3.2.2 Sales

Table 4 reports the proceeds of waste sales to recycling plants.

Table 4. Proceeds of waste sales to recycling plants

Waste	Quantity (t)	Sales (€/t)	Total sales (€)
Glass	2’945	303.00	892’529
Aluminium	194	15.00	2’913
Plastic	97	394.00	38’260
Paper and cardboard	2’049	32.00	65’590

3.2.3 Total cost

Table 5. Total cost of waste management after collection

Waste	Cost (€)				
	Step1		Step2		Total
	Transport	Disposal	Transport	Sales	
Undifferentiated	34'339	9'619'415	0	0	9'653'754
Organic	49'224	243'795	0	0	293'019
Glass	62'216	710'419	86'463	-892'529	-33'431
Aluminium	4'102	46'840	5'485	-2'913	53'514
Plastic	2'051	23'420	1'518	-38'260	-11'271
Paper and Cardboard	2'623	16'397	11'165	-65'590	-35'405

The total economic fluxes, obtained from Tables 1-4, are reported in Table 5.

Due to the involved quantity, the most expensive disposal is that referring to undifferentiated waste. Thanks to their sales, glass, plastic and card economic fluxes are in active.

4. ENERGETIC AND ENVIRONMENTAL ANALYSIS

Energetic assessments have been carried out evaluating fuel consumption necessary for transport and electric energy consumption required to select and recycle multi-material components.

Every waste during transport and treatment generates CO_2 and other pollutant emissions, that have been determined using the related emission factor; as concerns CO_2, the total amount emitted through the whole process has also been evaluated.

4.1 Step 1. From the collection to the selection plants

4.1.1 Transport

Fuel consumption FC_i (diesel, kg) necessary to transfer the i-th waste to the plant has been determined using the expression:

$$FC_i = N_i \times d_i \times fc \tag{3}$$

where:

- N_i is the number of required trips
- d_i is the plant distance (km)
- fc is the unitary fuel consumption (0,42 kg/km).

The corresponding energy consumption E_i (kWh) during the transport (Table 6) is then given by:

$$E_i = FC_i \times LCV \tag{4}$$

where *LCV* diesel *Low Calorific Value* (11,86 kWh/kg).

Table 6. Transport consumption

Origin	Destination	Waste	Distance (km)	N. trips	Consumption (kg fuel)	Consumption (kWh)
Campo Calabro (RC)	Sambatello (RC)	Undifferentiated	4.6	5'453	10'536	124'952
Campo Calabro (RC)	Vazzano (VV)	Organic	70.6	336	9'978	118'343
Campo Calabro (RC)	Palmi (RC)	Multimaterial	29.5	1'269	15'743	186'712
Campo Calabro (RC)	Campo Calabro (RC)	Paper and Cardboard	1.3	1'025	568	6'739

Moreover, j-th pollutant emissions generated during the transport of the i-th waste have been determined using the expression:

$$e_{ij} = FC_i \times EF_j \tag{5}$$

in which EF_j (g/kg) is the emission factor of the j-th pollutant [20], [21] (Table 7). The results are reported in Table 8.

Table 7. Emission factors of the main combustion products [20]

Pollutant	CO_2	PM	CO	NO_x	NH_3
Emission factor (g/kg fuel)	3'140	1.2	8	37	0.05

Table 8. Step 1 Transport emissions

Waste	Emissions (kg)				
	CO_2	PM	CO	NOx	NH_3
Undifferentiated	33'082	12.64	84.28	389.81	0.52
Organic	31'332	11.97	79.82	369.19	0.49
Multi-material	49'436	18.89	125.90	582.52	0.78
Paper and Cardboard	1’784	0.68	4.54	21.02	0.02

4.1.2 Selection/disposal

Energy consumed by the selection of i-th waste E_i has been evaluated through the expression:

$$E_i = P_i \times t_i \times N_{di} \tag{6}$$

where
- P_i plant power (kW)
- t_i working time (h)
- N_{di} number of yearly working days.

Consequently, the j-th pollutant emissions generated by the selection of i-th waste are computed through the expression:

$$e_{ij} = E_i \times EF_j \quad (7)$$

with EF_j emission factor of the j-th pollutant (kg/kWh).

Using average values, we have made the hypothesis that plants are able to select 75 t/day.

In Table 9 energy consumption, emission factors and CO_2 emissions for multi material and paper selection are reported. Table 10 reports emission factors and Table 11 the related emissions of the main gases (CH_4 and CO_2) originating from undifferentiated and organic wastes, which do not undergo energetic treatments.

Table 9. Energy consumption and CO_2 emissions originating from multi material and paper selection

Waste	Plant power (kW)	Working time (h)	N days	Energy (kWh)	Emission factor (kg CO_2/kWh)	Emission (kg CO_2)
Multimaterial	77	8	51	31456.8	0.22	6'920
Paper and Cardboard	42	8	34	11451.2	0.22	2'519

It can be seen that very high emissions originate from undifferentiated waste, due to its quantity; the most relevant ones are ascribable to CH_4, but also CO_2 amount is noteworthy.

Table 10. Emission factors of the main landfill and organic gas emitted [22], [23]

	Undifferentiated		Organic	
Pollutant	CO_2	CH_4	CO_2	CH_4
Emission factor (t/t waste)	0.87	23.68	0.396	4.00

Table 11. Undifferentiated and organic components emissions

Waste	Quantity (t)	Emissions (t)	
		CO_2	CH_4
Undifferentiated	65'438	56'931	1'549'572
Organic	2'523	999	10'092

4.2 Step 2. From selection plants to recycling ones

4.2.1 Transport

Fuel and energy consumption and the relative pollutant emissions have been calculated using the expressions described in 4.1.1. Table 12 reports the consumption values, Table 13 shows gas emissions, evaluated using emission factors reported in Table 7.

4.2.2 Recycling

The selected wastes undergo a recycling process. The plants unitary consumptions used in the analysis and the total energy consumption are reported in Table 14, CO_2 emissions are reported in Table 15.

Table 12. Transport consumption

Origin	Destination	Waste	Distance (km)	N. trips	Consumption (kg fuel)	Consumption (kWh)
Palmi (RC)	Naples	Glass	581	118	28'795	341'509
Palmi (RC)	Milan	Aluminium	1088	4	1'827	21'670
Palmi (RC)	Ragusa	Plastic	241	5	506	5'998
Campo Calabro (RC)	Catania	Paper and Cardboard	108	82	3'719	44'107

Table 13. Step 2 Transport emissions

	Emissions (kg)				
Waste	CO_2	PM	CO	NO_x	NH_3
Glass	90’416,40	34.55	230.36	1’065.42	1.44
Aluminium	5’737.12	2.19	14.62	67.60	0.09
Plastic	1’587.95	0.61	4.05	18.71	0.03
Paper and Cardboard	11'677.58	4.46	29.75	137.60	0.19

Table 14. Energy consumption by recycled material

Waste	Quantity (t)	Unit Energy (kWh/t)	Energy (kWh)
Glass	2’945	4.30	12’664
Aluminium	194	0.85	165
Plastic	97	15	1’455
Paper and Cardboard	2’049	2.75	5’635

Table 15. Recycling CO_2 emissions

Waste	EF (kgCO_2/kWh)	Emissions (kgCO_2)
Glass	0.22	2’786
Aluminium	0.22	36
Plastic	0.22	320
Paper and Cardboard	0.22	1’239

4.2.3 Saved energy

Saved energy by waste recycling has been evaluated as difference between energy consumed during production by raw material and from recycling.

Table 16. Production specific consumption

Waste	Production Energy by raw material (kWh/t)	Recycling Energy (kWh/t)
Glass	6.3	4.30
Aluminium	16	0.85
Plastic	45	15
Paper and Cardboard	7.6	2.75

From Table 16, reporting specific consumption referring to production by raw material and recycling, it can be seen that the greatest energy consumption is associated to plastic production (45 kWh/t), with reference to which the greatest energy saving is obtained (30 kWh/t), followed by that of aluminium (ca. 15 kWh/t). In Table 17 and in Figure 4 the respective total energy consumptions are reported: due to the collected quantities, the greatest ones are observed for glass, the recycling of which allows saving only 2 kWh/t. Moreover, Table 17 reports total emissions avoidable through recycling.

Table 17. Total consumption referred to production by raw material and recycling and relative avoidable emission

Waste	Quantity (t)	Production energy by raw material (MWh)	Recycling Energy (MWh)	Avoided emissions (tCO_2)
Glass	2’945	18.6	12.7	1.3
Aluminium	194	3.1	0.2	0.6
Plastic	97	4.4	1.5	0.6
Paper and Cardboard	2’049	15.6	5.6	2.2

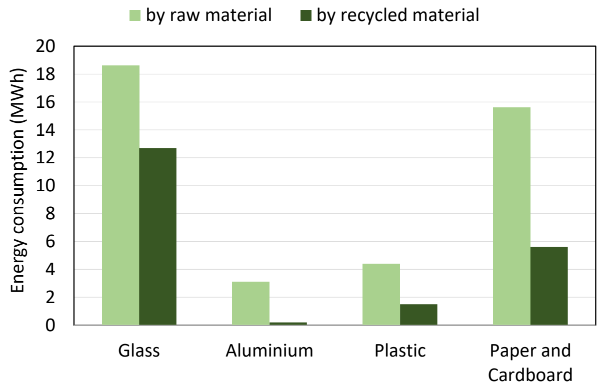

Figure 4. Energy consumption for material production

4.2.4 Total consumption and emissions

Table 18. Total energy consumption

Waste	Energy Consumption (MWh)				
	Step 1		Step 2		Total
	Transport	Treatment	Transport	Treatment	
Undifferentiated	125.00				125.00
Organic	118.30	0.00			118.30
Glass	169.89	28.63	342.00	12.66	553.18
Aluminium	11.20	1.89	22.00	0.17	35.25
Plastic	5.60	0.94	6.00	1.45	13.99
Paper and Cardboard	6.70	0.11	44.00	0.04	50.85

Table 19. Total CO_2 emissions

Waste	CO_2 Emissions (t)				
	Step 1		Step 2		Total
	Transport	Treatment	Transport	Treatment	
Undifferentiated	33.00	56'931.00			56'964.00
Organic	31.00	999.11			1'030.11
Glass	44.59	6.30	90.42	2.78	144.09
Aluminium	2.94	0.42	5.74	0.04	9.14
Plastic	1.47	0.21	1.59	0.32	3.59
Paper and Cardboard	1.78	2.52	11.70	1.24	17.24

Total consumption and CO_2 emissions referring to transport and treatment (Step 1 and 2) are reported in Tables 18 and 19.

Concerning multi-material components in Step 1, they have been determined using the respective weight percentages.

Due to the involved quantities, the most relevant emissions are originated from undifferentiated waste.

4.2.5 Scenarios

The analysed case has been compared with different scenarios (Table 20) showing increasing percentage of differentiated collection (35% and 70%), relating them to the least advanced disposal modality, landfill. In Table 21 the total cost of waste management in the scenarios is reported. Moreover, Figures 6 and 7 respectively show the scenarios cost referring to waste components and phases of disposal Steps.

Table 20. Analysed scenarios

Scenario	Description
0	100% undifferentiated waste to landfill
1	17.5% differentiated waste (*present case*)
2	35.0% differentiated waste
3	70.0% differentiated waste

Table 21. Total cost of waste management for the scenario

Waste	Cost (€)			
	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Undifferentiated	11’192’010	9’653’754	8’114’498	5’036’987
Organic		293’019	586’150	1’172’300
Glass		-33’431	-66’877	-133’755
Aluminium		53’514	107’015	214’030
Plastic		-11’271	-22’465	-44’930
Paper and Cardboard		-35’405	-87’224	-174’448
TOTAL	11’192’010	9’919’753	8’631’097	6’070’183

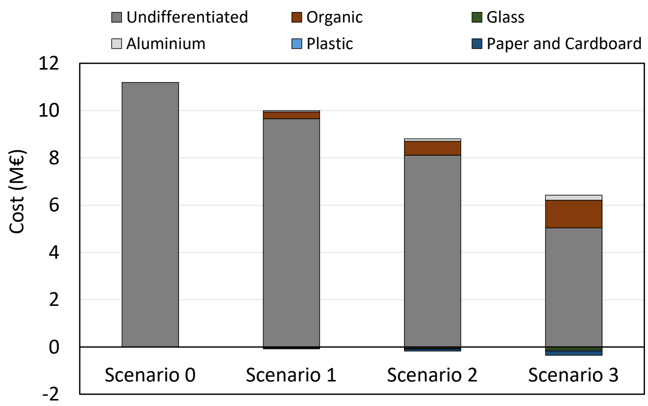

Figure 6. Cost of waste management scenarios referred to waste components

Particularly in Figure 7, referring to each phase of the two steps, also benefits can be represented, differently from Figure 6, which reports the final cost (or benefit) associated to each material disposal. It can be observed that, due to the recyclable material sales, increasing the percentages of differentiated collection can markedly reduce scenarios costs.

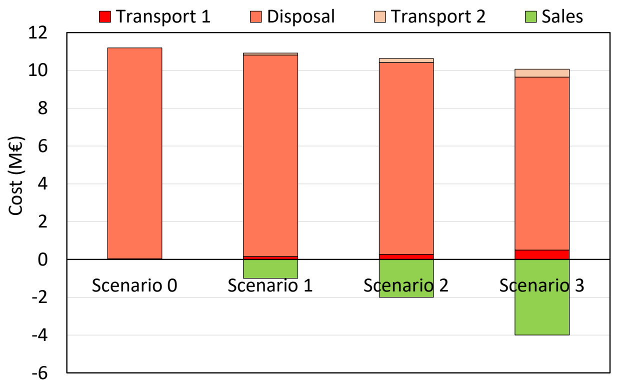

Figure 7. Cost and benefit of waste management scenarios referred to the Steps phases

Table 22. Scenarios total energy consumption

Total energy consumption (MWh)				
Waste	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Undifferentiated	144.88	125.00	105.04	65.21
Organic		118.30	237.03	473.70
Glass		553.18	1’079.70	2’159.39
Aluminium		33.25	69.51	139.02
Plastic		13.99	25.08	50.16
Paper and Cardboard		50.85	119.98	239.96
TOTAL	144.88	896.58	1’636.33	3’127.46

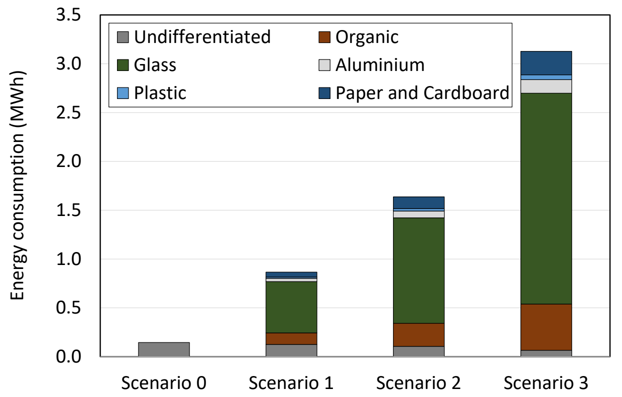

Figure 8. Scenarios energy consumption referred to waste components.

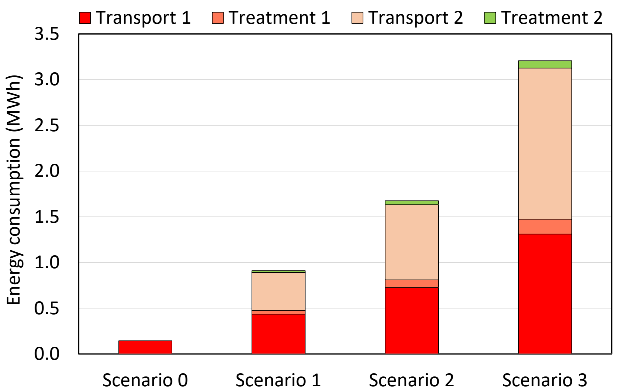

Figure 9. Scenarios energy consumption referred to Steps.

In Table 22 and Figures 8-9 the scenarios total consumptions are reported: the figures respectively refer to waste components and disposal steps. As it is possible to observe, consumption markedly increase as the percentage of differentiated selection increases, but this is pre-eminently due to the distance of the glass recycling plant.

Finally, Table 23 and Figures 10-11 show the corresponding scenarios CO_2 emissions; the figures respectively refer to waste components and Steps phases.

Table 23. Scenarios CO_2 emissions

CO_2 emissions (t)				
Waste	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Undifferentiated	66’044.39	56’964.00	47’883.90	29’723.42
Organic		1’030.11	2’061.76	4’123.43
Glass		144.09	288.87	577.74
Aluminium		9.14	18.31	36.62
Plastic		3.59	7.20	14.39
Paper and Cardboard		17.24	33.42	66.84
TOTAL	66’044.39	58’168.16	50’293.45	34’542.43

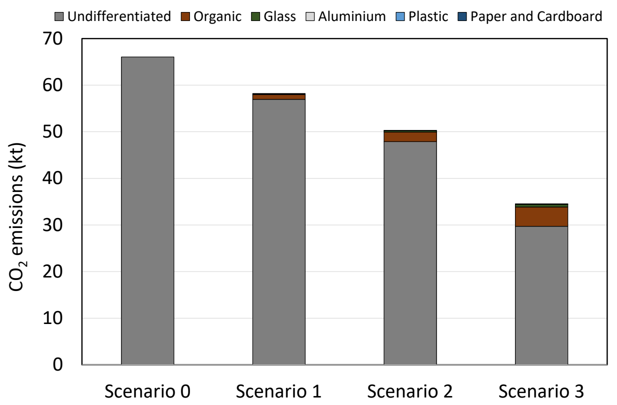

Figure 10. Scenarios CO_2 emissions referred to components.

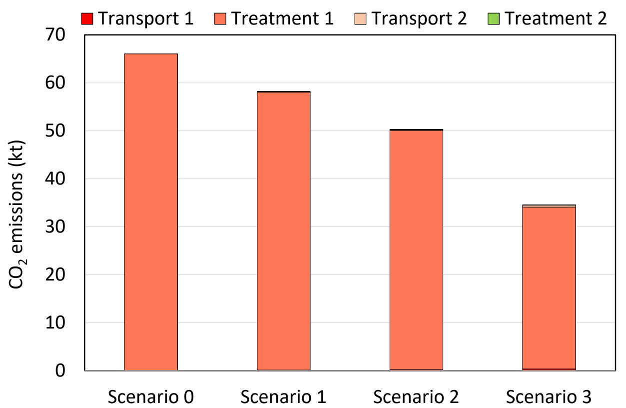

Figure 11. Scenarios CO_2 emissions referred to Steps phases.

It can be observed that, like cost, also CO_2 emissions reduce in advanced scenarios, thanks to the reduced quantities sent to landfill: for 70% differentiated selection, CO_2 amount becomes half the value observed in the analysed case (17,5%).

5. CONCLUSIONS

The management of urban solid waste (USW), in continuous and progressive increase in the last decades, has become one of the most important aspects concerning environment protection; its impact must be mitigated acting on the treatment modalities, recovering energy and reducing fluxes to landfill.

Within this frame, in the paper a case study has been analysed, concerning USW management in the city of Reggio Calabria, effecting an analytic evaluation, from an economic, energetic and environmental point of view, of the phases after collection (selection, transport, recycling), assessing costs and benefits, energy consumption and pollutant emissions.

From the energetic point of view, fuel consumption required for transport and energy necessary for selection and recycling have been evaluated; the related emissions have been calculated for the transport combustion products, for CO_2 emitted during the selection/treatment processes and the non-energetic ones, where also CH_4 emission has been computed.

From the economic point of view, the most relevant contribution, due to the delivery cost of large waste quantities into landfill, resulted that of undifferentiated waste; limitedly to transport, differently, the greater cost is imputable to glass.

Being the landfill close to the city, it is not responsible of the greatest consumption that, on the contrary, is associated to glass and pre-eminently due to the transport of its large quantities to Naples to be recycled. To such component is also associated the greatest saved energy for recycling, despite of the small unitary savings (2 kWh/t against 30 kWh/t of plastic).

As concerns emissions, the contribution of landfill is by far prevailing due to the relevant disposed quantities, followed by that of organic. For both the most relevant emissions are ascribable to CH_4, but also CO_2 amount is noteworthy, above all in comparison to that emitted by other components.

A comparison with different scenarios, showing increasing percentage of differentiated collection (35% and 70%), has been carried out, relating them to the least advanced disposal modality, landfill.

It can be observed that, due to the recyclable material sales, increasing the percentages of differentiated collection can markedly reduce scenarios costs. Also, emissions reduce in advanced scenarios, thanks to the reduced waste quantities sent to landfill disposal: when differentiated selection reaches 70%, CO_2 amount becomes half the value observed in the analysed case (17,5% differentiated selection).

Differently, energy consumption markedly increases as the percentage of differentiated selection increases, pre-eminently due to the distance of the glass recycling plant.

REFERENCES

[1] Burnley S.J. (2007). A review of municipal solid waste composition in the United Kingdom, *Waste Manag.*, Vol. 27, No. 10, pp. 1274–1285. DOI: 10.1016/j.wasman.2006.06.018

[2] Cannistraro G., Cannistraro M., Cannistraro A., Galvagno A. (2016). Analysis of air pollution in the urban center of four cities Sicilian, *Int. J. Heat Technol.*, Vol. 34, No. Special Issue 2, pp. S219–S225. DOI: 10.18280/ijht.34S205

[3] Ferreira F., Avelino C., Bentes I., Matos C., Teixeira C.A. (2017). Assessment strategies for municipal selective waste collection schemes, *Waste Manag.*, Vol. 59, pp. 3–13. DOI: 10.1016/j.wasman. 2016.10.044

[4] Azapagic A., Perdan S., Clift R. (2004). Sustainable development in practice: case studies for engineers and scientists, Chichester, West Sussex, England.

[5] Shekdar A.V. (2009). Sustainable solid waste management: An integrated approach for Asian countries, *Waste Manag.*, Vol. 29, No. 4, pp. 1438–1448. DOI: 10.1016/j.wasman.2008.08.025

[6] Cherubini F., Bargigli S., Ulgiati S. (2009). Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration, *Energy*, Vol. 34, No. 12, pp. 2116–2123. DOI: 10.1016/j.energy.2008.08.023

[7] Al-Salem S.M., Evangelisti S., Lettieri P. (2014). Life cycle assessment of alternative technologies for municipal solid waste and plastic solid waste management in the Greater London area, *Chem. Eng. J.*, Vol. 244, pp. 391–402. DOI: 10.1016/ j.cej.2014.01.066

[8] Al-Salem S.M., Lettieri P., Baeyens J. (2009). Recycling and recovery routes of plastic solid waste (PSW): A review, *Waste Manag.*, Vol. 29, No. 10, pp. 2625–2643. DOI: 10.1016/j.wasman.2009.06.004

[9] Jeswani H.K., Azapagic A. (2016). Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK, *Waste Manag.*, Vol. 50, pp. 346–363. DOI: 10.1016/j.wasman. 2016.02.010

[10] Cardinale T., Arleo G., Bernardo F., Feo A., De Fazio P. (2017). Investigations on thermal and mechanical properties of cement mortar with reed and straw fibers, in *11th AIGE 2017 2st AIGE/IIETA Int. Conf.*

[11] Baccilieri F., Bornino R., Fotia A., Marino C., Nucara A., Pietrafesa M. (2016). Experimental measurements of the thermal conductivity of insulant elements made of natural materials: preliminary results, in *10th AIGE 2016 1st AIGE/IIETA Int. Conf.*, pp. 1–7.

[12] Marino C., Nucara A., Pietrafesa M., Polimeni G. (2017). Natural and waste materials as building insulating elements: experimental measurements of thermal conductivities, (accepted for presentation), in *SDEWES17 - 12th Dubrovnik Conf. Sustain. Dev. Energy Water Environ. Syst. Oct. 4 - 8, Dubrovnik, Croat.*.

[13] Liamsanguan C., Gheewala S.H. (2006). Environmental assessment of energy production from municipal solid waste incineration, *Int. J. Life Cycle Assess.*, Vol. 12, No. 7, pp. 529. DOI: 10.1065/lca2006.10.278

[14] Jeswani H.K., Smith R.W., Azapagic A. (2013). Energy from waste: carbon footprint of incineration and landfill biogas in the UK, *Int. J. Life Cycle Assess.*, Vol. 18, No. 1, pp. 218–229. DOI: 10.1007/s11367-012-0441-8

[15] Astrup T.F., Tonini D., Turconi R., Boldrin A. (2015). Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations, *Waste Manag.*, Vol. 37, pp. 104–115. DOI: 10.1016/j.wasman.2014.06.011

[16] Browne J.D., Murphy J.D. (2013). Assessment of the resource associated with biomethane from food waste, *Appl. Energy*, Vol. 104, pp. 170–177. DOI: 10.1016/j.apenergy.2012.11.017

[17] Zhang C., Xiao G., Peng L., Su H., Tan T. (2013). The anaerobic co-digestion of food waste and cattle manure, *Bioresour. Technol.*, Vol. 129, pp. 170–176. DOI:

10.1016/j.biortech.2012.10.138
[18] Appels L., Baeyens J., Degrève J., Dewil R. (2008). Principles and potential of the anaerobic digestion of waste-activated sludge, *Prog. Energy Combust. Sci.*, Vol. 34, No. 6. pp. 755–781. DOI: 10.1016/j.pecs.2008.06.002
[19] Calabrò P.S., Panzera M.F. (2017). Biomethane production tests on ensiled orange peel waste, in *11th AIGE 2017 2st AIGE/IIETA Int. Conf.*
[20] EMEP/EEA air pollutant emission inventory guidebook - 2016, EEA Report No 21/2016, Copenhagen K Denmark, 2016.
[21] Marino C., Nucara A., Pietrafesa M., Pudano A. (2016). The assessment of road traffic air pollution by means of an average emission parameter, *Environ. Model. Assess.*, Vol. 21, No. 1. pp. 53–69. DOI: 10.1007/s10666-015-9489-8
[22] Eggleston S., Buendia L., Miwa K., Ngara T., Tanabe K. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories.*
[23] De Stefanis P., Landolfo P.G., Mininni G. (1998). Gestione dei rifiuti ad effetto serra, in *Conf. Naz. Energ. e Ambient*, *ENEA*.

NOMENCLATURE

C	cost of disposal modality, €
C_a	hourly driver cost, €/h
C_d	unitary travel cost, €/km
d	distance, km
e	pollutant emissions, g
E	energy consumption, kWh
EF	pollutant emissions factor, g/kg fuel
fc	unitary fuel consumption, kg fuel/km
FC	fuel consumption, kg fuel
LCV	low calorific value, kWh/kg
M_{tot}	total waste mass, t
N	number of trips
N_d	number of days
P	power plant, kW
t	time, h