carbon dioxide and the production of purified water. The avoided CO_2 is calculated by considering the carbon emission of a fossil fuel used for the production of the same amount of electric energy. The total saving in terms of carbon dioxide emission for all 47 plants reaches almost 300,000 t/y, while the purified water available for the district water piping is up to 115 million litres. Furthermore, Figure 14 compares the total biomass input to the considered plants and the remaining wastes to the disposed either as a fertilizer or to landfill. Depending on the initial composition of the manure exploited in each bioenergy system, the remaining amount of waste ranges from 3 to 6 %; this result demonstrates the high efficiency of the integrated approach to the exploitation of the manure from the considered animal families.

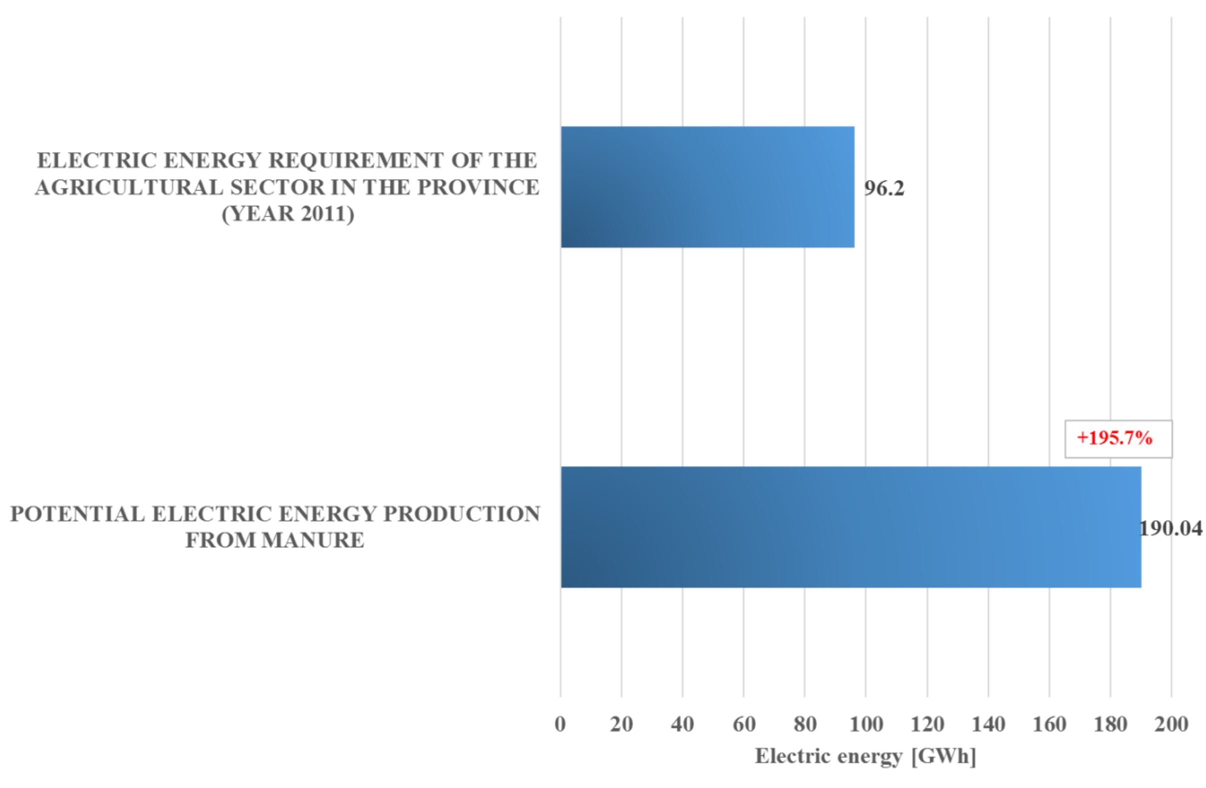

Figure 11. Comparison between the potential annual electric energy production from the manure of all the considered animal families for all municipalities and the electric energy requirement of the whole agricultural sector in the province of Modena in 2011.

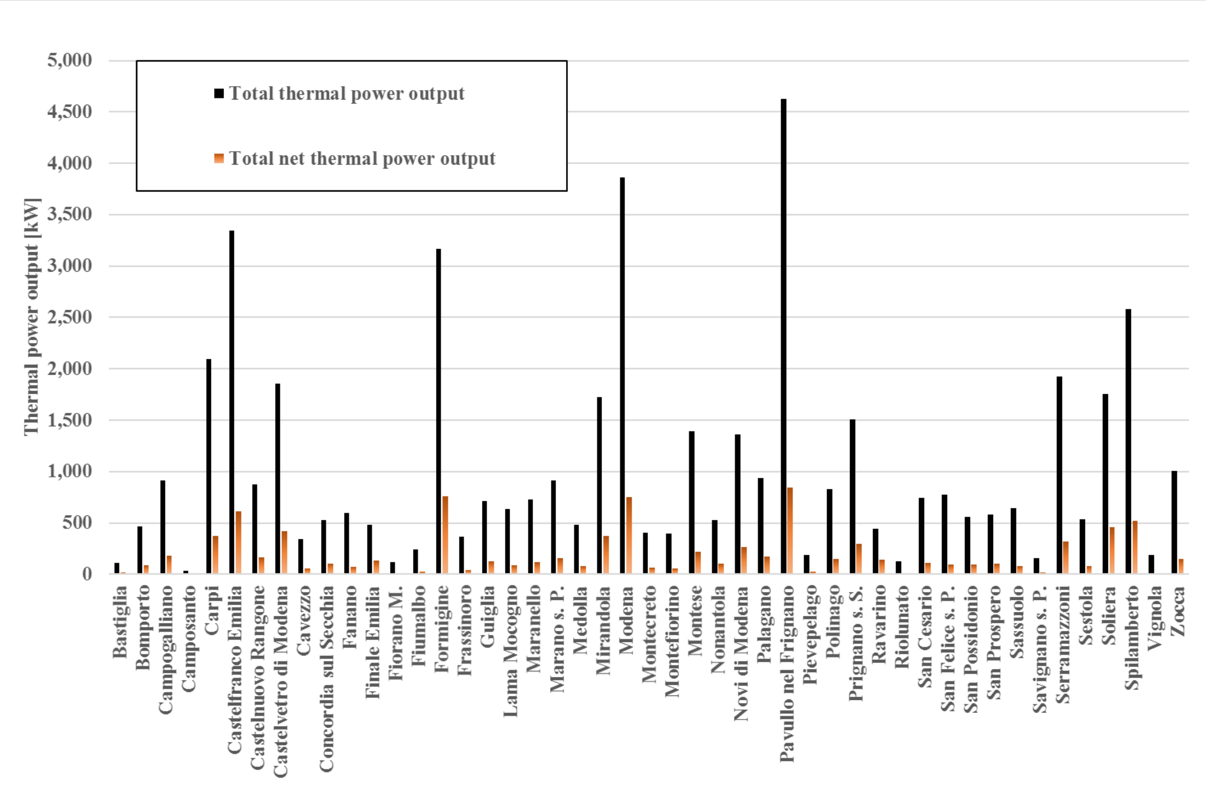

Figure 12. The thermal power output of the integrated plant exploiting the manure from all the considered animal families for each municipality.

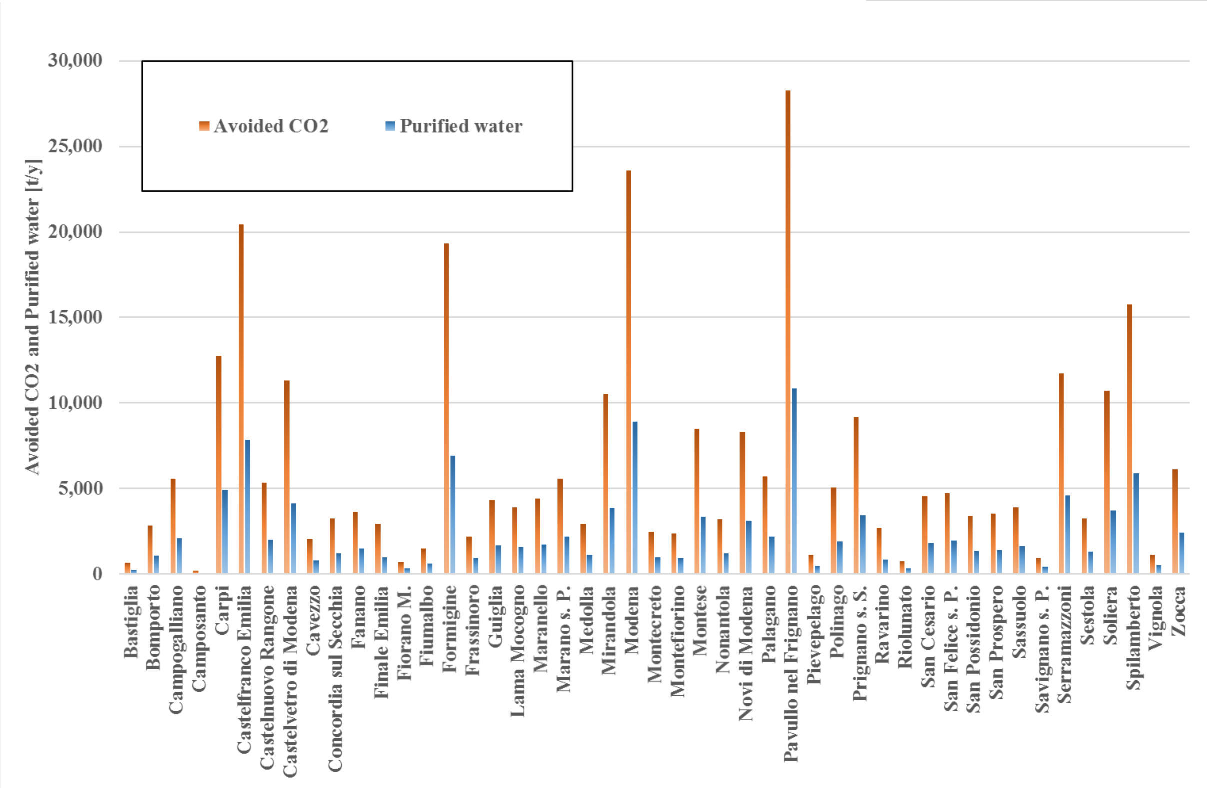

Figure 13. Avoided CO_2 and purified water production of the integrated plant exploiting the manure from all the considered animal families for each municipality.

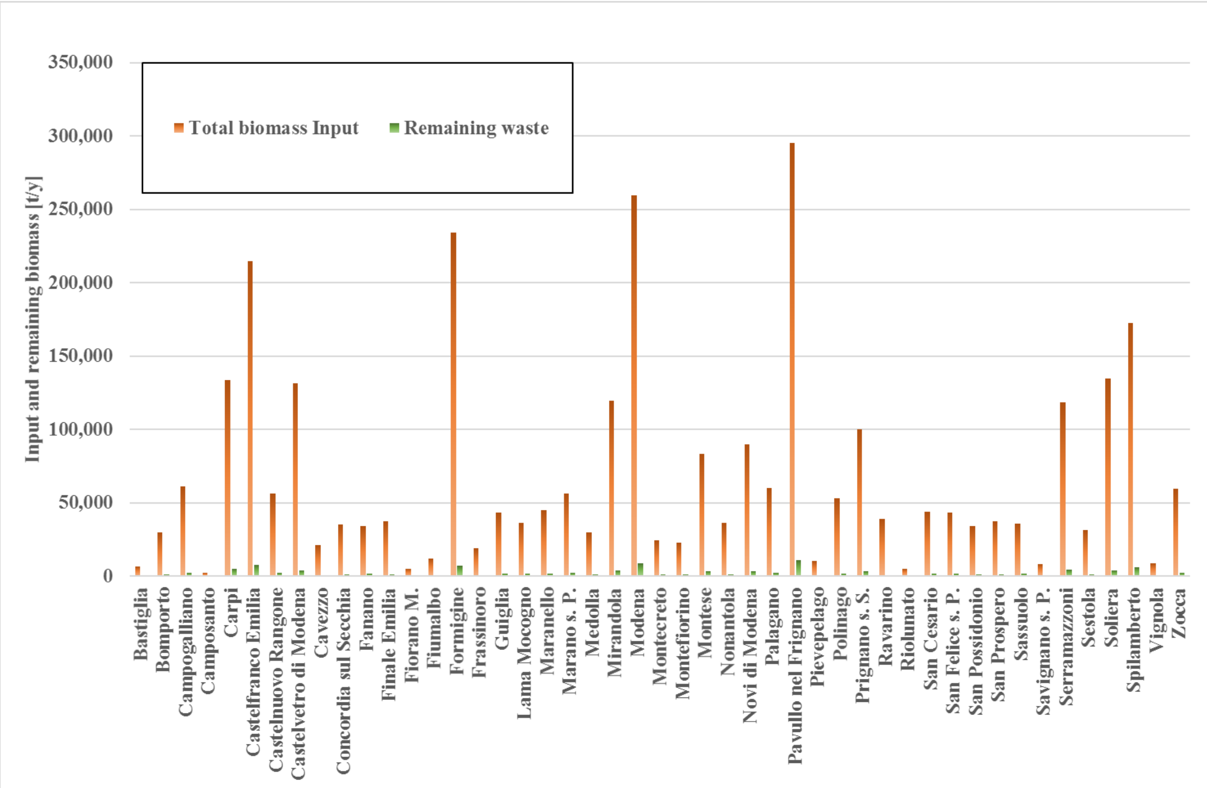

Figure 14. Total biomass input and remaining waste of the integrated plant exploiting the manure from all the considered animal families for each municipality.

A second scenario of distributed exploitation of the manure from the animal farming of the province is considered by assuming a different plant both for each municipality and for each animal family manure. This example represents the most distributed case of energy production and it is useful to address the contribution of the different animal families in the power production from manure.
Figure 15 reports the total electric power output of the integrated plant exploiting the manure from the different animal families for each municipality. As expected by comparing the heads number of the animal families listed in Table 1, the manure from pigs and cows provides the largest contribution to the electrical energy output of the considered plants, see Figure 16. The bovine convers approximately the 21% of the heads in the province while they can potentially provide the 70% of the electric energy recovered from the manure; conversely the swine heads are almost the 70% of the total amount of animals raised in the province and produce the 20% of the electric power output. On the other hand, even though the poultry heads are a large number, i.e. the 7.7% of the entire population, the potential energy output is rather low when compared to the other animal families. This result can be observed also in terms of size of the plants for the 47 municipalities. The size of the single plant for each district, i.e. the first scenario, is similar to the sum of the size of the plant for bovine manure and the size of the swine manure one. Few exceptions can be outlined for the municipalities where large farms of different animal families are located. Similar considerations can be made when addressing the net thermal power output of the integrated plant exploiting the manure from the different animal families for each municipality, see Figure 17. Due to the very small size of some the plants, the heat by the CHP system is not enough to sustain the digester temperature and the sludge drying process. This second scenario is useful to investigate the contribution of the manure from the different animals' families to the energy that can be recovered from the wastes of the animal farming sector but it is characterized by critical aspects that suggest to exploit the manure following a different strategy.

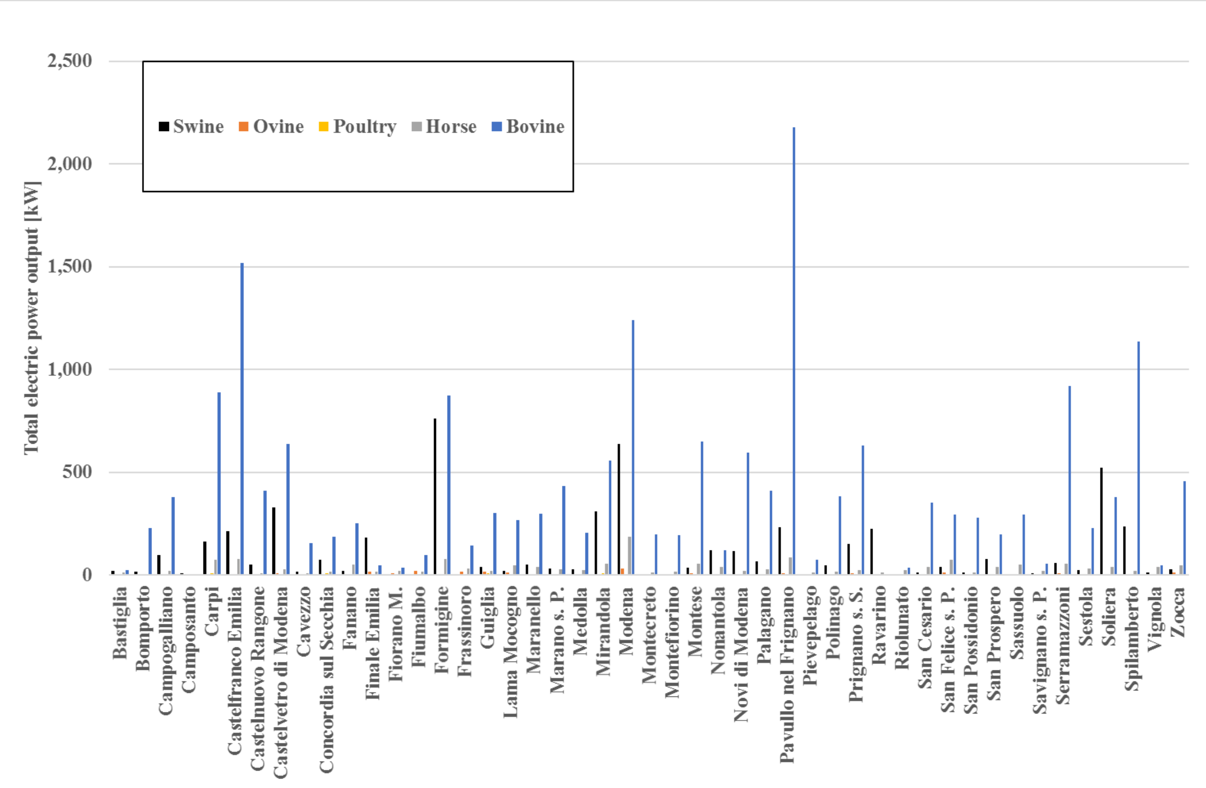

Figure 15. Total electric power output of the integrated plant exploiting the manure from the different animal families for each municipality.

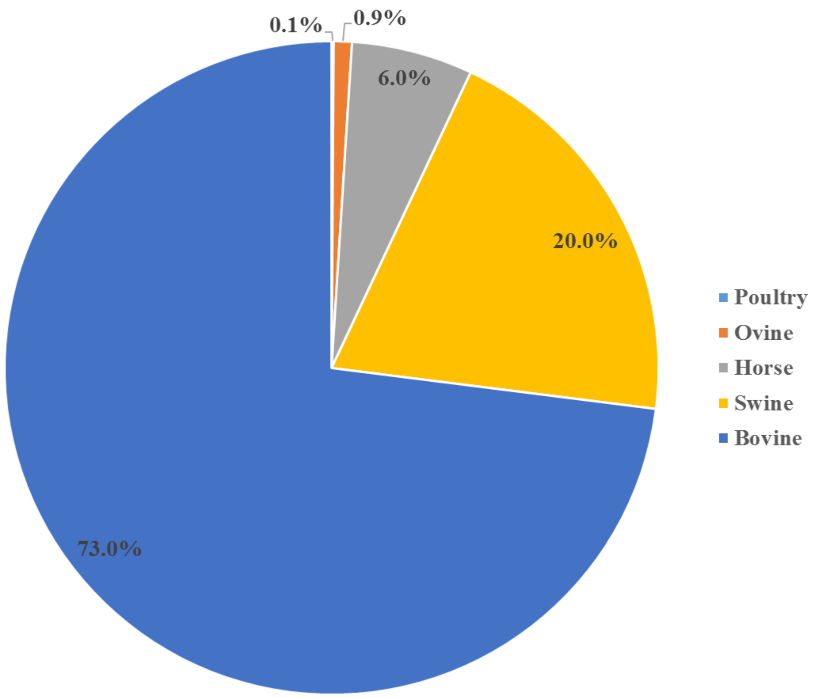

Figure 16. Contribution of the manure from the different animal families to total electric power production.

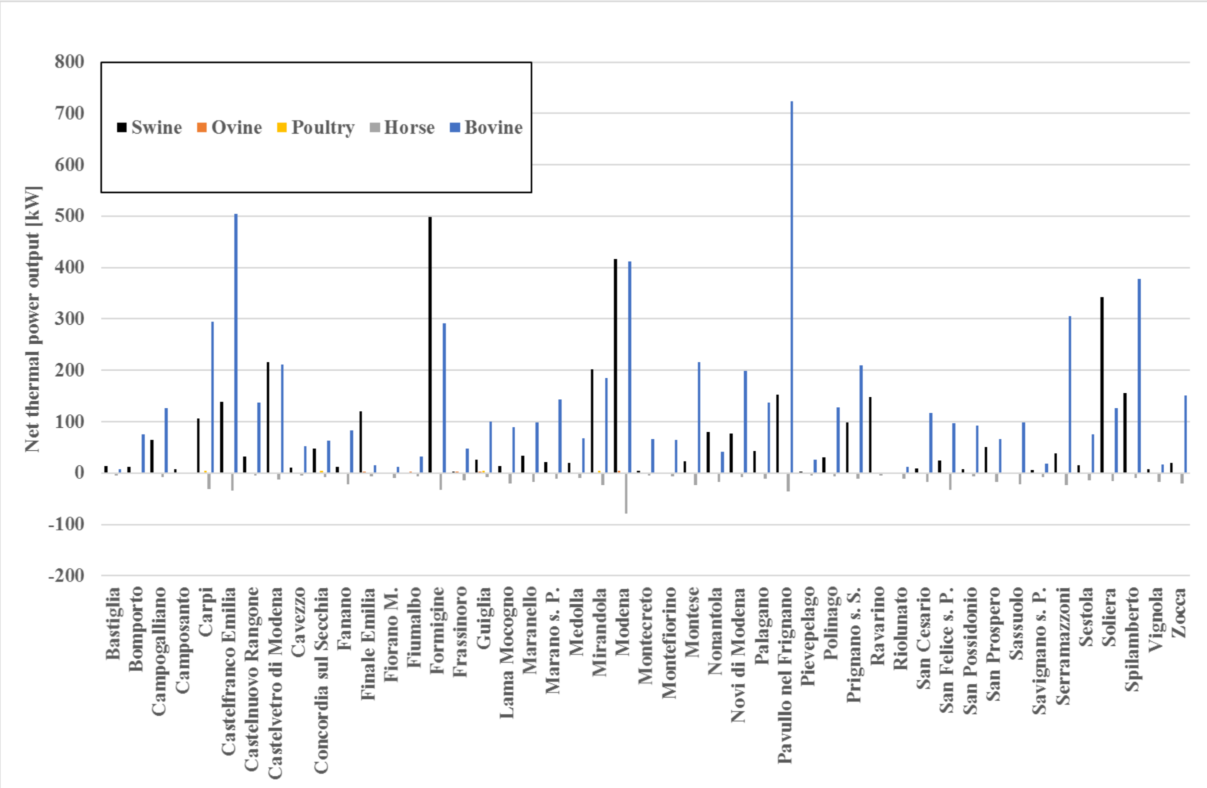

Figure 17. Net thermal power output of the integrated plant exploiting the manure from the different animal families for each municipality.

In the third scenario, the municipalities of the province of Modena are grouped considering the adjoining districts and the results obtained in the scenarios analysed previously. Thus, 20 groups

are formed and the bioenergy systems exploiting the manure from the districts of each group are investigated, see Figure 18. The main guidelines adopted for creating the 20 areas are the proximity and the resulting size of the plant. The first criterion is used in order to minimize the effects of transportation on the biomass supply costs as well as the carbon dioxide emission due to the vehicles. Thus, each area is characterized by a maximum radius of 20 km from its centre. Secondly, the aim of the partition of the municipalities is obtaining an average plant size close to 1 MW in terms of electric power output. Figure 19 shows that this target is reached for almost all areas; the only exception is the group # 19 which is located in the highest part of the mountain Apennines of the province of Modena. In this case, the first criterion is considered more stringent than the plant size due to the characteristics of the territory which make the transportation more difficult. Nevertheless, the electric power output of this plant is not negligible and it is close to 0.5 MW; similarly, the net thermal power output is positive, thus the bioenergy systems recover enough heat to sustain the processes on the integrated plant.
On the other hand, 4 plants result larger than the reference size. In particular, the areas #7, #8 and #9 are characterized by an electric power output of more than 2 MW and the three areas include a total number of 5 municipalities. In fact, this zone of the province is where a very high concentration of animal farms can be observed and a further subdivision of the manure supply chain should refer to the locations of each farm rather than the whole municipality.
Similar consideration can be drawn for area # 17, which includes only one municipality characterized by a very large amount of animals farmed.

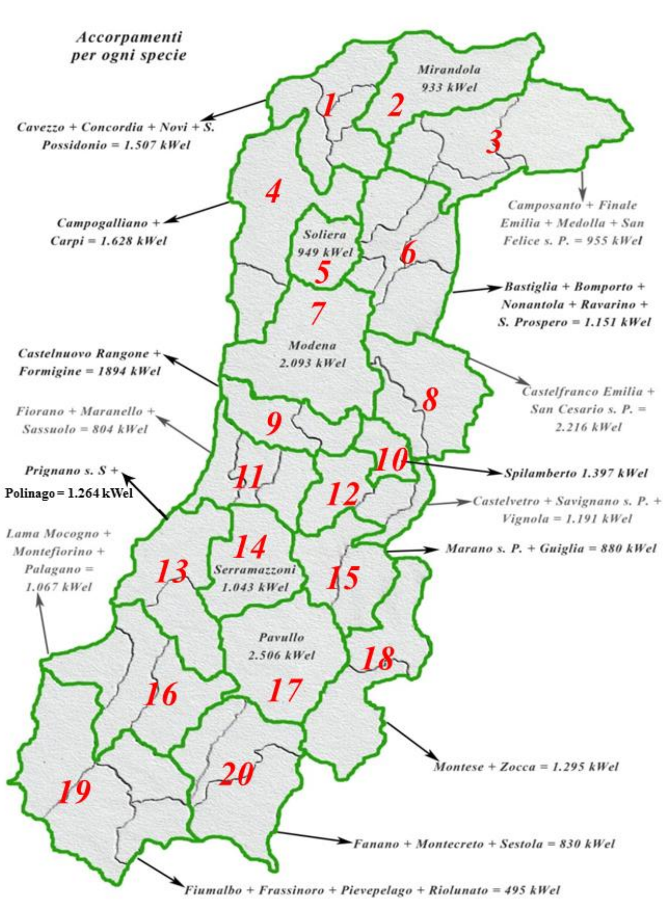

Figure 18. Centralized exploitation of the manure in groups of adjoining municipalities.

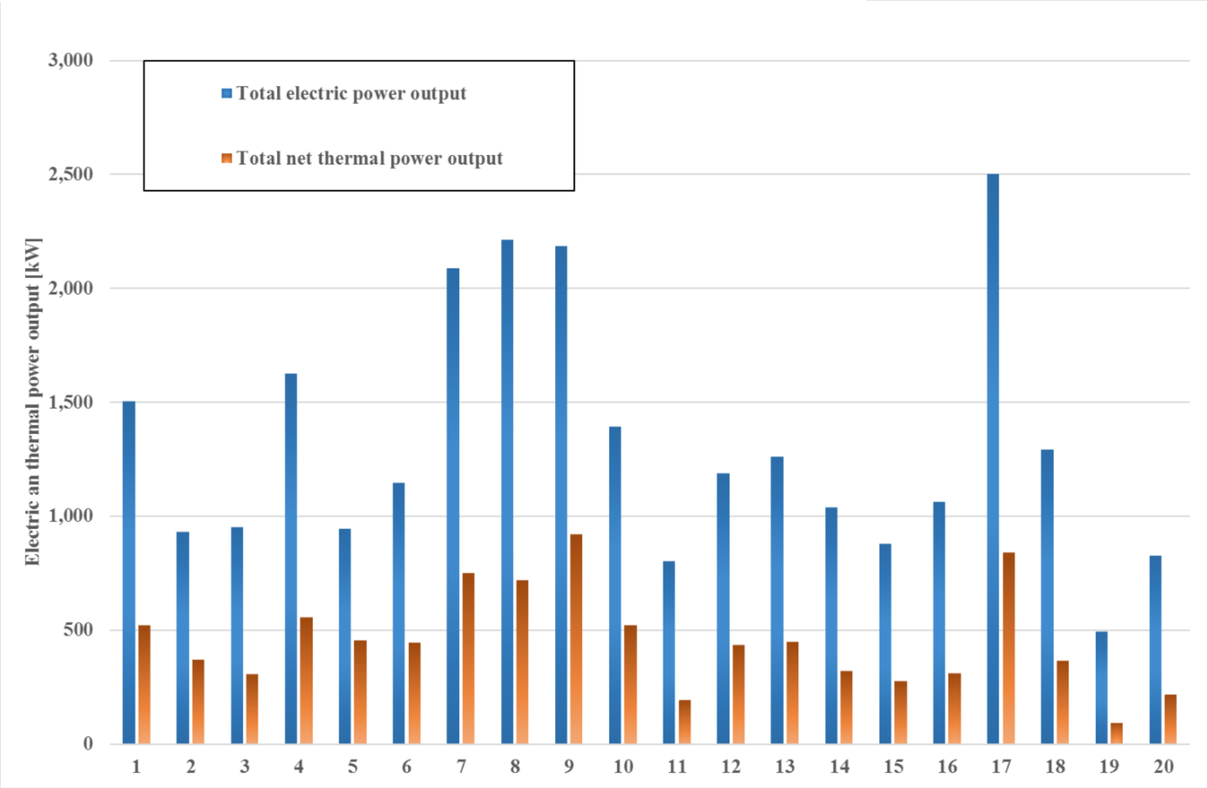

Figure 19. Electric and thermal power output of the integrated plants exploiting the manure from all the considered animal families for each group of municipalities.

CONCLUSION

The paper focused on the development of a new numerical tool for the evaluation of different waste to energy technologies; in particular, anaerobic digestion, gasification and incineration are accounted for in the code and a number of biomasses can be selected as an input to the bioenergy systems. The tool aimed at creating a platform for the simulation of different scenarios of WTE processes for the exploitation of a given biomass composition. The considered biomasses included vegetable and animal wastes as well as the fractions of the MSW. The performance of the bioenergy systems was evaluated using previously validated numerical model and the main outputs of the resulting plant were given in terms of electric and thermal power production, avoided carbon dioxide emission and remaining wastes.

The proposed numerical tool was used to evaluate the potential application of an integrated waste to energy system to the manure available from the animal farming in the province of Modena in Italy. The anaerobic digestion and gasification processes were taken into account as well as a purification system for the liquid part of the digester sludge.

Different scenarios concerning the manure supply chain were analysed ranging from a distributed exploitation of the livestock wastes in each municipality of the province to centralized bioenergy systems located at the centre of the areas grouping several districts.

The results of the numerical code showed that several municipalities in the size of the potential integrated plant was remarkable and 8 systems resulted larger than 1 MW. Furthermore, the calculations demonstrated that the exploitation of the solid part of the digested manure in the gasifier contributed for approximately the 20% of the total power production. In addition, the annual electric energy produced from the animal farming manure proved to exceed by the 195.7% the energy requirement of the whole agricultural industry in the province. The integrated plant demonstrated also to minimize the remaining waste to dispose; in fact,

depending on the initial composition of the manure exploited in each bioenergy system, the remaining amount of waste ranged from 3 to 6 %.
Finally, a scenario was considered by grouping the municipalities of the province of Modena into 20 areas in which one plant exploited the manure from the animal farms located in that group. The areas were formed using the proximity of the different municipalities and the resulting size of the plant as guidelines. Using these criteria, it was possible to define 20 plants with an average size of 1 MW with a supposed maximum biomass supply distance of 20 km.

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