Comparison of environmental impacts of municipal waste before and after the introduction of PAYT systems using Life Cycle Assessment.

The cases of Aveiro, Larnaka and Lisbon

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December 2021

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Date December 2021

ISBN 978-989-8649-36-2

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Project LIFE PAYT – Tool to reduce waste in South Europe (**LIFE 15 ENV/PT/000609**)

Co-funded by the LIFE programme of the European Commission

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1. Introduction

This study was carried out within the LIFEPAYT project in order to evaluate the environmental impacts of municipal waste management before and after the introduction of PAYT tariffs.

This comparison is based on the Life Cycle Assessment (LCA) methodology. LCA is a structured and comprehensive methodology to quantify the environmental impacts of a product or service along its entire life (from extraction of raw materials to final disposal). According to the ILCD Handbook (JRC – IES, 2010), the elaboration of LCA is organised into four stages, as seen in Figure 1. The description of the LCA here performed for LIFEPAYT project follows this structure, and is explained in the following sub-sections

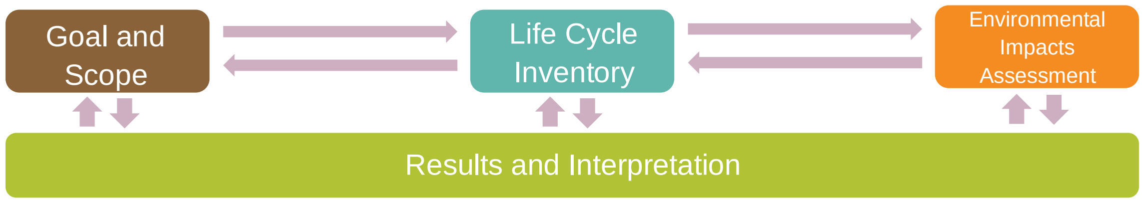

Figure 1. Stages of LCA

1.1. Goal and scope: goal definition, functional unit and modelling framework

The goal of the study in this case was to analyse the environmental performance of municipal waste management in each of the five locations at the beginning and in the end of the project LIFEPAYT, to verify the environmental consequences of the application of PAYT schemes. The assessment covers the collection and treatment of residual household waste and of the main separate collection fluxes of recyclable materials (according to its particular configuration in every location), referred to a time frame of one year. In accordance, the **functional unit** (FU) was always fixed as the amount of municipal solid waste (MSW) yearly collected in the target area considered. The exact value (annual amount of MSW) corresponding to the FU was obtained from waste characterisation campaigns carried out within sub-action C1.2 of project LIFEPAYT. An attributional framework was chosen for the LCA modelling.

Moreover, MSW management systems interact with other external systems – for instance, recycling industries –, so that the intended assessment corresponds to a type C1 goal decision-context situation (JRC – IES, 2010; Laurent, et al., 2014). Even though the analysed system was considered to provide the single function of managing municipal solid waste, a multifunctionality solving procedure through system expansion was needed to account for the environmental credit derived from the recovery of valuable materials and energy. Regarding cut-off criteria for the analysis of the unit processes, all materials sent to recycling as end-of-life (EoL) treatment option were counted as avoided waste, i.e. no environmental burden was allocated to the system originating the recycled material.

1.2. Goal and scope: definition of the studied systems and boundary settings:

Performing the LCA was possible in three of the five municipalities involved in project LIFEPAYT: Aveiro, Larnaka and Lisbon, while in Condeixa and Vrilissia the data obtained from the other tasks did not allow to obtain reliable results. For each one of the assessed municipalities, its correspondent MSW management system – which was the object of LCA – is represented in Figures 2–4, along with the boundaries encompassing the set of analysed elements (unit processes) and the material flows connecting them.

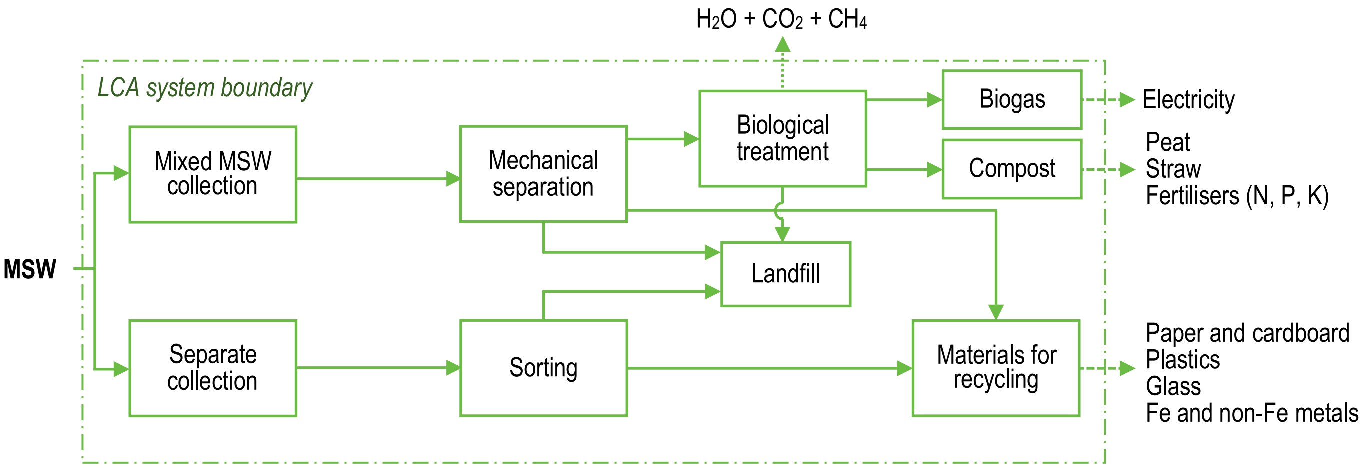

Figure 2. MSW management system in Aveiro.

In **Aveiro**, the management system of **mixed (unsorted) MSW** consists on a Mechanical-Biological Treatment (MBT) facility (Figure 2), where in a first stage (mechanical) materials suitable for recycling are recovered from the mixed MSW, namely: metals and the most valuable plastics – mostly polyethylene (PE) and polyethylene terephthalate (PET).

In the following second stage, the mostly remaining biowaste is biodegraded through anaerobic digestion for producing biogas – used as fuel in gas engines for electricity production – and thereafter, the residue of digestion is transformed into compost, suitable for agricultural application. In the composting process, a large part the organic matter contained in biowaste is released to the atmosphere after biodegradation processes in form of carbon dioxide (CO_2), water (H_2O) and to some extent, methane (CH_4) and other greenhouse effect gases (GHG). In parallel, MSW from separate collection are sorted in another section of the same facility and packed for being sent to recycling companies. Materials neither suitable for biological treatments nor for recycling are mostly landfilled, since production of refuse-derived fuel (RDF) is currently no longer relevant.

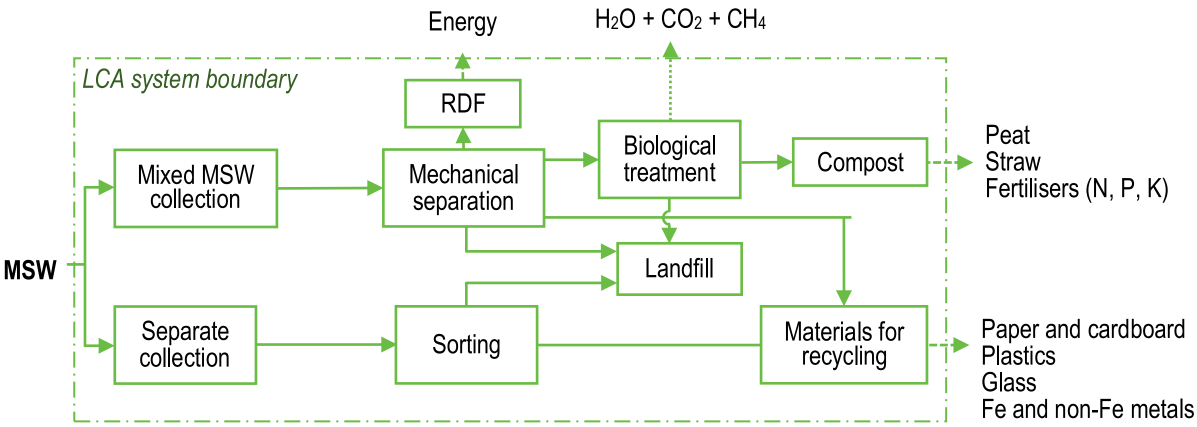

Figure 3. MSW management system in Larnaka

In Larnaka, the MSW management system consists also in a MBT facility (Figure 3), but in this case is focused in only composting as biological treatment instead of anaerobic digestion, with the refuse either valorised as RDF or landfilled. As in Aveiro, the recovered materials from separate collection are sorted in the same place for later recycling.

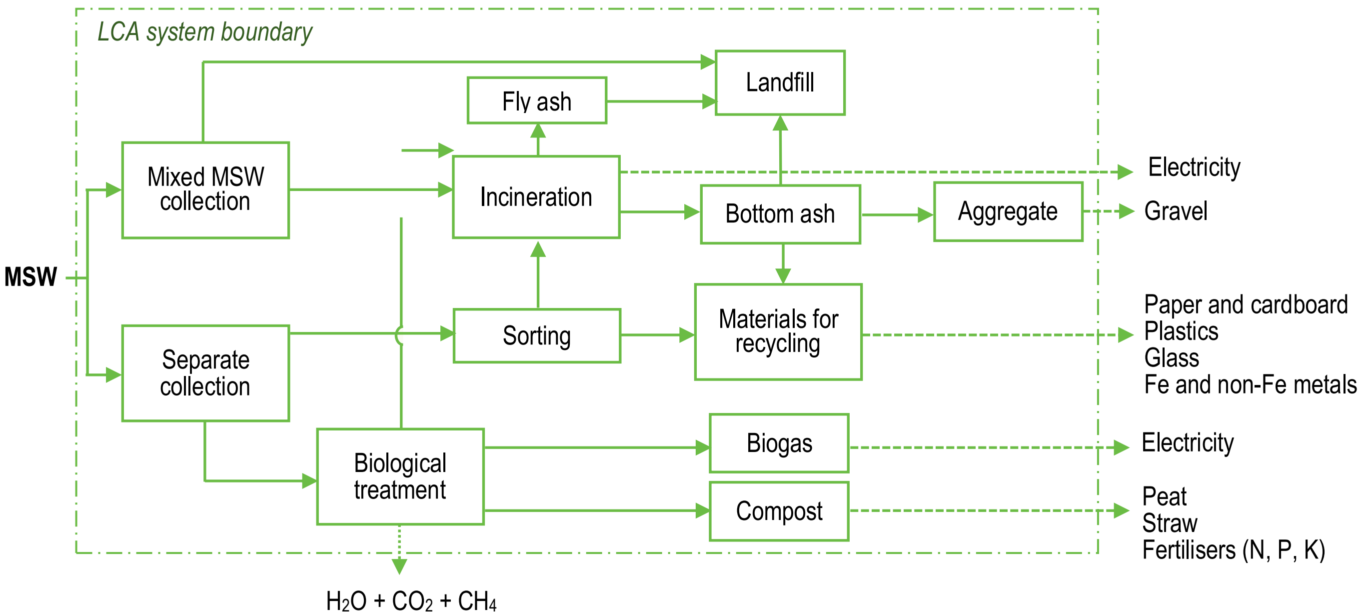

Figure 4. MSW management system in Lisbon

Lastly, in Lisbon (Figure 4) there is a rather different MSW management system, in this case based on a Waste-to-Energy (WtE) facility combined with an MBT facility. In this scheme, mixed MSW is incinerated in a dedicated thermal power plant, while biowaste collected separately is processed through anaerobic digestion to produce biogas for electricity generation and materials form separate collection are sorted for recycling. The refuse from these operations is also incinerated in the power plant. The incineration leaves two types of residue: fly ashes, which are considered a hazardous waste and therefore disposed of in a specially dedicated landfill, and bottom ashes, from which metals are recovered for recycling, being thereafter subject to a transformation into an aggregate material suitable for road construction, with a similar function as gravel in pavements. If demand from this product is not enough for processing all of the bottom ashes, the remaining part is landfilled.

The unit processes described above require the consumption of resources and energy to take place, and subsequently they generate pollutant emissions released to nature; all of these effects are accounted in the LCA as negative impacts on the environment. Conversely, the products obtained from valorisation processes are environmentally "credited" as positive for environment, since they are assumed to replace primary materials (i.e. not recycled, but made from resources extracted form nature) previously fulfilling the same function, hence preventing the consumption of these raw materials. These "substitutions" are summarised as follows:

- Compost: replaces conventional fertilisers (according to its equivalent concentration in form of K_2O, N and P_2O_5) and also a mix of ¼ peat and ¾ straw as soil conditioner in a 1:1 mass ratio (Hermann et al., 2011).
- Electricity from biogas and Waste-to-Energy (WtE): replaces the mix of the electricity generation sources present in the country considered at that moment. If originated from biowaste, this form of energy can be considered as renewable.
- Energy (heat) from RDF: replaces an alternative resource for energy in the same application considered. In this study, natural gas was chosen.
- Recycled materials: every recovered material (glass, metals, paper/cardboard and plastics) replaces a market mix of the corresponding primary not recycled material,

and secondary recycled material. For this second component the net effect of the substitution is zero, hence the environmental credit is obtained by replacing only primary materials. The ratios for mixes applied in this study are shown in Table 1, which also includes a correction faction to be applied for representation of the existent loss of quality between secondary and primary materials. The numbers in Table 1 are adapted from the work of Bala Gala (2015). A further discussion on this issue was previously included in the Report on the Development of Environmental Indicators for the project LIFE PAYT.

Table 1. Loss of quality factors and market mixes of recyclable materials (Bala Gala, 2015).

Material	Loss of quality factor	% primary (not recycled)	% secondary (recycled)
Glass	1	55	45
Fe-metals (steel)	1	50	50
Non Fe-metals (Al)	1	63	37
Paper	0.83	53.5	46.5
Plastics	0.75	88	12

2. Life Cycle inventory

The most effort and time-consuming phase in LCA corresponds to the elaboration of the Life Cycle Inventory (LCI), which consists in a compilation of all inputs (raw materials, energy, equipment, etc.) and outputs (by-products, pollutant emissions, wastes, etc.) associated to the studied systems – as previously defined in Section 1.

For a representative assessment of each case studied, indicators should be based upon a sound set of primary data with good quality. Frequently, this is not the case in waste management studies, where the availability of data is scarce at a local scale level, making necessary to adopt assumptions and extrapolations from larger scales.

In this case, this information was obtained from the waste characterisation campaigns (data regarding quantities of municipal waste generated) and from the responsible entities (municipalities and waste management companies), for modelling of waste collection and treatment processes. If data from these direct sources are not available, information gaps were filled with data from similar facilities, found in the published literature and life cycle databases, namely ecoinvent 3.5® (Doka, 2007).

Regarding the definition adopted for the functional unit, its actual value was determined by the characterisation campaigns to be different between the initial and final moment of the project, as expected. The whole set of values for the three locations is shown in Table 2. All the calculations for the items comprised in the LCI are always referred to the values taken by FU in each case.

Table 2. Values of FU before and after the project implementation.

MSW fraction	FU (tonnes/year)					
	Aveiro		Larnaka		Lisboa	
	Before project	After project	Before project	After project	Before project	After project
Mixed MSW	449	312	735	505	7103	7324
Biowaste	----	----	----	----	8160	9069
Glass	6	16	11	34	1248	1493
Paper/cardboard	29	57	84	42	1273	1341
Plastic/metals	20	31	35	51	489	555
TOTAL	**503**	**416**	**866**	**632**	**18724**	**19782**

2.1. Modelling of MSW collection

The modelling of the MSW collection systems in each of the three municipalities analysed has been done attending to the material assets present in the analysed systems before LIFE PAYT implementation, namely: carrier bags, waste bins and containers and collection vehicles.

For the second assessment, after LIFE PAYT implementation, the elements introduced by the project have been added (new PAYT containers in Aveiro and Lisbon and bags for door-to-door collection in Larnaka). For the detailed modelling, data of constituent raw materials (polyethylene plastics, steel, rubber, etc.) were taken from ecoinvent 3.5® database. The total material amounts required for each element are summarised in Table 3 for bags, bins and containers.

Table 3. LCI for MSW collection.

Asset	Amount per FU (kg)					
	Aveiro		Larnaka		Lisboa	
	Before project	After project	Before project	After project	Before project	After project
Carrier bags	1435	996	484	886	11809	12176
Household bins	335	335	75	75	----	----
Street containers (for mixed MSW)	80	89	----	----	4672	4380
Bins / containers (for separate collection)	167	334	100	100	7792	8175

Collection vehicles were modelled also according to ecoinvent 3.5 database. Fuel consumption of collection operations was based on field data for Aveiro and Lisbon, and was estimated with the EMEP/EEA methodology (EMEP/EEA, 2016) for Larnaka – see Table 4; this methodology was also used along with ecoinvent database for determining the pollutant emissions derived from fuel consumption.

Table 4. LCI for fuel consumption in MSW collection.

	Amount per FU					
	Aveiro		Larnaka		Lisboa	
	Before project	After project	Before project	After project	Before project	After project
Fuel consumption (L)	3700	5023	4641	4675	171511	187330

2.2. Modelling of MSW treatment

According on the diagrams shown in Figures 2–4, the material flows on each treatment facility were calculated through mass balances, based on the data publicly available or, if not possible, indirectly estimated from national statistical databases. The mass values were always referred to FU and to the compositions obtained on the characterisation campaigns. Taking the assigned values for FU as the input flow to the system, in the end, values were determined for all the main output flows, as shown in Table 5.

Table 5. LCI for main output flows from MSW treatment.

Outputs	Amount per FU					
	Aveiro		Larnaka		Lisboa	
	Before project	After project	Before project	After project	Before project	After project
Electricity (MWh)	11.2	7.3	----	----	2959.6	3157.3
Thermal energy (MWh)	----	----	12.0	24.6	----	----
Compost (t)	5.1	3.3	15.2	39.6	95.6	168.6
Replaced Fe-metals (t)	3.5	3.8	8.5	12.7	32.2	37.9
Replaced non-Fe metals (t)	0.5	0.5	0.9	6.8	4.2	5.0
Replaced glass (t)	4.8	13.8	9.4	28.3	920.1	1100.4
Replaced paper (t)	13.4	25.4	37.1	18.7	522.4	550.3
Replaced plastics (t)	14.2	12.0	12.8	14.2	195.8	222.1
Replaced gravel (t)	----	----	----	----	32.0	849.3
Direct GHG emissions (t)	70.3	41.9	30.9	53.5	4456.4	4452.0
Ashes/Refuse landfilled (t)	313.7	254.7	719.0	432.0	3655.6	3180.9

The processes involved (anaerobic digestion, composting, incineration, etc.) were modelled as in ecoinvent 3.5 database, including the values for pollutant emissions derived.

3. Results and discussion: environmental impacts assessment

The assessment of environmental impacts stage in LCA consists in the assignation of measurable environmental impacts to the items comprised in Life Cycle Inventory, using a standardised impact assessment method. The impact categories for the assessment were carbon footprint (contribution to climate change) and fossil resources depletion. These two particular categories were chosen, in accordance with the Environmental Indicators previously defined, due to their relevance for the public to illustrate the most concerning environmental impacts generated by these activities and how PAYT application can influence them.

The assessment of carbon footprint is a widely extended methodology of communicating the environmental impacts in a quick and simple manner. Carbon footprint is usually reported through the value of equivalence in emissions of carbon dioxide (CO_2 eq.). Its relevance to the waste treatment sector is justified, since this sector is the fourth largest contributor to GHG emissions within EU with roughly 3% of total emissions (EEA, 2019), mostly caused by the anaerobic decomposition of organic matter in landfills, originated diffuse emissions of carbon dioxide and methane. Fuel consumption during waste collection and transport is also another significant contribution to GHG emissions caused by waste management.

Regarding depletion of fossil resources, this another relevant contribution from waste management processes to environmental impacts caused by the direct and indirect energy consumption of management operations. Direct consumption of energy takes place mainly during the waste collection stage, due to the fuel needed by the collection vehicles. But also, waste treatment facilities become energy suppliers if some energy recovery is implemented there – incineration (WtE) or biogas production and use.

The impact assessment method chosen for evaluating these two impact categories was the ReCiPe Midpoint (Hierarchist) Version 1.06 (Huijbregts, et al., 2017), but for carbon footprint category, the characterisation factors for global warming approved by IPCC in 2013 were applied (Myhre, et al., 2013). These assessment methodologies are included in the commercial LCA software SimaPro 9.0 (PRé Sustainability, 2019), which was used for this project.

The overall aggregated results are shown in results of the assessment are shown in Table 6, while the more detailed assessment, disaggregated on the different stages and elements of the MSW management system to show their individual contributions, are shown in the following sub-sections 3.1, 3.2 and 0 for Aveiro, Larnaka and Lisbon, respectively. Positive values in Table 6 represent actual harmful impacts on the environment, while negative values are interpreted as prevented impacts, thus resulting in beneficial consequences for the environment.

Table 6. Overall results for environmental impacts assessment.

	Amount per FU					
Impact category	Aveiro		Larnaka		Lisboa	
	Before project	After project	Before project	After project	Before project	After project
Carbon footprint (t CO_2 eq.)	153	134	335	109	1981	1765
Fossil resources depletion (t oil eq.)	-5.0	2.3	-4.4	-20.1	-290	-337

3.1. Results in Aveiro

The results of the environmental impacts assessment of MSW management in the target area of Aveiro are shown in Figure 5 for carbon footprint and Figure 6 for depletion of fossil resources. Again, values above 0 in both figures represent prejudicial impacts, whereas values below 0 stand for beneficial effects.

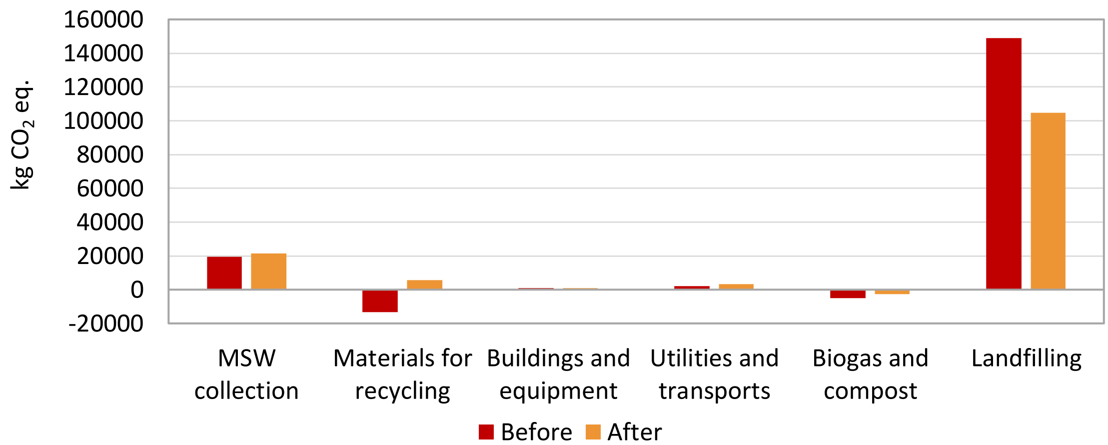

Figure 5. Carbon footprint of MSW management in Aveiro before and after the project.

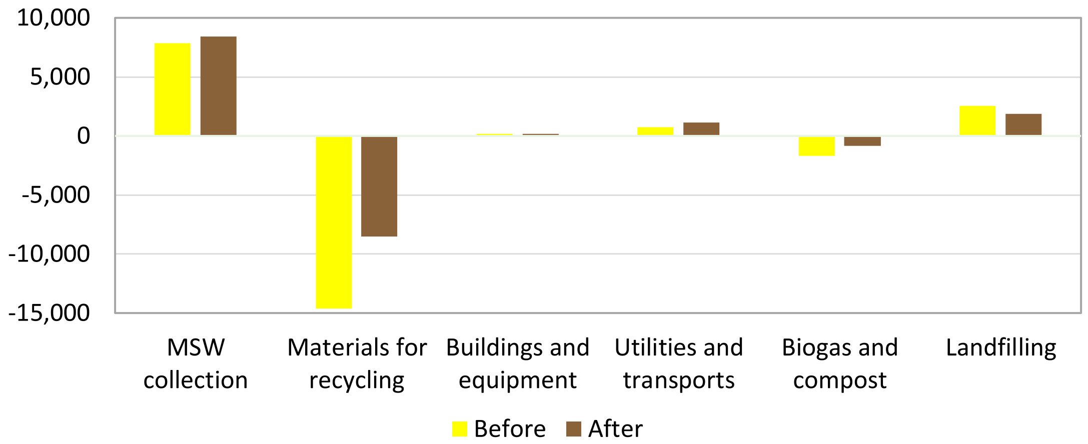

Figure 6. Fossil resources depletion of MSW management in Aveiro before and after the project.

From the results of carbon footprint in Figure 5 it can be easily concluded that the currently most environmentally impacting activity of municipal waste management in the target area is landfilling (current final destination for the majority of municipal waste), which contributes to GHG emissions due to leaked methane, not captured by the biogas collection structures installed. On the contrary, Figure 6 shows that the most environmentally beneficial consequence corresponds to the recovery of materials for recycling, thus preventing the consumption of non-renewable resources – here expressed in form of oil equivalents.

This result reinforces the pertinence of the LIFE PAYT project implementation in diverting municipal waste from residual waste treatment facilities, especially landfills, towards prevention and recycling. In fact, the reduction of mixed MSW production observed before and after the project implies a decrease of landfilled waste which is the main cause for the reduction of GHG emissions obtained.

Regarding depletion of fossil resources, the result seems counterfactual: even though the source separation of materials for recycling has increased, the value obtained in this aspect is less beneficial. For an explanation it must be realised that the main increase on recycling corresponds to paper and cardboard. Contrarily to other materials, the recycling processes in paper industry do not imply net savings of energy, therefore consumption of energy resources is still required. However, it must not be concluded from this fact that paper recycling is not environmentally worthy, since the alternative end-of-life options for waste paper and cardboard are considerably worse in environmental terms:

that is the case of landfilling, for instance. Regarding the impact of collection, although the overall MSW generation has decreased, it is however higher due to the diversion of materials to the separate collection schemes, which are typically less efficient than the more optimised mixed MSW collection, and also due to the higher complexity and material requirements of the electronic PAYT street containers.

3.2. Results in Larnaka

In analogous manner to Aveiro, the results for the assessment in Larnaka are shown in Figure 7 and Figure 8 for carbon footprint and depletion of fossil resources, respectively.

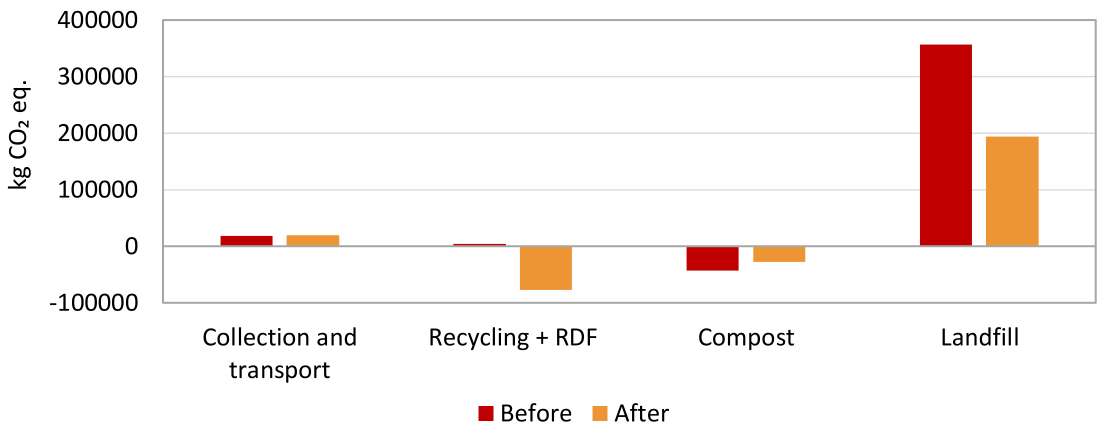

Figure 7. Carbon footprint of MSW management in Larnaka before and after the project.

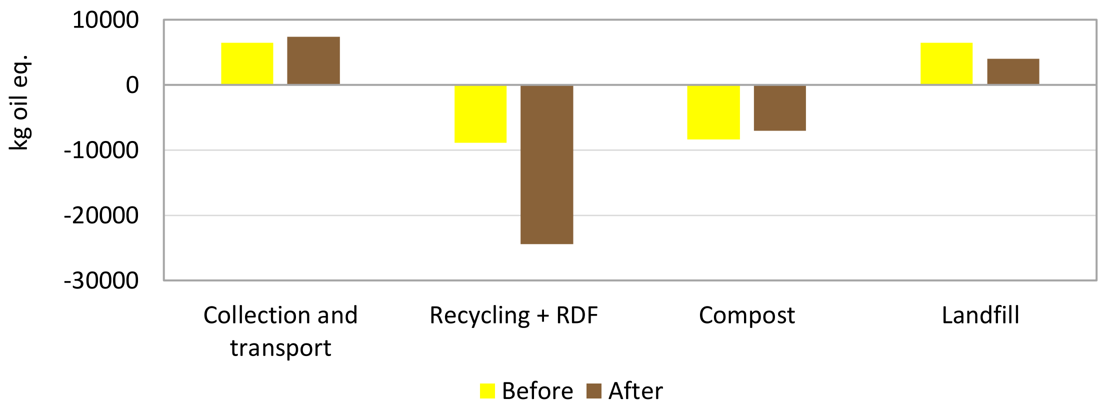

Figure 8. Fossil resources depletion of MSW management in Larnaka before and after the project.

The results obtained in Larnaka are somewhat similar to those of Aveiro. This is not surprising, since both treatment schemes are similar, based on MBT. Again, the environmental impacts are mostly dominated by the effects of landfilling, which nevertheless have been substantially reduced due to the decrease of mixed MSW experienced during the period of the project. On the other side, the recovery of materials for recycling constitutes an environmentally net beneficial outcome which has been expanded during the project. In this case, the increase in separate collection has not been focused on paper and cardboard, but on the other materials, such as glass. Therefore, the net energy savings attributed to recycling are more relevant.

3.3. Results in Lisbon

Finally, for Lisbon, the results are presented in Figure 9 and Figure 10 for both categories carbon footprint and fossil resources depletion, in the same manner as for Aveiro and Larnaka.

The major contribution for GHG emissions comes in this case not from the landfilled residue, but from waste incineration.

Although the energy generation from MSW incineration contributes to replace conventional electricity generation based on fossil fuels, the calorific power of municipal waste is significantly due to the presence of plastics and other non-renewable materials, along with renewable combustible materials such as paper, tissues and wood. Therefore, the incineration of MSW cannot be considered as totally carbon-neutral, thus resulting in effective net GHG emissions released.

On the other hand, the recovery of materials for recycling and the outcomes of biological treatments (renewable energy and compost) result always in prevented GHG emissions and prevented resources consumption.

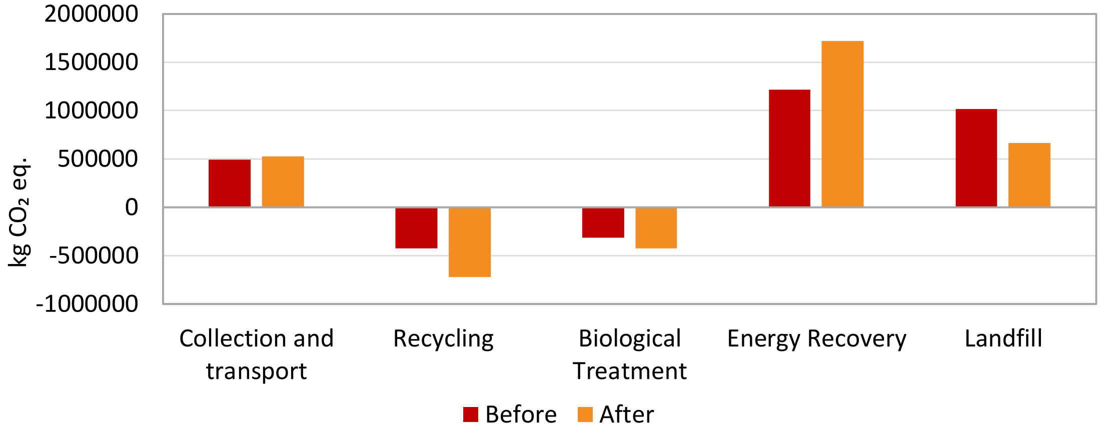

Figure 9. Carbon footprint of MSW management in Lisbon before and after the project.

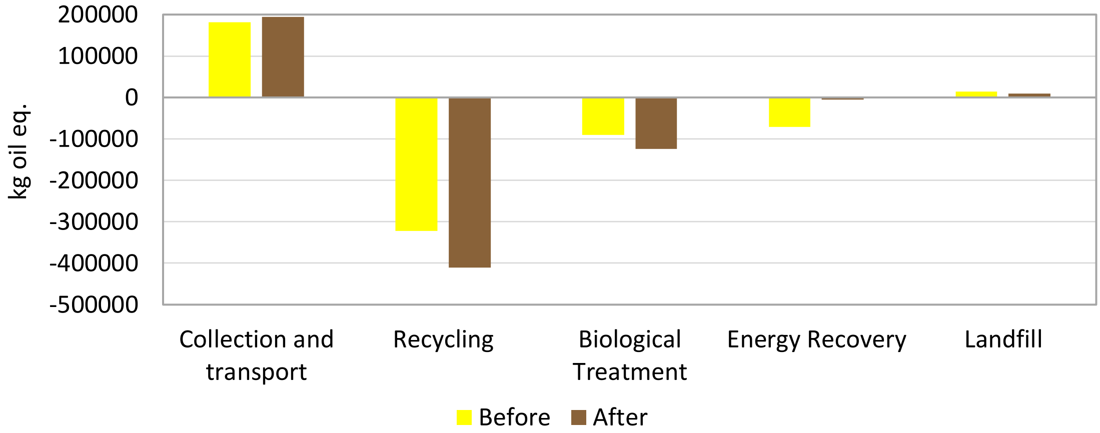

Figure 10. Fossil resources depletion of MSW management in Lisbon before and after the project.

In Figure 9 it can be noticed that, while GHG emissions increased by 40% between the beginning and end of the project to the growth of mixed MSW generation during that period, GHG emissions originated by landfilling treatments considerably decreased by 35% in the same period.

A clear reason for this discordance between the two results cannot be found within the scope of the project; it should be taken into account that the impacts of these activities are not only due to the waste inputs amount, but also to the internal performance of the technical processes involved: for instance, less generation of ashes during the combustion stage or an increased recovery of those ashes for reuse in road construction reduces the need of residual landfilling.

4. Conclusions

The assessment performed has demonstrated that some environmental effects have been noticed in the analysed areas during the period of LIFE PAYT project. The ratio of source separation of recyclable materials for separate collection and recycling has increased in the three cases assessed, while the generation of unsorted mixed municipal waste has been reduced in two of them – Aveiro and Larnaka, those where the project focused on residential households, reinforced by the promotion of home composting.

These changes in the waste streams induced some effects upon performance of the waste management systems – namely on energy consumption – and on the environmental impacts derived from these activities – namely on carbon footprint and prevention of primary raw materials consumption.

In those cases where the MSW treatment consists on MBT, most of the final outcome corresponds to refused materials sent to a sanitary landfill, this being the final disposal destination for more than 50% of the generated MSW. This affects very negatively the environmental result in terms of carbon footprint, due to diffuse methane emissions originated in landfills. On the other hand, recycling processes provide an environmental benefit very effective in terms of preventing the consumption of fossil resources, which even offsets the energy consumption of other MSW management activities such as collection. In conclusion: efforts like those intended in LIFE PAYT project, focused in both diverting waste from being landfilled and enhancing recycling activities will bring the most beneficial environmental effects.

Even though the gathering of the relevant data has been the most common difficulty found in the LCA performing process, it has been confirmed the ability of this methodology to correctly reflect the changes on the environmental consequences induced by the alteration of waste flows, in both quantity and composition.

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Co-funded by the LIFE programme of the European Union
LIFE15 ENV/PT/000609