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ORIGINAL PAPER

Athens-Biowaste Model: Cost and Carbon Footprint Calculation of the Collection at Source and Treatment of Biowaste

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Abstract This paper gives a brief introduction of the so called "Athens Biowaste" model and demonstrates its outcomes through its application on three different case study areas. The model has been developed aiming to support municipalities in building a separate biowaste collection scheme, estimating the direct investment and operational costs and identifying the areas where substantial GHG savings in $CO_{2\ eq.}$ could be achieved. The model has been applied in three different Municipalities, representing European urban, suburban and rural areas, varying in population and building characteristics. In all areas, two collection scheme types were examined, namely door-to-door and road containers schemes. All scenarios modelled showed that the investment cost for establishing a separate collection scheme was approximately 10€ per inhabitant using existing waste collection vehicles. Operational cost is directly linked to the type of the collection scheme applied, the participation rate and the collection frequency. The operational cost per tonne of biowaste was reduced approximately by 50 % when the participation rate increases from 25 to 64 %, while cost increased from 40 to 60 % in all examined cases when the collection frequency is doubled. GHG emissions are mostly dependent on waste treatment methods and to a lesser extent on the collection and transportation conditions. The Athens Biowaste model can assist Municipalities in evaluating different biowaste source separation schemes and estimating the level of influence on the total waste management cost and GHG emission savings.

Keywords Biowaste · Source separation · Model · Cost · Carbon footprint

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Introduction

In EU-28 the contribution of waste management activities to greenhouse gas (GHG) emissions is estimated at about 3 % of the overall emissions in 2012 representing the fourth largest GHG emitting sector after energy, agriculture and industrial processes [1]. Moving towards a recycling society, with a high level of resource efficiency, indicates that the waste sector is also moving to becoming a major saver of emissions instead of being a minor source of global emissions [2]. All waste management practices generate GHG, both directly (i.e. emissions from the process itself) and indirectly. The indirect emissions can be further divided to upstream indirect activities (i.e. emissions from the production of energy used in the process) and downstream indirect activities (i.e. avoided emissions when substituting materials and energy carriers by activities in the waste management chain) [3]. The latter implies that emissions can be avoided in all other sectors of the economy, having positive consequences for GHG emissions from the energy, forestry, agriculture, mining, transport and manufacturing sector [2].

During the past decade, several studies [4–8] focused on estimating direct and indirect GHG emissions from municipal solid waste (MSW) management using Life Cycle Assessment (LCA) tools or dedicated waste LCA tools (e.g. EASEWASTE, WRATE, LCA-IWM). A recent review [9] has shown that differences among these models arise due to technical assumptions, technology type, inventories used and output data. In addition, the outcome of 25 comparative LCA studies on alternative food waste management options [3] has shown that both absolute values and relative ranking of management systems differ significantly in terms of global warming impact. In all cases, though, it is clearly demonstrated that separate collection and recycling have a beneficial effect in terms of GHG emissions reduction, while landfilling usually implies increases unless energy recovery is applied [6]. Furthermore, there is a general global consensus that climate benefits deriving from waste avoidance and recycling far outweigh other waste management options including energy recovery from waste [2].

Apart from the estimation of GHG emissions, the economic assessment of different waste management options is equally important when it comes to decision making [7]. The general perception is that separate collection of biowaste leads to an increase in the total cost of the service. Comparative analyses on waste collection cost have shown that significant cost savings can be obtained as long as the participate rate in source separation programs is above a certain threshold value [10]. In this direction, a biowaste source separation cost model developed by WRAP, Kerbside Analysis Tool (KAT), assists local authorities in the UK to review the efficiency waste and kerbside recycling collection systems and to forecast the likely performance and cost of potential changes to the service.

In Greece biowaste source separation schemes were launched for the first time at selected areas in Athens and Kifissia municipalities within the framework of the Athens-Biowaste project (LIFE10/ENV/GR/00605) aiming to divert biodegradable organic waste from landfill and produce good quality compost at the MBT facility in Attika Region. Based on the two-year experience gained from the implementation of the scheme, a model has been developed in order to assist decision makers in developing biowaste separate collection programs, estimating related investment and operational costs and evaluating the effect of the service in terms of GHG emissions variation throughout the MSW management system. The Athens-Biowaste model does not substitute LCA models in terms of GHG estimates, but it aims at demonstrating the influence of separate collection and treatment options on the overall carbon footprint of the municipal waste management system in place.

The objective of this paper is to demonstrate the outcomes of the model in three different case study areas and identify the key parameters that contribute to cost-efficient and GHG saving measures when establishing separate collection systems for biowaste.

Materials and Methods

Description of the Model

The model has been developed in the framework of the Athens Biowaste project, as a decision support tool for Municipalities which seek to establish a separate collection scheme for biowaste. Apart from step-by-step building of the collection scheme, the model provides estimations of direct investment and operational costs allowing the user to evaluate different scenarios. It calculates the GHG emissions which are related to biowaste collection and treatment but it also determines GHGs resulting from the overall MSW management system. This option allows the user to primarily identify the parameters controlling GHG emissions.

All technical assumptions, indicators and equations used in the model are based on the work carried out within the framework of the "Athens-Biowaste" project and on international experience related to this particular field. All input parameters have been carefully selected aiming to be suitable for local authorities which plan to organize relevant schemes and to remain simple and coherent for decision makers. The model has been developed in Microsoft Excel platform and is accompanied by a Guide Manual [11]. It is available upon request on Athens-Biowaste website www.biowaste.gr, while the manual can be directly downloaded from the website. The following table shows the main data of the model namely input data, default values, estimated values and output data (Table 1).

Basic Assumptions and Equations Used in the Model

Biowaste Collection Scheme

The model considers the following separate collection schemes which are most commonly applied for biowaste:

- Door-to-door collection (D–D) scheme. In this collection scheme each household or building has its own separate bin, varying in size.
- Road containers collection (R–C) scheme. In this collection scheme one bin covers several households and buildings. This system is mostly used in Greece, since residential buildings do not have a dedicated areas for the temporary storage of waste.

Table 1 Basic structure and functions of the model

Data	Input by user	Can be amended by the user		Output (result)
		Default values	Estimated values	
Municipality data: name, population, density, no. of households	X			
Area where separate collection will be implemented: area name, population, households, density, building characteristics, tourist activity, no. of large biowaste producers	X			
Municipal solid waste (MSW) generation estimate, MSW quantities to be separate collected and recycled, treated as mixed waste or landfilled		X	X	
Biowaste composition in MSW, total biowaste generation, estimate per inhabitant and per household		X	X	
Estimated quantities of Biowaste collected at source: participating rate, expected biowaste quantities to be collected		X	X	
Biowaste management: biowaste treatment technology, distance, transfer time, waiting time	X			
Type of separate collection scheme suggested: door-to-door or road containers			X	
Type of equipment/consumables suggested: kitchen caddies, plastic or metallic bins, biodegradable bags			X	
Biowaste separate collection scheme collection and transportation system: no of summer or peak period months, biowaste collection frequency, collection employees per vehicle, employees' working days and hours, routes per vehicle per day, time from vehicle parking to the centre of the area in question, collection time for automatic and manual loading of bins		X		
Biowaste separate collection scheme fleet management: weekly quantities collected, collection routes required per week, vehicles required, existing vehicles to be used and existing collection vehicles for current MSW collection and transportation			X	
Prices per item: bins, biodegradable bags, vehicles, awareness campaign, other equipment		X		
Annual cost per item: annual salaries, petrol price, vehicle maintenance cost, annual bin replacement, etc.		X		
CO_2 emission factors: bulk nitrous oxide (N_2O) and Methane (CH_4) emission factors for rigid heavy duty vehicles, GHG emissions from the treatment of waste		X		
Investment and operational cost of biowaste separate collection				X
Cost–benefit of current and new MSW management system				X
Carbon footprint for total MSW collection, transportation, treatment and landfilling: $CO_{2\ eq.}$ of current collection and treatment system, $CO_{2\ eq.}$ of new collection and treatment System, savings per year				X
Separate biowaste collection optimisation	X			X

Table 2 Building characteristics of a municipality

Type of buildings	Percentage in the municipality (%)
A. Detached houses *with* garden (serving one household)	
B. Detached houses *with* garden or open car park ≤4 floors (serving multi households)	
C. High-rise buildings *with* garden or open car park >4 floors	
D. Buildings *without* garden or open car parks ≤4 floors	
E. High-rise buildings *without* garden or open car park >4 floors	

The selection of biowaste separate collection scheme is related to the case study's building characteristics and especially the availability of common areas (i.e. garden, open car park). Table 2 provides information on the classification of residential buildings according to houses configurations and the availability of common areas. It is suggested that door-to-door collection schemes should be applied in areas where detached houses with garden and/or

Table 3 Loading time per bins and employees

	Bins loaded without mechanical lift (up to 50 L)	Bins loaded with mechanical lift
Minutes per bin (1 loader)	0.8	1.32
Minutes per bin (2 loaders)	0.4	1.10

open car park cover more than 60 % of the total residential buildings. This assumption has been made following the evaluation of different communities in Attica region based on their building characteristics.

In addition, the model accounts for 2 and 10 % w.w. impurities level when door-to-door and road containers schemes are applied respectively as reported in composition analysis studies on segregated biowaste.

Collection Time

Collection time refers to the time required to unload biowaste from the bin to the waste collection vehicle. The collection time is estimated based on average loading time values for two bin types as recorded in the Athens Biowaste project (Table 3). Other studies [12] report lower values (less collection time) probably because biowaste separate collection is already in place and performance, in most cases, is optimised.

Collection Routes and Vehicles

The collection routes are calculated by correlating (a) the collection time, the time between collection points, the time required to transfer the material to the treatment plant and the collection employees rest breaks and (b) the daily working hours of the collection employees. Next, the model calculates the required number of waste vehicles and it estimates their capacity according to the quantity of loaded biowaste per collection route. It is important to note that collection routes are primarily determined by the total collection time rather than the capacity of the vehicle or biowaste quantity.

Investment Cost

The model estimates investment cost by using average European market prices which can be found in the "Athens Biowaste" Guide for separate collection [13]. It considers procurement costs for 10 L kitchen caddies, bins for separate collection (35–1100 L), waste collection vehicles (or the use of existing vehicles), biodegradable bags (for 10 and 50 L bins) and awareness campaign. The cost of the awareness campaign is related to the population served and includes the following items, campaign identity (logo, banner, and bins' stickers), information leaflets and personal letters to citizens, information kiosk and school activities.

Operational Cost

The operational cost includes the following categories:

- collection personnel cost (driver 18,000 EUR/yr and loaders 15,000 EUR/yr),
- fuels for collection assuming consumption of 5 L-h—vehicle,
- fuels for transportation assuming consumption 0.5 L-km—vehicle,
- vehicle cost for service and insurance, assumed 5–8 % of the vehicles' investment cost,
- annual bins replacement cost, assumed 5 % of the bins' initial investment cost,
- awareness campaign, assumed 5–10 % of the campaign initial investment cost,
- part-time administrative personnel, consisting of one biowaste co-ordinator (20.000 EUR/yr) and one bins' supervisor (15,000 EUR/yr),
- biodegradable bags (annual renewal), if needed.

The aforementioned cost assumptions have been made following various interviews with the participating Municipalities in the Athens-Biowaste project as well as reviewing values from KAT model [14] and other European market values. It is noted that fuel consumption is not related to the type of vehicle and the latter only affects emissions of $CO_{2\ eq.}$, as described in the carbon footprint section.

Cost–Benefit Analysis

To implement a cost-benefit analysis for the introduction of the biowaste separate collection scheme, an integrated approach is required. In this study the cost-benefit analysis performed provides information on the annual waste management cost impact of the new service applied for biowaste. Thus, the model provides a rough estimation of the current and the new MSW management costs including all waste management stages from collection and transportation to treatment and landfilling. The new costs are estimated considering that collection costs are increased, while certain quantity of biowaste is diverted from landfill in order to be treated separately.

Carbon Footprint

In the present study carbon footprint analysis considers the GHG emissions in units of $CO_{2\ eq.}$ of the current MSW waste management system and the system which employs separate collection and treatment of biowaste. For estimating carbon footprint, the model uses emission factors from different studies including the Waste and Climate Change—Global Trends and Strategy Framework Report [2] and the 2011 Guidelines to Defra/DECC‘s GHG Conversion Factors for Company Reporting [15], which include total CO_2, CH_4 and N_2O emissions in terms of $CO_{2\ eq.}$. Values for CH_4 and N_2O are presented as $CO_{2\ eq.}$ using Global Warming Potential (GWP) 100-year factors from the 4th assessment report of the Intergovernmental Panel on Climate Change (IPCC) (GWP for $CH_4 = 25$, GWP for $N_2O = 298$). The GHG emissions coefficients used in the model are summarized in Table 4 (negative values indicate GHG savings).

As far as collection and transportation are concerned, GHG emissions are estimated based on fuel type and consumption according to literature [16]. In addition, CH_4 and N_2O, specific emission factors (in g-km) were used, sourced from COPERT 4 methodology [16].

Model Application

The model has been applied in three different Greek Municipalities. These areas are considered representative of European urban, suburban and rural areas and have varied characteristics, such as population and building characteristics. The selected case studies are described below.

- A suburban area of 17,500 inhabitants (Nea Erythraia) in the Municipality of Kifissia.
- An urban area of 48,000 inhabitants (3rd Municipal Community) of the City of Athens which consists of the south western districts of Athens: Akropolis, Votanikos, Rouf, Ano and Kato Petralona and part of Elaiona
- An island (rural area) with 4977 inhabitants (Milos Island) which is situated in the southwest of Cyclades islands.

For the cases of Milos and Kifissia, both separate collection types were modelled (i.e. door to door and road container systems). More information on the scenarios examined for each case study are presented in Table 5.

Results and Discussion

Basic Requirements of Separate Collection Scheme

Table 6 presents the collected quantity of biowaste for each case study on a weekly basis, the number of collection routes and the required number of waste vehicles. It should be noted that in Milos island biowaste collection is doubled during the summer period, while in Kifissia the number of collection routes increases when the door-to-door scheme is applied due to the large number of bins that need to be collected.

Table 4 Net GHG emissions per treatment method

Waste management method	Net emissions (kg $CO_{2\ eq.}$/t of waste treated/disposed)	Data sources
Anaerobic digestion (source separated biowaste)	−126	DEFRA [15]
Composting (source separated biowaste)	−42	DEFRA [15]
Recycling of waste fraction (source separated)	−711	DEFRA [15] (average values of open and close loop recycling for MSW)
MBT (anaerobic|RDF|incineration RDF|landfill)	−157	Estimated values based on mass balances and DERA 2011 values for MSW
MBT (anaerobic|recycling|landfilling)	−321	
MBT (Biodrying|incineration SRF|landfilling)	−229	
MBT (composting|RDF|incineration RDF|landfilling)	−145	
MBT (composting|recycling|landfilling)	−309	
Mixed waste incineration	−37	DEFRA [15]
Uncontrolled or engineered landfill without biogas recovery	786	UNEP [2]
Landfilling (biogas recovery)	26	UNEP [2]
Landfilling (biogas incineration)	162	UNEP [2]

Table 5 Case studies scenarios for biowaste source separation

	MILOS Door-to-door	MILOS Road containers	KIFISSIA Door-to-door	KIFISSIA Road containers	ATHENS Road containers
Municipality name	Milos		Kifissia		Athens
Type of municipality	Rural		Urban		Urban
Total population (municipality)	4977		71,259		664,046
Population density (inh./km^2)	31		2011		17,043
Case study area	Whole municipality		One district—N. Erythraia		3rd district
Population of case study area	4977		17,500		48,000
Number of households	2074		6731		21,819
Building characteristics	>75 % detached houses		>60 % detached houses		>75 % non-detached houses and high-rise buildings
Area basic characteristics	High tourist activity with monthly peaks during summer, detached houses with garden and traditional architectural structure		Suburb of Athens, high living standard, detached houses with yard		High population density with multi-family building arrangements
Type of biowaste separate collection scheme modelled	Door-to-door	Road containers	Door-to-door	Road containers	Road containers
Expected participation rate in biowaste separate collection scheme	37.50 %				
Expected biowaste quantities to be collected (t/year)	547		1038		2846
Expected biowaste quantities to be collected without impurities (t/year)	536	492	1017	934	2562
Biowaste treatment technology	Composting				
Distance between a) centre of the area and b) biowaste treatment facility or transfer station (km)	9		22		15
Transfer time to biowaste treatment facility or transfer station (min)	15		30		30
Waiting time in the biowaste treatment facility or transfer station (min)	10		20		20
No of months of the summer or peak period	4				
Biowaste collection frequency (normal/peak period) − number per week	1 (n) 2 (p)				
Loaders per vehicle (normal/peak period)	1 (n) 2 (p)				
Employees' working hours per day	6.2				
Employees' working days per week	5				
Routes per vehicle per day	1 (n) 2 (p)				

n: normal period, p: peak or summer period when higher collection frequency may be required

Investment and Operational Costs

The investment cost for establishing a biowaste separate collection scheme depends on the size of the municipality, as shown in Table 7 and includes the following:

- Kitchen caddies. Kitchen caddies are given to the citizens free of charge as a motivation to participate to the source separation scheme.
- Biodegradable bags. The bags are usually distributed free of charge during the first months of the service

Table 6 Collection requirements of biowaste separate collection schemes examined

	MILOS Door-to-door	MILOS Road containers	KIFISSIA Door-to-door	KIFISSIA Road containers	ATHENS Road containers
Weekly quantities of biowaste collected (t/week)	8,10 (n) 17,44 (p)		19,95		54,73
Collection routes required per week	3 (n) 5 (p)	2 (n) 3 (p)	8 (n) 13 (p)	3 (n) 4 (p)	7 (n) 10 (p)
Vehicles required	1	1	2	1	1
Existing vehicles utilised	–	–	1	1	1

n: normal period, p: peak or summer period when higher collection frequency may be required

Table 7 Investment cost of biowaste separate collection schemes examined

	MILOS Door-to-door	MILOS Road containers	KIFISSIA Door-to-door	KIFISSIA Road containers	ATHENS Road containers
1. Kitchen caddies	12,444€	12,444€	40,386€	40,386€	130,914€
2. Bins	24,749€	9212€	61,659€	17,154€	53,139€
3. Vehicles[a]	110,000€	120,000€	70,000€	–€	–€
4. Biodegradable bags	18,899€	20,609€	61,336€	62,405€	205,238€
5. Awareness campaign	5889€	5889€	11,328€	11,328€	24,022€
Total	171,981€	168,155€	244,709€	131,273€	413,314€
Inv. cost per inhabitant	35€	34€	14€	8€	9€
Inv. cost per inhabitant (without vehicle cost)	12€	10€	10€	8€	9€

[a] It was assumed that Kifissia and Athens will use one existing vehicle

operation (3 months considered in the studies examined) aiming to motivate public participation.

- Vehicles. The cost for a new waste collection vehicle is usually 50 % of the total investment cost for establishing a source separation scheme. However, municipal authorities can use existing vehicles to reduce the investment cost.
- Bins and awareness campaign. This cost is relatively low compared to the above mentioned costs.

As shown in Fig. 1, the investment cost per inhabitant is approximately 10€, when the procurement of new vehicles is not required. The cost per inhabitant is reduced, on average, to less than 3€ per inhabitant in the case when only the basic equipment is included namely the bins and the awareness campaign.

The personnel cost constitutes the largest single cost of the biowaste separate collection service amounting to more than 50 % of the total operational cost, while fuel consumption and vehicle maintenance are secondary costs. More details on the operational costs are given in Table 8.

As shown in Fig. 2, the operational cost per tonne of the biowaste collected varies in all case studies, as it depends on several factors which are briefly described below.

- *The separate collection scheme*. A door-to-door collection scheme which is well established in northern European countries is less popular in Greece, due its different housing characteristics. Although several studies have shown that door-to-door collection increases participation, this was not clearly evident in the case of Athens Biowaste project. However, a door-to-door scheme can indeed ensure very low impurities levels to segregated biowaste (below 2 % w.w) compared to road containers collection schemes. As shown in Fig. 3, the operational cost of a door-to-door collection scheme is higher, as it requires additional routes for serving a specific area, due to the large number of bins, resulting in more personnel and fuel consumption.
- *The participation rate* indicates the percentage of total households which systematically participate in the collection scheme. As the participation rate increases, it is obvious that the collected quantities increase and thus the cost per tonne significantly decreases. This is easily explained by the fact that more quantities are collected per collection route. Figure 4 shows that the operational cost is significantly influenced by different participation rates.
- *The collection frequency* is also a critical factor since it affects the total annual collection routes. Collecting twice per week means that the minimum routes required for serving an area, have to be multiplied by two. In

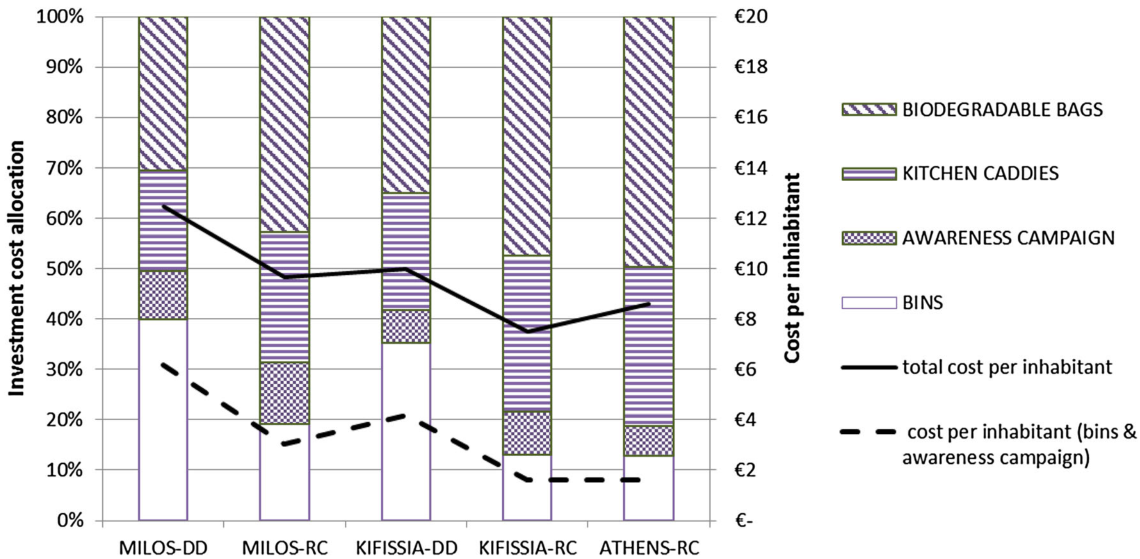


Fig. 1 Investment cost for the introduction of biowaste source separation schemes in the examined case studies (without vehicles)

Table 8 Operational cost of biowaste collection schemes examined

	MILOS Door-to-door	MILOS Road containers	KIFISSIA Door-to-door	KIFISSIA Road containers	ATHENS Road containers
1. Collection personnel	25,136€	11,390€	74,953€	20,986€	61,227€
2. Fuels	8616€	3944€	31,645€	9263€	21,068€
3. Vehicle cost	8000€	8000€	7000€	8000€	8000€
4. Bins replacement	1237€	461€	3083€	858€	2657€
5. Awareness campaign	589€	589€	793€	793€	1201€
6. Administrative personnel	3422€	3422€	12,031€	12,031€	29,000€
Total	46,999€	27,806€	129,505€	51,931€	123,154€
Cost per tonne of biowaste collected (without impurities)	88€	57€	127€	56€	48€

southern European countries, such as Greece, the collection of MSW is usually performed on a daily basis, especially during the summer period. This implies that the biowaste collection frequency cannot be performed on a weekly or fortnight basis, as commonly applied in northern European countries. Figure 5 shows that the operational cost increases proportionally to the collection frequency in the case studies examined.

- *Number of employees per vehicle*. The number of staff required to carry out biowaste collection is an important consideration for any collection service. Most of the schemes operate successfully with one driver and one loader. Two loaders per vehicle will accelerate the collection process, but not always in a cost-efficient way. However, in some urban areas biowaste collection operates with two loaders per vehicle in order to collect bins from both sides of a road aiming to reduce the number of routes per vehicle.
- *Distance to biowaste treatment plant*. The distance between the served area and the biowaste treatment plant influences the duration of the collection routes, the fuel consumption and the driver's working hours.

Cost–Benefit Analysis

At first sight the total collection cost increases when a new biowaste collection scheme is established in addition to the existing MSW collection services i.e. recyclables and other MSW streams. However, MSW management integration which takes into account the overall municipal cost for the collection, transportation, treatment and landfilling of waste, can result in total cost savings when biowaste source separation schemes are applied. In order to investigate the cost impact of the new biowaste service applied in the examined case studies, the following annual costs were considered.

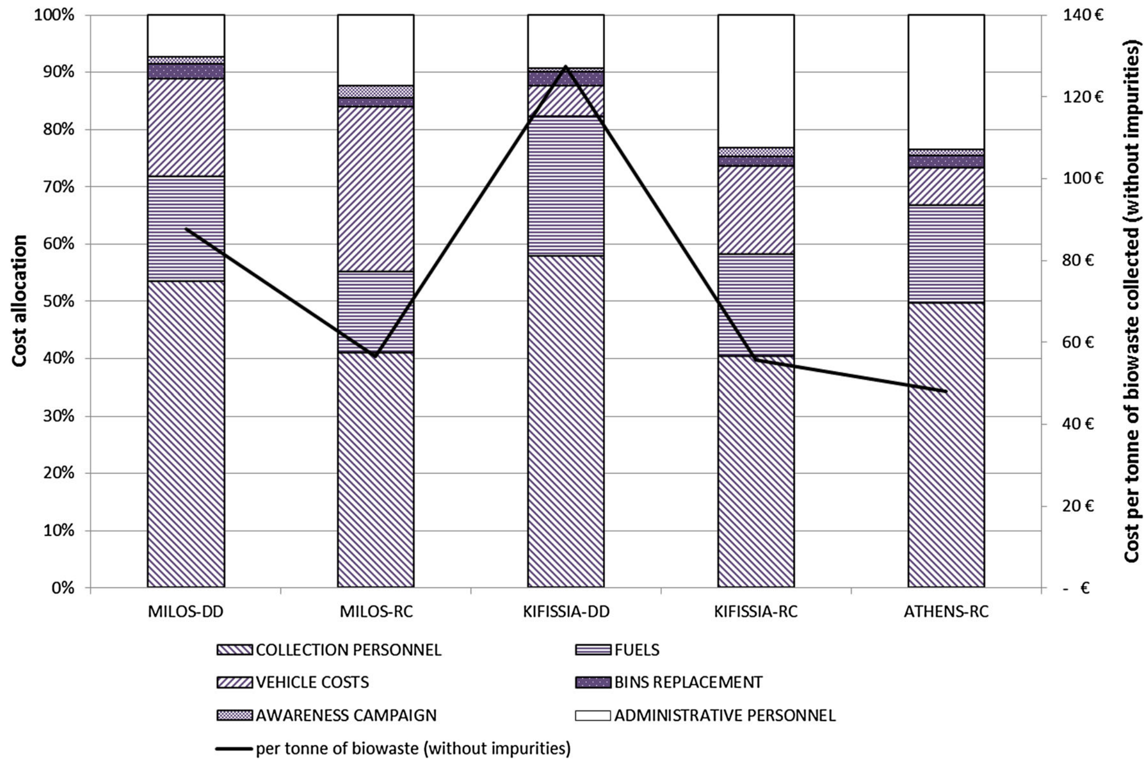


Fig. 2 Operational cost of the biowaste source separation schemes in the examined case studies

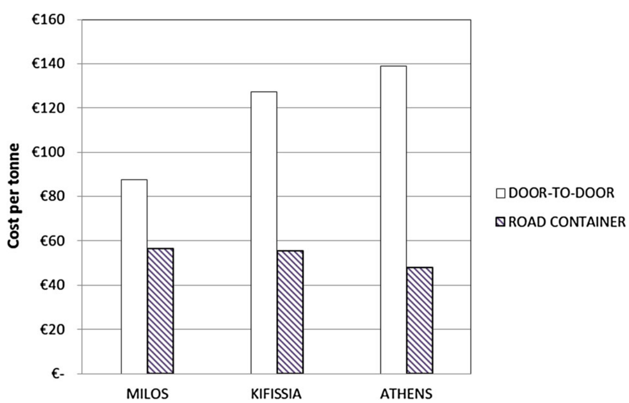


Fig. 3 Comparison of operational cost between different collection schemes

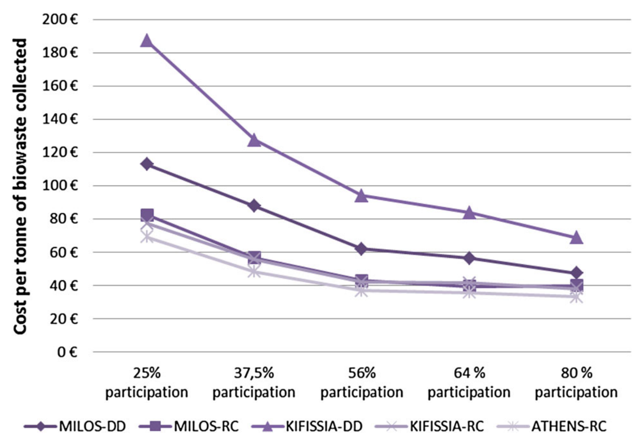


Fig. 4 Operational cost as a function of the participation rate in the examined case studies

– *Current MSW collection and transportation cost*. A typical value of MSW collection and transportation cost in Greek municipalities with a high collection frequency is between 80 and 100€-t.
– *Current MSW treatment/landfilling cost*. This cost refers to the gate fee for the treatment of mixed MSW (if any treatment exists). The gate fee for landfilling and the landfill tax in Greece is governed by Law 4042/2012.
– *New MSW and biowaste collection and transportation cost*. This refers to the new collection and transportation cost of biowaste and the remaining mixed MSW. This cost category is estimated by adding the annual operating cost of the biowaste collection scheme to the current MSW collection cost assuming that the latter is reduced by 10 % due to the decrease of the amount of mixed MSW that need to be collected.
– *New MSW treatment/landfilling cost*. The cost is estimated from the current MSW treatment/landfill cost excluding diverted source separated biowaste. Impurities from the material collected are included in cost estimations.

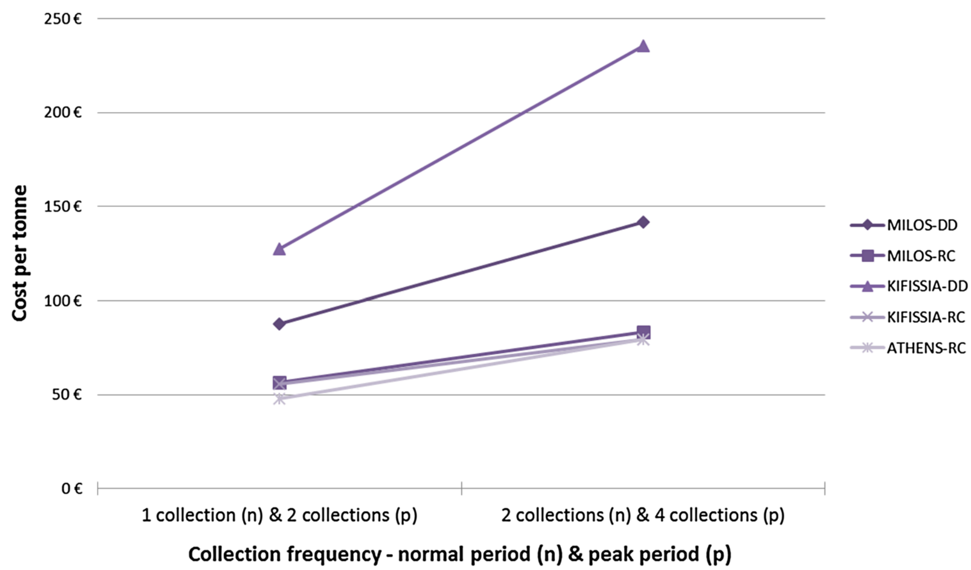


Fig. 5 Operational Cost as a function of the collection frequency in the examined case studies

Table 9 Cost–benefit analysis of integrated waste management before and after biowaste separate collection and treatment for each scenario modelled

	MILOS Door-to-door	MILOS Road containers	KIFISSIA Door-to-door	KIFISSIA Road containers	ATHENS Road containers
Current MSW management cost					
Current MSW collection cost	331,349€	331,349€	582,540€	582,540€	1597,824€
Indicative collection cost for MSW (per tonne)	100€	100€	80€	80€	80€
Current MSW treatment/landfilling cost	281,646€	281,646€	617,234€	617,234€	1827,163€
Gate fee for treatment of mixed MSW (per tonne)	0€[a]	0€[a]	90€	90€	90€
Gate fee for landfilling (per tonne)	25€	25€	45€	45€	45€
Landfill tax (per tonne)	60€	60€	60€	60€	60€
Total	612,995€	612,995€	1,199,774€	1,199,774€	3,424,987€
New MSW management cost					
New MSW and biowaste collection cost	345,213€	326,020€	653,791€	576,217€	1,561,195€
% reduction of current collection frequency	10 %	10 %	10 %	10 %	10 %
New MSW treatment/landfilling cost	235,448€	236,542€	509,215€	512,950€	1,541,127€
Biowaste treatment cost	19,135€	19,135€	36,318€	36,318€	99,614€
Gate fee for biowaste treatment (per tonne)	35€	35€	35€	35€	35€
Total	599,797€	581,697€	1,199,323€	1,125,485€	3,201,937€
Cost–benefit[b]	−13,198€	−31,299€	−451€	−74,289€	−223,050€

[a] Currently no treatment facilities are in place in Milos Island

[b] Negative values indicate benefit

– *Biowaste treatment cost*. Refers to the gate fee charged for biowaste treatment.

Table 9 shows the results of the cost–benefit analysis for all five scenarios examined.

In the case of road container collection schemes, the total MSW management cost decreases between 5 and 7 %, while the cost increases as the served population of the case study area decreases (Fig. 6). When door-to-door collection schemes are applied, the relevant cost savings are obviously lower than the road container schemes, whereas the cost-benefit decreases as the size of the municipality served increases.

Considering that the MSW treatment methods do not change in the Municipality and their respective costs are fixed (gate fee for treatment and landfilling or landfill tax) than the total cost is regulated by MSW collection and

Fig. 6 Cost reduction of current MSW management plan after the introduction of the biowaste source separation in the selected areas

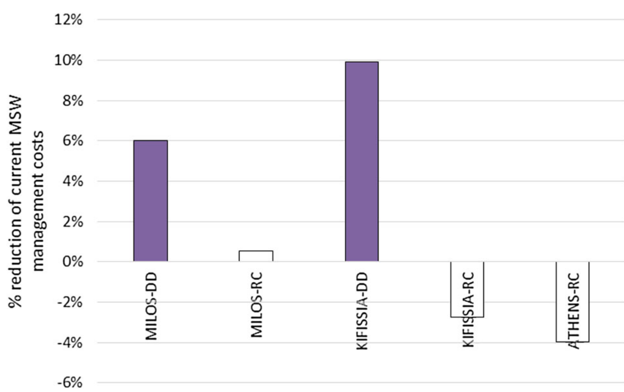


Fig. 7 Percentile modification requirements of current MSW collection cost to achieve break-even point when applying the examined biowaste source separation schemes

transportation frequency. This means that the break-even point should be identified after the biowaste separate collection service is established. Figure 7 shows that 3 out of the 5 case studies have to reduce the MSW collection cost by 1–10 % in order to avoid an increase to the total MSW management cost when applying biowaste source separation services. It is stressed, that the latter can achieved by altering the collection frequency. It is also evident that in the case of door-to-door collection schemes it is more difficult to achieve the break-even point compared to road container systems. Therefore, more effort and careful planning should be made when applying biowaste door-to-door programs in order to avoid total cost increase.

Carbon Footprint

The GHGs emissions resulting from the introduction of biowaste separate collection scheme, are related to the application of the new collection routes and the selected method for biowaste treatment. Compared to the existing MSW management system, the initiation of a source separation program for biowaste leads to direct GHGs savings due to waste diversion from landfills and indirect (downstream) savings by substituting materials (i.e. fertilizers) with the produced compost.

Table 10 shows that all scenarios examined result in GHG savings compared to the existing MSW management systems. Substantial savings (800 kg $CO_{2\ eq.}$-t of biowaste) are observed in the case study of Milos Island, where disposal in landfill is still the only waste management

Table 10 GHG emissions from overall waste management before and after biowaste separate collection and treatment for each scenario modelled

	MILOS Door-to-door	MILOS Road containers	KIFISSIA Door-to-door	KIFISSIA Road containers	ATHEN Road containers
A. Net CO2 eq. for current waste management system (t/year)					
MSW collection/transportation	52	52	156	156	361
Recycling of separated collection materials	0	0	−873	−873	−1388
MSW treatment	0	0	−379	−379	−1340
MSW landfilling	2604	2604	125	125	356
Total A (current)	2656	2656	−971	−971	−2011
B. Net CO_2 eq. for new waste management system after biowaste separate collection (t/year)					
MSW and biowaste Collection/transportation	63	54	200	158	365
Recycling of separated collected materials	0	0	−873	−873	−1388
MSW treatment	0	0	−379	−379	−1340
MSW landfilling	2183	2218	99	101	289
Biowaste treatment	−23	−21	−43	−39	−108
Total B (new)	2224	2251	−996	−1033	−2181
GHG savings in CO_2 eq. (t)	−432	−405	−25	−62	−171
GHG savings in CO_2 eq. (kg/t of biowaste collected)	−807	−823	−25	−66	−67

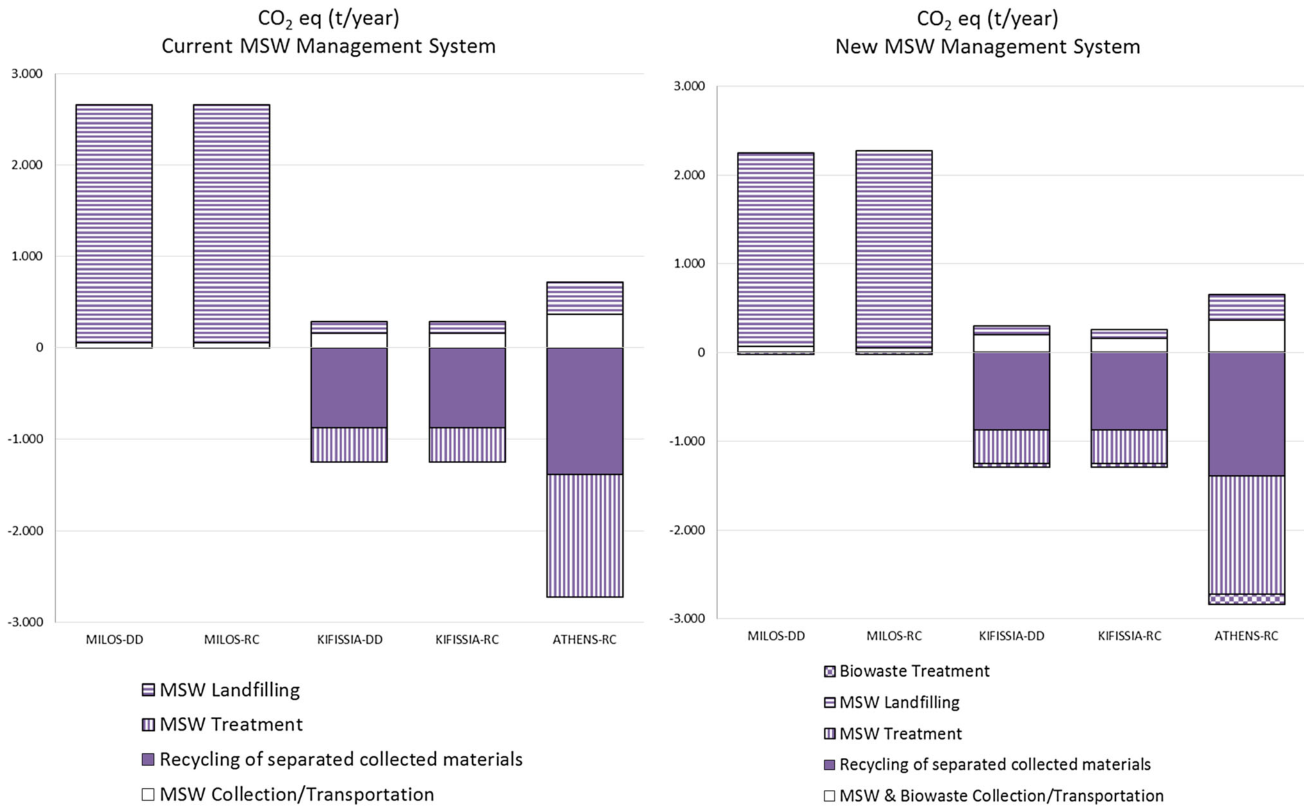
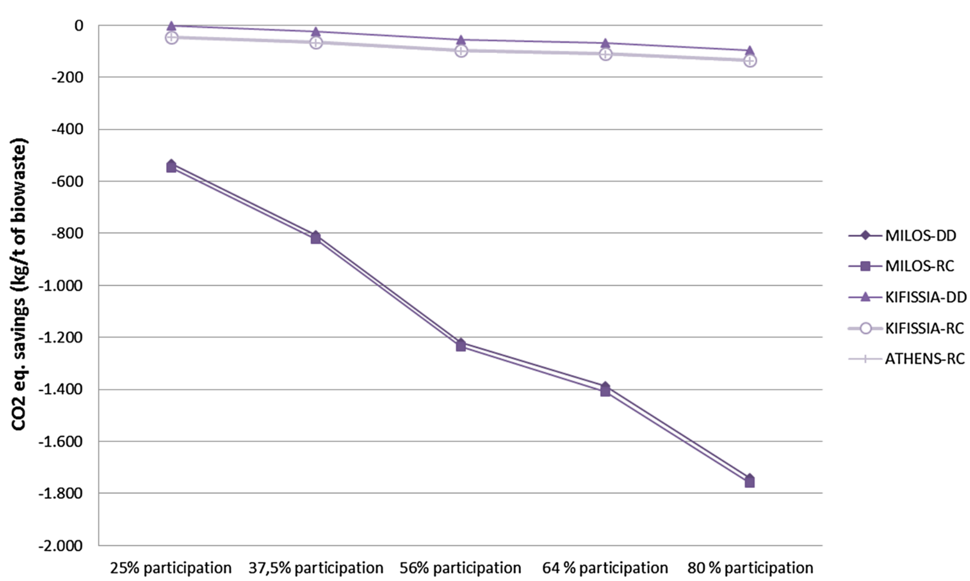


Fig. 8 GHG emissions resulting from the overall MSW management plan before and after the introduction of the examined biowaste separate collection and treatment schemes

Fig. 9 GHG savings as a function of the participation rate in the examined case studies



option. As illustrated in Fig. 8, landfilling of waste in Milos contributes to more than 98 % of the total GHGs, implying that waste diversion provides substantial opportunities for GHG savings. In Athens and Kifissia case studies the current waste management system involves the separate collection of recyclables and mixed MSW treatment resulting in GHG savings that range from 100 to 150 kg $CO_{2\ eq.}$-t of MSW. The establshment of biowaste separate collection schemes to the existing MSW management system in the above mentioned areas leads to further GHG savings that range from 3 to 9 %.

As discussed in recent studies [6, 7], waste collection and transportation play a minor role in the total GHGs emissions, while recycling of separate collected materials has a major contribution to GHG savings. In addition, waste treatment technologies always add to the overall savings to a greater or lesser extent, especially when compared with landfill practises.

As presented in Fig. 4, the participation rate affects the annual operational cost of the total MSW management plan. In terms of GHG emissions, the increase of participation rate (Fig. 9) affects mainly the case study of Milos Island since more biowaste is diverted from landfill, whereas in Athens and Kifissia municipalities no significant improvement is recorded (both municipalities apply common waste treatment methods). The latter confirms the fact that GHG emissions are mostly affected by the selected MSW treatment methods.

Conclusions

In Greece, the separate collection of municipal biowaste has been introduced in the City of Athens and the Municipality of Kifissia within the framework of the Athens-Biowaste project. Based on the project findings and international experience, a model has been developed aiming to assist decision makers in developing biowaste separate collection schemes, estimating related investment and operational costs and evaluating the influence of biowaste separate collection to the overall MSW management plan.

The objective of this paper is to demonstrate the outcomes of the model through its application in three different case study areas and identify the key parameters that contribute to cost-efficient and GHG saving measures when introducing separate collection systems for biowaste. The model was applied in three Greek Municipalities with different characteristics namely an urban area in Athens Municipality, an suburban area in Kifissia Municipality (large number of detached houses with gardens) and the Greek Island of Milos (small island with tourist activity). The establishment of door-to-door and road container biowaste collection programs was investigated for each selected area except for the case of Athens Municipality where the implementation of door-to-door collection scheme was considered practically unfeasible.

In all cases the investment cost for establishing a separate collection scheme was approximately 10€ per inhabitant, considering that existing vehicles could be utilised. This cost is reduced to less than 3€ per inhabitant when only the basic equipment is included, namely the bins and the awareness campaign. The operational cost is directly linked to the type of the collection scheme applied in the area, the participation rate and the collection frequency. In the door-to-door collection schemes, the operational cost was found to be higher since additional routes are required for serving a specific area. Additionally, by increasing the participation rate from 25 to 64 %, the operational cost per tonne of biowaste is reduced approximately by 50 %. Thus, participation rate is a critical factors which influences significantly the cost-efficiency of biowaste separate collection.

Collection frequency is another important factor when applying source separation schemes. This parameter is considered a high burden for biowaste separate collection programs especially in southern European countries, such as Greece, which demand increased collection frequency during the summer period. This is evident by the significant rise of the operational cost by 40–80 % in all case study areas when doubling the collection frequency.

The examination of the overall MSW management cost before and after the establishment of biowaste separate collection in all case studies, has shown that cost savings occur when the current MSW collection cost is reduced by 0–10 %. In most road container collection schemes, cost savings incurred even without amending current MSW collection cost, whereas in door to door systems the collection frequency throughout the MSW management system should be altered to prevent total cost increase. This means the break-even point must be determined after the biowaste separate collection is established.

GHG emissions, are predominantly dependent on the waste treatment methods applied, while the relative contribution of waste collection and transportation is rather minor. The introduction of source separation schemes for biowaste in the examined case studies results in GHG savings the level of which varies accoding to the existing MSW management plan. More specifically, substantial savings (800 kg $CO_{2\ eq.}$-t of biowaste) occur when biowaste is diverted from the landfill (case of Milos Island), whereas savings in the range of 3 to 9 % are estimated when separate collection of recyclables and MSW treatment are already in place (case of Athens and Kifissia Municipalities).

The Athens-Biowaste model can assist municipalities and waste management authorities in establishing separate collection schemes for biowaste and estimating their influence throughout the MSW management plan in terms of overall cost and GHG emission savings. It should be underlined that biowaste separate collection and treatment is certainly the best environmental option for handling biowaste, however comprehensive planning and optimisation are needed.

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