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ScienceDirect

Energy Procedia 119 (2017) 602–614

Energy Procedia

www.elsevier.com/locate/procedia

International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES17, 21-24 April 2017, Beirut Lebanon

Anaerobic digestion as sustainable source of energy: A dynamic approach for improving the recovery of organic waste

Marco Ragazzi[a], Manfredi Maniscalco[a], Vincenzo Torretta[b], Navarro Ferronato[b], Elena Cristina Rada[a,b*]

[a] *Department of Civil, Environmental and Mechanical Engineering, University of Trento, via Mesiano, 77, 38123, Trento, Italy*
[b] *Department of Theoretical and Applied Sciences, University of Insubria, 46 Via G.B. Vico 46, Varese 21100, Italy*

Abstract

Organic waste fraction disposed to landfill induce the release of greenhouse gas and leachate due to its degradation. The collection and treatment of such typology of waste is imperative in order to decrease environmental pollution and improve recycling rates. The aim of this study is to define a flexible and economically viable system to process all the RMSW and the OFMSW coming from SC, in a territory with low recycling rates. To that purpose, the survey provides a dynamic system which comply with future increases in the efficiency of SC systems. Dry anaerobic batch reactors are considered in order to treat RMSW and to operate the OFMSW, as long as SC improves. Four scenarios were considered, in particular for 10%, 25%, 50% and 75% SC rate. Biogas production has been estimated for evaluating the potentiality of each SC rate, since it can be exploited for generating electric energy and heating. Biogas generation is enhanced of the 21% by increasing from 10% to 75% SC, making the system more profitable under an energetic point of view. Moreover, the amount of electric energy which could be sold per year for each SC scenario was calculated, resulting as 631,293 kWh for the 10% SC and 442,527 kWh for 75% SC. Considerations on the exportability of the approach were also added in the paper, highlighting the affordability of the anaerobic digestion system in other countries.

Peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD).

Keywords: Anaerobic digestion; municipal solid waste; circular economy; renewable energy; environmental sustainability

* Corresponding author. Tel.: +39 0461282613; fax: +39 0461282672
E-mail address: elena.rada@unitn.it

1876-6102
Peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD).
10.1016/j.egypro.2017.07.086

1. Introduction

MSW usually consists of more than 50% in putrescible matter and its management is a great issue worldwide, in particular for developing countries [1, 2]. MSW are commonly disposed to landfills or open dump sites affecting the environmental sustainability by the release of contaminants like leachates and GHG, generated by the high amounts of putrescible waste which increase the pollution potential of the sites [3, 4]. At the same time, the organic fraction can be considered as a source of energy and fertilizer since biological treatments, in particular composting and AD, are a viable way to treat and exploit the OFMWS and wastewater sludge for co-digesting procedures [5-8]. With respect to the aerobic process, which generates exhausted air mainly composed by CO_2, NH_3, H_2O, O_2 and N_2, and a solid fraction (compost), the main advantage of AD is related to the energy recovery process [9]. Indeed, the anaerobic procedure generates methane which can be used for producing electric energy. One cubic meter of biogas can generate an electrical energy of 2.5 kWh [10], whereas putrescible waste can generate about 128 m^3 t^{-1} of biogas [11], resulting in the production of 150-300 kWh of electric energy per ton of waste treated [9]. The energy value can increase at 500-750 kWh t^{-1} if the biogas is generated from animal manures [12]. On the contrary, aerobic composting required 30-35 kWh of energy per ton input [13]. Although the investment cost for AD are 1.2-1.5 times higher than aerobic composting, the energy exploitation associated to the first process makes it more attractive [14].

In this frame, economic incentives on energy production play also an important role. Indeed, different companies working in the agricultural sector, food industry and livestock are moving toward the AD for energy production [15-21]. The same situation can be noticed regarding the OFMSW. In fact, within the EU, the interest on this waste stream keeps growing due to rising energy costs associated with the processing of wet waste, the prohibition of landfilling any putrescible refuse (EU Landfill directive 99/31/EC) and the need to comply with regulations for the disposal of animal by-products [22, 23]. AD is also a response to the increase of the global consumption of energy and to the limited availability of fossil fuels, together with the raise in waste production and the associated environmental and structural issues related to its treatment [24,25]. The topic concerning environmental sustainability, focused on the choice of the waste treatment process, becomes a paramount aspect during the decisional progression involving the technology that should be adopted [26]. The application of AD plants can meet the request of sustainable development, with benefits also in term of reduced odor impact around the plant, when compared with aerobic composting.

The design phase of a waste treatment facility is strictly bonded also into the EU regulations and the laws of the marketplace. Besides, only integrated solutions, that can transversally consider all the major issues, should be taken into account. Environmental problems, renewable energy request at national and international level, the quantity and quality of the waste produced and the economic requirements should be studied before the design phase of a plant [27, 28].

In the present work, the viability of an AD plant in a context with very low SC rates (and therefore it is not possible to operate only on the source separated streams) is analysed. Besides, the strong lack of waste treatment units was considered for all the refuse streams since it can be generally found in the developing countries. This work was meant to suggest a possible unique system capable of treating, through AD process, both the RMSW and the OFMSW, coming from a continuously evolving SC process, without having to operate substantial changes in the structure of the plant itself during the years. In this study, four progressive conditions of SC were considered: 10%, 25%, 50% and 75% referred to an area in the South of Italy. The solution proposed is based on the utilization of batch reactors. Most of them will be loaded with RMSW during the first period. Afterwards, they will be converted to the treatment of source separated putrescible waste as long as SC increases. Through this solution, there is no need of changing the total number of AD reactors. The two waste streams should be always kept and treated separately in order to avoid contamination of OFMSW coming from SC with RMSW, since only with OFMSW as input it is possible to produce high quality compost. From the unsorted waste, instead, a bio-stabilized matter is generated, which can be landfilled or used for capping activities. The digesters working temperature was chosen in order to always be able to process all the incoming waste in all the conditions. An estimation of the biogas produced was also performed, considering the transformation ratio of the VS into biogas which is exploited by a cogeneration unit. The approach was theoretically applied to the municipality of Agrigento, Sicily (Italy). This province, with a population of 474,493 inhabitants, presents a level of selective collection which remarks an underdeveloped condition in the SWM, as can be faced in the whole Sicily. The example and the assumptions of the study can help policy makers and local governments to plan future SWM systems, introducing the AD like a solution for a sustainable development.

Nomenclature

MSW	municipal solid waste
GHG	greenhouse gas
AD	anaerobic digestion
OFMWS	organic fraction municipal solid waste
RMSW	residual Municipal Solid Waste
VS	volatile solids
EU	European union
SWM	solid waste management
SC	selective collection
W	weight
V	volume
l	length
w	width
h	high
ρ	density
m	mass
b	biogas generation
η	yield
LHV	lower heating value
TS	total solid
P	power
CHP	combined heat and power
n	number
CIC	certificate of Input in consume

Subscripts

r	reactor
us	undersieve
el	electric
OF	organic fraction
fil	filling

2. Materials and methods

2.1. Study area

Sicily presents SWM characteristics far to be optimized. The vast majority of the MSW produced is landfilled and the levels of SC are the lowest at national scale, according to the latest waste management report [29]. The yearly MSW production in the province of Agrigento, for years 2013 and 2014, is respectively 209,375 t y^{-1} and 208,091 t y^{-1}, while SC percentages remained almost steady, ranging between 13.4% and 13.2% respectively. In the province, a composting plant is already present, treating approximately 10,000 t y^{-1} of organic waste from SC. This structure handle roughly all the source separated OFMSW coming from the municipalities of the west side of the province, where SC of the OFMSW reaches, in most of the villages, values higher than 80%.

The theoretical plant object of this study was, therefore, thought to process all the refuse left and so all the MSW coming from the municipalities of the east side. With this assumption, the RMSW that should be processed is nearly 160,000 t y^{-1}. The plant was designed for treating all the RMSW and considering four SC steps (10%, 25%, 50% and 75%). The assumption is that the SC system finally gathers the 75% of the putrescible fraction and achieves the 75% recycling chain. As a result, the SC of the putrescible fraction cover nearly the 38% of the whole SC system.

In order to evaluate the exploitability of the OFMSW from SC was necessary to carry out the total quantitative of the OFMSW by multiplying its quantity by the rates 0.1, 0.25, 0.5 and 0.75, while for the RMSW by reducing the total amount of MSW of the 10%, 25%, 50% and 75%, respectively, taking into account the amounts of the putrescible waste recovered by the SC. The OFMSW is about the 36% of the total MSW and was evaluated considering the published official data of the region [30]. Before feeding the bioreactors for treating the RMSW, a sieving operation through an 80 mm mesh was considered. The sieving system produces an undersieve, which represent the 41% of the total RMSW, with 64% organic fraction. A simple scheme of the waste flow examined in the study is depicted in Figure 1.

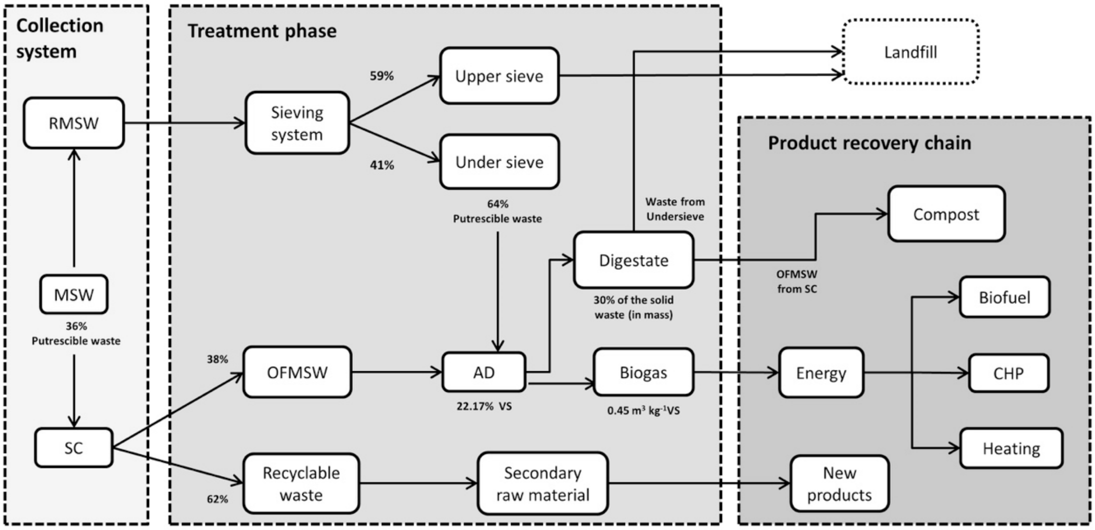

Fig. 1. Theoretical waste flow studied for the case of Agrigento (Italy)

The organic amounts and the total quantity of material that is fed into the bioreactors have been evaluated for the four SC scenarios. In Table 1 the organic fraction coming from SC and the sieving process and the treated RMSW are reported for the four SC scenarios. The data required to project the plant were assumed by a literature review and by direct information collected by the owners of the facilities already present in Italy.

Table 1. Amount of waste obtained by the four SC scenarios.

Waste typology		Selective Collection Rate			
		10%	25%	50%	75%
RMSW	t y^{-1}	141 724	118 103	78 736	39 368
Total undersieve	t y^{-1}	58 556	48 797	32 531	16 266
Total undersieve per day	t d^{-1}	160.4	133.7	89.1	44.6
OFMSW in undersieve	t y^{-1}	38 036	31 697	21 131	10 566
Total OFMSW from SC per year	t y^{-1}	5 986	14 980	29 956	44 935
Total OFMSW from SC per day	t d^{-1}	16.4	41	82.1	123.1
Total waste for AD	t y^{-1}	64 542	63 777	62 487	61 201

2.2. Reactor design aspects

For the reactors design it was considered to operate with an inoculum which significantly increased the average microbial activity, with an amount in the range of 40% and 50% [31]. Standard bioreactors dimensions were assumed as 30m long, 5m high and 7m width and usually filled up to 3.5m. The densities considered for the project are reported in Table 2 whereas the digestate produced by the process was assumed to be equal to the 30% in mass of the MSW inflow into the plant [32].

Table 2. Densities of the material fractions fed into the digesters

		OFMSW	RMSW	Undersieve RMSW	Inoculum
Density	t m^{-3}	0.56	0.35	0.49	0.5

The density value regarding the undersieve were evaluated like the weighted average of the density of each fraction and considering that it is constituted of OFMSW and RMSW. The amount of fresh refuse (W_{RMSW}) that can be processed in a singular reactor was calculated as:

$$W_{RMSW} = (1 - \%_{inoculum}) \cdot V_{filling} \cdot \rho_{us} = 207.5\ t \tag{1}$$

where ρ_{us} is the waste density obtained by the undersieve, $\%_{inoculum}$ the inoculum amount in percentage, whereas $V_{filling}$ is the available volume for waste treatment inside the reactor, calculated as follow:

$$V_{filling} = l_r \cdot w_r \cdot h_{filling} = 30\ m \cdot 7\ m \cdot\ 3.5\ m = 735\ m^3 \tag{2}$$

Where l_r, w_r and $h_{filling}$ are the lengths, the width and the filling high of the reactor. Regarding the inoculum amount, it was firstly considered the lower value, equal to 40%. With respect to the thermal properties of the envelope, all the external elements of the bioreactors were considered thermally insulated. It was assumed to locate the bio-rectors one next to the other, in contact on the longest side, in order to reduce the thermal dispersion. The length of the reactors was considered 0.5 meters longer to allow the operation of loading and unloading and for ensuring a volume sufficient to contain the incoming waste.

2.3. Biogas production and consumption

Values reported in literature were considered regarding the conversion from the VS contained in the input (putrescible) stream to the volume of gas produced. Generally, it is assumed a generation of 0.5-0.8 m3 kg^{-1}VS, for a total solid and VS content ranging respectively from 15% to 30% and from 80% to 95% respectively [33, 34]. In this case a project value of 0.45 m^3 kg^{-1}VS was adopted.

The characterization of the organic fraction inflow into the plant, instead, was defined as follow: 73.8% of water and 26.2% of TS of which 84.6% are volatiles. It is, therefore, easy to compute that 22.17% of the incoming organic stream is made of VS. Having all the parameters, it was possible to calculate the potential production of biogas (V_{biogas}) in m^3 as:

$$V_{biogas} = m_{of} \cdot \%_{VS} \cdot b_{rate} \cdot\ 1000 \tag{3}$$

Where m_{of} is the weight (in tons) of the organic fraction inflow the bio-reactor, b_{rate} is the biogas generation rate per kg of VS and $\%_{VS}$ is the amount of volatile solid detectable within the organic matter. Finally, the biogas consumption was calculated knowing the power produced, the efficiency in the generation and the LHV of the biogas and methane produced, applying the following equations:

$$m_{biogas,turbine} = \frac{P_{el}}{\eta_{el} \cdot LHV_{biogas}} \quad (4)$$

$$m_{biogas,boiler} = \frac{P_{boiler}}{\eta_{boiler} \cdot LHV_{natural\,gas} \cdot 0.6} \quad (5)$$

Where η_{el} and η_{boiler} are the energetic yields of the turbine and of the boiler, respectively, whereas P_{el} and P_{boiler} are the powers produced. The boiler can ensure a 90% thermal efficiency, against the near 60% of the CHP unit. The LHV of biogas and natural gas were assumed equal to 6 kWh m^{-3} and 9.6 kWh m^{-3}. It was also supposed that the percentage in volume of methane in the biogas is equal to 60% [35].

3. Results

3.1. Number of bioreactors

To evaluate the number of bioreactors needed to run the plant, it was firstly calculated the number of cycles that can be performed by each reactor in a year. It was considered the possibility of operating in mesophilic (optimum temperature at 35°C) or thermophilic (optimum at 55°C) conditions. In the first case, the digestion process lasts approximately 28 days and so 13 cycles can be completed. In the second one, since 22 days are necessary, 16 entire cycles can be ensured [36, 37]. As reported in (1), the total waste that can be treated in each reactor is equal to 207.5 tons, allowing a cumulated yearly capacity of 3320.3 tons ($W_{RMSW,annual}$) that can be treated in thermophilic conditions by a single unit. The total theoretical number of reactors needed to process the RMSW coming from the sieving process is calculated as:

$$n_{\,reactors,RMSW,10\%SC} = \frac{W_{annual,10\%SC,undersieve}}{W_{RMSW,annual}} = \frac{58\,556\,[t]}{3\,320.3\,[t]} = 17.64 \cong 17 \quad (6)$$

Where $n_{reactors}$ is the number of reactors which are required for the treatment process, whereas $W_{annual,undersieve}$ is the total amount of waste obtained by the undersieve which should be treated. This approach is repeated for each SC scenario. It must be pointed out that this represents a simplified procedure since it was considered the amount of input waste constant during the year without any fluctuation.

The same evaluation was carried out for the OFMSW obtained by the SC. The geometry adopted for the previous case means the increase of the time storage, therefore It was established to operate with 20m long reactors. Moreover, in this frame, can be possible to obtain 10m x 7m x 5m smaller digesters, which can be loaded easily in case of the reduction of incoming waste. Such precaution also can be adopted for treating the RMSW from undersieve with high SC rates permitting a storage time lower than four days. For instance, considering a 10m long digester and 50% inoculum, 4 days of waste storage are necessary to have the desired amount to fill the reactor, since the volumes which should be occupied are calculated as:

$$V_{fil,2} = l_{r,2} \cdot w_r \cdot h_{filling} = 10\,m \cdot 7\,m \cdot\ 3.5\,m = 245\,m^3 \quad (7)$$

$$W_{OF} = (1 - \%_{\,inoculum}) \cdot V_{fil,2} \cdot \rho_{OF} = 68.6\,t \quad (8)$$

Where W_{OF} is the OFMSW in weight that should be fed into the reactor, whereas ρ_{OF} is the density of the OFMSW reported in Table 2. This is in line with the 10% SC of the OFMSW, which provides about 17 tons per day of organic waste. With these dimensions (10m, 7m, 5m), 6 bioreactors are needed to process the annual OFMSW, operating in thermophilic conditions. Similarly, it was calculated the number of bioreactors needed for all the waste streams in all SC scenarios. Totally, the reactors needed for the yearly process are 20, allowing the use of the same plant for each SC scenario. Reactor numbers for each state and waste typology are reported in Table 3.

Table 3. Number of reactors required for each SC scenario.

Number of Reactors	Reactor lengths	Selective collection rate			
		10%	25%	50%	75%
OFMSW	20 m	3	3	1	
	30 m		2	8	14
RMSW	20 m			2	3
	30m	17	15	9	3

3.2. Biogas production

It was carried out a simplified analysis to evaluate the potential biogas generation, to further define a possible usage. The calculation has been conducted using (3). In Table 4 the estimated values of the biogas produced are reported for each of the four SC scenarios, besides the ones relative to the organic fraction separated at the source. The biogas production is enhanced of the 21% by the increase in the SC from the 10% to the 75% (supposed linear) since a higher share of the organic fraction can be recovered, making the system more profitable in an energetic point of view. This could represent a driving force to reach higher levels in SC in the shorter time possible.

Table 4. Biogas produced by the organic waste obtained for each SC scenario.

Biogas obtained (m^3 y^{-1})	Selective Collection Rate			
	10%	25%	50%	75%
OFMSW-SC	597 605	1 494 013	2 988 026	4 482 093
OF-RMSW	3 793 826	3 161 522	2 107 681	1 053 841
Total	4 391 431	4 655 535	5 095 707	5 535 934

3.3. Monthly thermal load required

For the cases of 10%, 25% and 50% SC, since all the bioreactors operate in thermophilic conditions, the same results were obtained, while a reduction in the power requirement was noticed for 75% SC because the reactors treating the OFMSW run in mesophilic state. This choice has been considered for the low amount of material which should be treated, particularly from the undersieve of the RMSW. As a result, the 75% SC allow saving energy thanks to the low heating required.

To set the calculation, it was computed the hourly external temperature during the entire year. To proceed, it has been taken the weather data at national level. Hence, it has been possible to evaluate an average hourly external temperature for each month, starting from the daily values. To simplify the problem, instead of considering all the twelve months, results were grouped assuming the following five groups of month determined by average values:

1. December, January, February and March
2. April and November
3. May and October
4. June
5. July, August and September

Regarding the cases of 10%, 25% and 50% SC, since the internal operative temperature is the same, the hourly thermal load is equal, as reported in Figure 2. For 75% SC, instead, since the digester units which treat the OFMSW operate in a mesophilic temperature range, the thermal energy required is lower.

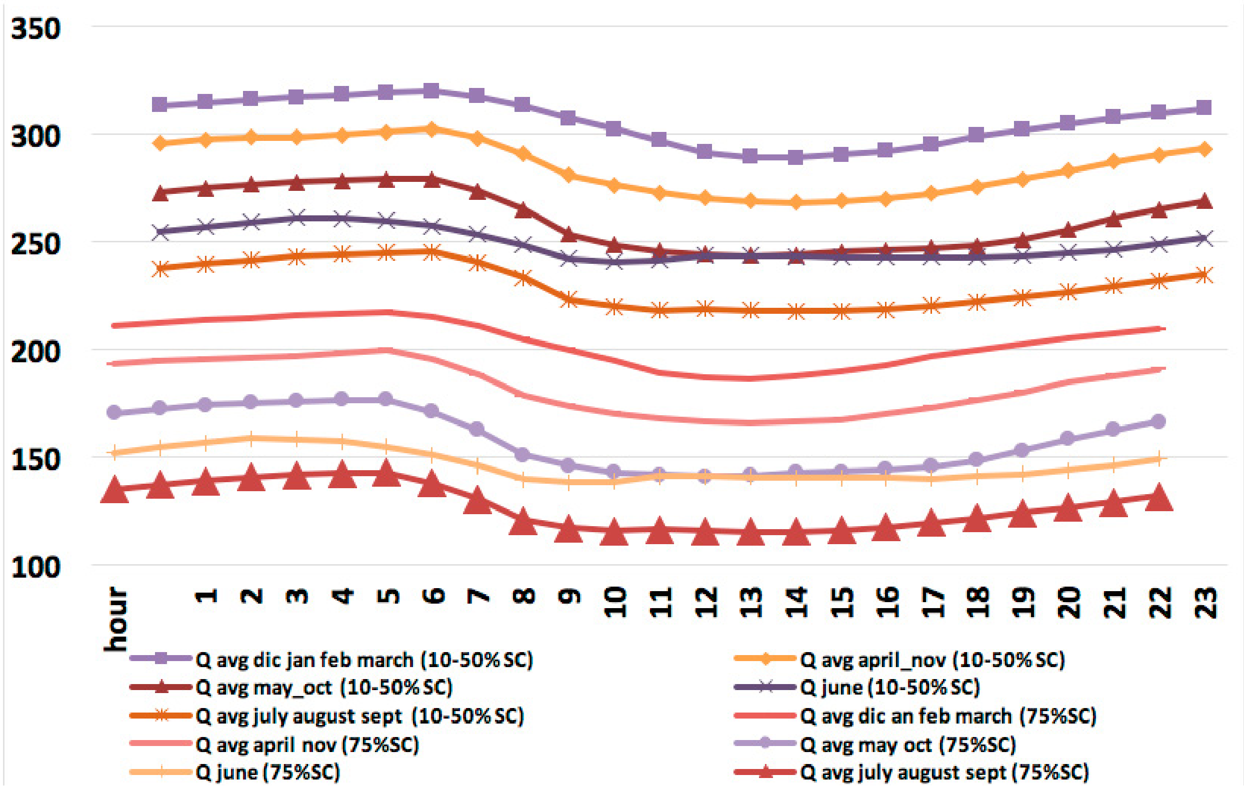

Fig. 2. Hourly thermal energy (kWh) required for hitting the AD plant.

3.4. Power production unit and evaluation of biogas consumption

After the calculation of the thermal and electrical energy required for the pre-treatment units, it is possible to estimate the energy produced. It has been chosen to operate with a CHP unit during the day working hours, when the electrical load is high due to the pre-treatment processes, and a boiler to furnish the thermal power during the night hours. That's because the boiler can ensure a thermal efficiency of 90%, against the near 60% of the CHP unit. This allows reducing as much as possible the biogas consumption, and improving the extended of bio-methane conversion for car fuel. It was chosen a micro turbine of 600kW$_{el}$, capable of producing around 1040 kWh, through the exploitation of the thermal energy contained in the gas, together with an industrial boiler which can ensure 350kWh of energy and a storage unit of the thermal energy.

The turbine can run with biogas whereas the boiler needs a previous conversion to bio-methane. Since the turbine will be often working in partial load conditions, it was necessary to determine the efficiency values in each working situation. This procedure started from the electrical conversion design value furnished by the micro-turbine producing company, and equal to the 33%, and by re-creating the efficiency curve. For the waste heating procedure, it was supposed that operating with the turbine at maximum power, it is possible to gain the hourly 600 kWh to match the thermal requirements. For each hour of the day it was evaluated the biogas consumption, according to the turbine and boiler loads. The amount of biogas for both conditions was evaluated through (4) and (5). Values regarding biogas consumption and the remaining amount were calculated in accordance to the production of biogas estimated and reported in Table 5.

Table 5. Estimation of biogas consumption and remaining amounts.

Biogas consumption [m^3]	Selective Collection Rate			
	10%	25%	50%	75%
From December to March	329 762.75	333 343.17	328 471.86	254 304.42
April and November	160 342.38	161 087.70	158 378.58	126 041.71
May and October	154 863.04	156 168.40	153 641.09	124 991.48
June	75 975.75	76 558.37	75 294.13	62 336.04
From July until September	221 973.96	223 390.98	219 491.65	186 437.71
During the year	942 917.89	950 548.62	935 277.30	754 111.36
% self-consumed per year	21.5%	20.5%	18.4%	13.6%
For sale per year	3 448 513.11	3 704 986.08	4 160 430	4 781 822.54

3.5. Economic analysis

A simplified economic analysis is implemented to roughly evaluate how the plant will perform during its whole life. The main products obtained by the AD which can be sold are [38]: Electric energy, digestate and bio-methane.
In Table 6 are reported the products obtained by the AD plant analysed.

Table 6. Product obtained by the AD process

		Selective Collection Rate			
		10%	25%	50%	75%
Biomethane					
from OFMSW [m^3 y^{-1}]	m^3 y^{-1}	358 563	869 408	1 792 815	2 689 256
from RMSW [m^3 y^{-1}]	m^3 y^{-1}	1 667 995	1 283 983	660 842	137 237
Total sold [m^3 y^{-1}]	m^3 y^{-1}	2 023 558	2 153 391	2 453 657	2 826 493
from RMSW for trucks [m^3 y^{-1}]	m^3 y^{-1}	42 600	42 600	42 600	42 600
Energy					
Electric energy	kWh	631 294	612 740	526 621	442 527
Digestate					
Total OFMSW from SC	t y^{-1}	5 986	14 980	29 956	44 935
Digestate produced	t y^{-1}	1 795.8	4 494	8 986.8	13 480.5

Since the biogas produced is the highest valuable product of the process, it should be exploited the most. Regarding the production and usage of bio-gas, the highest prizes are reached when it is converted into bio-methane and sold from a personal gas station. The price of the methane in Italy can vary from 0.78 to 1.22 € per m^3 although the price for introducing the bio-methane into the system is about 0.68 € per m^3. This is the value considered for evaluating the economic revenues. At the same time, a fraction of bio-methane can be used as fuel for the tracks which operates in the AD plant.

The fuel used for the truck is not an actual revenue, but it can be considered alike in the case in which the owner of the plant is the same agency that operates the waste collection. A compactor truck can work 1 000 km with 250 l of fuel with a PCI of 11.86 kWh kg^{-1} and a density of 0.83 kg l^{-1}. It has been supposed that a compactor track can travel 16 500 km $year^{-1}$ so can consume 4 125 l of fuel, equal to 3 436 kg. Since 1 kg of diesel fuel is equal to 1.23 m^3 of methane, it has been estimated that the each truck required 4 260 m^3 of bio-methane per year. The cost of bio-methane is about 0.97 € kg^{-1}.

Other two main products can be exploited: the electric energy and the digestate. The electric energy can be sold at 0.05316 € kWh^{-1} while the digestate composted at 8 € m^{-3} (about 16 € t^{-1}). The amounts of digestate considered are only the ones obtained by OFMSW from SC since are of high quality and the only amounts that can be sold for agriculture usage. It must be noticed that the price of the digestate derived from the market of the manure for agriculture and not from the process. Indeed, the production cost is quite higher and the prize cannot cover the entire process [39].

The Italian energy system managing authority sets a form of incentives through the emission of CIC, in relation to the global energy content of the entire biogas produced. In particular, as regard the presented case study, the CIC obtainable should be

- 20 years subsidize with 1 CIC =10 Gcal of bio-methane produced from the RMSW
- 20 years doubled subsidize 1CIC every 5 Gcal for the production coming from the OFMSW after SC
- A further 50% increase in the financing, if the bio-methane is produced for being used as car fuel and is distributed from a personal gas station.

So, regarding the biogas consumed within the plant, it can be assumed that only the fraction coming from the RMSW treatment can be exploited since it presents lower subsidizes. The rest can be sold, after having converted it in bio-methane. Such incentives are available only in Italy, so they were not included in the study, in order to make the calculations valid also for other situations.
In Table 7 are reported all the items regarding the possible revenues obtainable by AD treatment plant.

Table 7. Production of digestate and relative income due to material sale after composting process

		Selective collection rate			
		10	25	50	75
Costs					
Initial investment	€	11 800 000			
Operational and maintenance	€ y^{-1}	1 300 000			
Revenues					
from electric energy	€ y^{-1}	33 560	32 573	27 995	23 525
from bio-methane	€ y^{-1}	1 376 019	1 464 306	1 668 487	1 922 015
from compost	€ y^{-1}	28 732.8	71 904	143 788.8	215 688
Total revenues	€ y^{-1}	1 409 579	1 568 783	1 696 482	2 161 228
Total revenues per month	€ $month^{-1}$	117 465	130 732	141 374	180 102
Yearly gain	€ y^{-1}	109 580	268 783	396 482	860 000

Regarding the plant investment, it was supposed a total cost of the system equal to 10,000,000 €, plus 1,800,000 € for 10 garbage truck, for a total amount of 11,800,000 € and operational and maintenance yearly cost of 1,300,000 € [40, 41]. It is evident from Table 7 how it is relevant the improvement of the SC and the introduction of national incentives in order to decrease the times for the recovery of the investment.

4. Discussion

In the dynamic approach proposed in this study has been considered a high scale AD plant for improving environmental sustainability, recycling rates and energy provision for the local population. In general, AD can be considered for treating biomass such as animal manure and sludge from urban wastewater or crop residues, although the best resources for producing bio-methane are food waste because of its high moisture (80%) and VS (95% of TS) [38, 42]. Biogas has potential for diverse applications such as heating, CHP, transportation fuel or bio-methane for different applications and can be coupled also with a gasification process which could be beneficial from an energy efficiency point of view [43]. However, It is different for developing countries, where the lack of financial resources and environmental technology do not let to developing efficient plant at large scale [24].

AD in large or small scale can be an answer to the needs of urban energy and it can replace other fuel such as coal or wood, mitigating GHG emissions [42]. Anyhow, the technology is only a small issue towards a sustainable SWM. The most difficult challenge for developing AD technologies is the public inclusion and the awareness in ecological issues. The SC of putrescible waste is, indeed, of utmost importance in order to improve recycling rates and build technological facilities which can improve SWM future perspective. Therefore, the introduction of sensitivity campaigns and the inclusion of all stakeholders is imperative, most of all in developing countries, where NGOs, private service providers, international aids and university international agreements should be encouraged [44, 45]. So, an integrated approach is necessary, which considers social, economic, institutional, legal and environmental issues, and led to obtaining the best practicable way to manage waste [46]. For instance, small scale biogas plants have been introduced in developing countries in order to provide natural gas for cooking and a more sustainable way of living. However, there are still many issues regarding operational and maintenance, regulation and know-how for continuing the application of this technology [47, 48].

The inclusion of the citizens or local stakeholder is recommended in spite of the provision of disposal fees or economic incentives to recycle since disposal fees can increase the illegal dumping and are difficult to collect, particularly in developing countries. Moreover, residents may be discouraged to separate at the source the waste when they believe that there are technologies which separate and recycle waste next to landfills without efforts. These perceptions should be clarified through participative planning, open technological debate, pilot projects and social surveys [49, 50]. Moreover, the installation of sorting equipment in all households held the increase of the source separation ratio as well as the amount of SC of OFMSW [51].

The survey can help policy makers to understand which is the direct consequence for developing SC rates and improving the collection system of the OFMSW adopting a large scale AD plant. The methodology presented gives a clear comparison about the development of the scenarios regarding the improvement of the SWM which means higher economic advantages and higher amounts of energy available. Indeed, improving the amounts of OFMSW from SC, the volumes of methane are increased and there is an extensive production of digestate which can be used for the agriculture, in a sustainable development [52-55]. Moreover, it should be considered the importance of the improvement of SC also for the energy and economic save in the pre-treatment of the RMSW, which decrease by the improvement of the SC. This consideration has not been underlined in section 2.5 since it is not a direct income due to the AD process. However, it has been underlined how a sort of national incentives are important for introducing AD plants in a territory since the benefits are visible only at long term. As regard MSW quantities, future perspective should take into account the variation on the amounts of waste during the years, depending on the situation which characterized each area. Indeed, the model suggested can be applied and considered for other case studies and improved for a specific area, changing the objectives during the years and planning future investments in the SWM.

5. Conclusion

Four main scenarios of selective collection have been studied and the municipal organic waste examined amounted to 60,000 tones year^{-1}. The main goal of this work was to establish an approach useful to introduce waste treatment processes which could be adopted in contexts where both SC procedures and sustainable waste management were not developed. The method provided in this paper can be a suitable way to allow policy makers and project developer to forecast future objective and sustainable ways to improve recycling rates and invest in treatment facilities. This could be implemented together with a reduced landfill disposal and a high degree of energy recovery from the waste, due to the biogas conversion from the organic fraction. The ability of reaching all these goals with just one waste treatment plant, accompanied by a more and more profitability of the system as long as SC increased, could be of great appeal for all the cases which are still facing emergency situations regarding refuse management. Solid waste handling mostly refers to ecological issues, especially in such context where recycling and sustainable technologies are not developed, and economically unfordable barriers which means human health risk and environmental pollution.

The theoretical plant object of this study process all the refuse coming from the municipalities and considering four SC steps (10%, 25%, 50% and 75%). The assumption is that the SC system finally gathers the 75% of the putrescible fraction and achieves the 75% recycling chain with 38% SC covered by the separation of the putrescible fraction. By the adoption of a dynamic anaerobic digestion process in batch reactors the biogas produced is enhanced of the 21% by the increasing in the SC from the 10% to the 75%, making the system more profitable in an energetic point of view. Moreover, for the first three scenarios a thermophilic condition has been suggested while a mesophilic one for the 75% SC. As a result, the 75% SC allow save energy by the low heating requirements as well as improve the economic incomes.

Discontinuous AD plants, as the one presented here, could be of a great importance for all the countries, or regions, which still are facing an emergency situation in the waste treatment process and want not only to find a solution to avoid landfill disposal of putrescible material, but also to enhance the source separation of waste. In fact, the possibility of handling, always in the same plant, all the refuse produced and in all the difference selective collection contexts, together with the greater revenues coming from the treatment of the highest possible share of OFMSW, could represent an important turning point when government administration has to decide the waste management procedure that should be adopted.

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