Resources, Conservation and Recycling 85 (2014) 42–53

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Environmental evaluation of plastic waste management scenarios

L. Rigamonti[a,*], M. Grosso[a], J. Møller[b], V. Martinez Sanchez[b], S. Magnani[a], T.H. Christensen[b]

[a] Department DICA, Politecnico di Milano, Piazza Leonardo da Vinci, 32, Milano, Italy
[b] Department of Environmental Engineering, Technical University of Denmark, Kongens Lyngby, Denmark

ARTICLE INFO

Article history:
Received 14 December 2012
Received in revised form
23 November 2013
Accepted 18 December 2013

Keywords:
Plastics
Life cycle assessment
Material recovery
Energy recovery
Municipal waste

ABSTRACT

The management of the plastic fraction is one of the most debated issues in the discussion on integrated municipal solid waste systems. Both material and energy recovery can be performed on such a waste stream, and different separate collection schemes can be implemented. The aim of the paper is to contribute to the debate, based on the analysis of different plastic waste recovery routes. Five scenarios were defined and modelled with a life cycle assessment approach using the EASEWASTE model. In the baseline scenario (P0) the plastic is treated as residual waste and routed partly to incineration with energy recovery and partly to mechanical biological treatment. A range of potential improvements in plastic management is introduced in the other four scenarios (P1–P4). P1 includes a source separation of clean plastic fractions for material recycling, whereas P2 a source separation of mixed plastic fraction for mechanical upgrading and separation into specific polymer types, with the residual plastic fraction being down-cycled and used for "wood items". In P3 a mixed plastic fraction is source separated together with metals in a "dry bin". In P4 plastic is mechanically separated from residual waste prior to incineration.

A sensitivity analysis on the marginal energy was carried out. Scenarios were modelled as a first step assuming that marginal electricity and heat were based on coal and on a mix of fuels and then, in the sensitivity analysis, the marginal energy was based on natural gas.

The study confirmed the difficulty to clearly identify an optimal strategy for plastic waste management. In fact none of the examined scenarios emerged univocally as the best option for all impact categories. When moving from the P0 treatment strategy to the other scenarios, substantial improvements can be obtained for "Global Warming". For the other impact categories, results are affected by the assumption about the substituted marginal energy. Nevertheless, irrespective of the assumptions on marginal energy, scenario P4, which implies the highest quantities of specific polymer types sent to recycling, resulted the best option in most impact categories.

1. Introduction

Plastic constitutes an increasingly important fraction of municipal solid waste (MSW) and in Europe it is much debated how this waste fraction should be managed. The paper by Lazarevic et al. (2010) is a useful guidance about the most convenient management schemes for this material. Based on an extensive literature review, seventy seven scenarios were selected and classified into four categories, based on the dominant technology in the scenario: mechanical recycling, feedstock recycling, incineration, landfilling. The conclusion of the study is that mechanical recycling is generally the best option, even if changes in the virgin material substitution ratio and in the level of organic contamination can make incineration preferable. Shonfield (2008) reported the life cycle assessment (LCA) of a range of plastic recovery technologies, including comparisons between different options for the disposal of plastic contained in household waste. The results are particularly sensitive to the quality of the produced plastic, which influences the virgin material substitution ratio: the best choice is to focus on technologies that produce high quality recyclate; when it is not possible to obtain an adequate quality, plastic should be used in the production of refuse derived fuel (RDF) or as a reducing agent in blast furnaces. Astrup et al. (2009) in their study concluded that the substitution of virgin plastic is the preferred option when the source separated plastic is of good quality; when dealing with mixed plastics, its use as a fuel in substitution of coal is the environmentally preferable option. The substitution of wood should be avoided when considering the effects on global warming. Also Al-Salem et al. (2009) reviewed the recovery routes for plastic waste, coming to the conclusion that both material recycling and energy recovery in different forms play a role in the sustainability of the end of life of municipal waste derived plastic items.

* Corresponding author. Tel.: +39 02 2399 6415; fax: +39 02 2399 6499.
E-mail address: lucia.rigamonti@polimi.it (L. Rigamonti).

0921-3449/$ – see front matter
http://dx.doi.org/10.1016/j.resconrec.2013.12.012

There is a general agreement on the fact that clean fractions of individual plastic polymers should be recycled, but the debate is still open on how to properly manage the mixed and potentially dirty plastics found in waste. It has to be assessed whether the benefits of recycling or recovery of such streams outweigh the efforts for their separate collection. For example, Frees (2002) found that extensive cleaning of food containers using hot water may lead to energy consumption comparable to the energy gained from incineration of the containers.

2. Materials and methods

2.1. Goal and scope

The aim of the paper is to contribute to the existing debate around plastic waste management. As both material and energy recovery can be performed on such a waste stream, and different separate collection schemes can be implemented, different plastic waste recovery routes were analysed. Goal of the study was thus to compare, following a life cycle approach, different options for the management of plastic fraction, in order to address the challenges associated with such a critical material.

Five scenarios were modelled. In the baseline scenario (P0) the plastic is not source separated at all, which means that it is treated together with the residual waste (RW); 90% is sent to a waste-to-energy plant (WTE), while 10% to a mechanical-biological treatment plant (MBT) producing RDF. In scenarios P1–P4, a range of potential improvements in plastic management is introduced, meaning that out of the total plastic present in the gross waste, a certain amount is separated at the source (P1–P3) or by introducing a dedicated material recovery facility (MRF), for P4. Section 2.3 describes in detail the scenarios.

The functional unit is the management of 1 tonne of plastic as present in the gross waste. A typical waste composition of Western Europe was selected, as reported in Møller et al. (2012) (Table SM.1 of Supplementary Material). MSW produced in this region has a relatively high content of paper and a medium content of kitchen waste, while total plastic represents 10% in weight. Section 2.2 reports the composition of the plastic fraction.

System boundaries include the treatment in the MRFs, the plastic recycling, and the WTE and MBT plants. Waste collection and transport were included, too. Section 2.5 reports the inventory data used in the modelling.

Beyond treating waste, some of the analysed activities (e.g. plastic recycling and energy recovery from the RW) allow for the production of secondary materials and/or energy. These are called "multifunctional" processes, and the supplementary functional outputs are called "co-products". In the LCA modelling, instead of using allocation between functions, we have identified which products are replaced on the markets by the arising co-products and we have included their replacement in the model. This methodology is called "substitution by system expansion" or "avoided burden method" (Finnveden et al., 2009). The system was modelled using a consequential LCA approach, i.e. by identifying and modelling marginal technologies for energy production and other technologies affected by changes in the waste management system. The possibility of cascade effects from increased capacity of the waste-to-energy (WTE) plants involving diversion of other waste types to incineration were not considered. The long-term marginal for electricity was assumed to be produced at coal-based power plants. This was also identified as the most widely used electricity marginal by Mathiesen et al. (2007) who reviewed a number of articles on LCA of energy systems. As it is difficult to identify the marginal heat because district heating comprise of many small independent networks, an average heat mix was constructed based on data on European fuel mixes for heat production (IEA, 2010).

Table 1
Composition of plastic in municipal solid waste.

Distribution of plastic fraction (% wet weight)	Average
Bottles	27
Soft	36
Hard	11
Non-recyclable	26

The analysis was carried out with the LCA-waste-model EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies) developed by DTU Environment, Technical University of Denmark, and described in details by Kirkeby et al. (2006). Section 2.4 illustrates the adopted characterisation method and the selected impact categories.

2.2. The plastic fraction

The plastic in MSW is composed of plastic bottles made of polyethylene terephthalate (PET) or high density polyethylene (HDPE), of soft plastic or plastic films made of low density polyethylene (LDPE) and of hard plastic made of HDPE. The remaining plastic material fraction is regarded as non-recyclable mixed plastic.

The distribution of the four fractions out of the total plastic in MSW is shown in Table 1, and it was calculated as an average of data from Italy (Corepla, 2011) and France (ADEME, 2009). The assumed polymer composition of plastic material fraction is based on data from Italy and shown in Table 2.

2.3. Plastic waste management scenarios

As a general approach, plastic waste management scenarios were defined by taking into account the peculiarity of this material and some of the most common practices in Europe. When compared to other packaging materials (iron, aluminium, paper, etc.) what is commonly referred to as "plastic" is in fact still a very heterogeneous fraction. As a consequence, an important sorting step is required prior to recycling, aimed at:

- removing non-plastics fractions,
- sorting by different polymers (PET, PE),
- sorting by different colours (PET only).

After sorting, the different plastic flows are sent to the recycling process, which yields some further residues.

The modelled scenarios are:

- P0: Plastic is not collected separately, nor it is mechanically sorted from the RW. The plastic is thus treated as RW according to the following hypothesis: 90% in weight to WTE and 10% in weight to MBT.

Table 2
Polymer composition of plastic fractions in municipal solid waste in Italy (Corepla, 2011).

Material plastic fraction (% wet weight)	PET	PE		Mix
		LDPE	HDPE	
Bottles	25		8	
Soft		39		
Hard			5	
Non-recyclable				23
Total (%)	25	39	13	23

Table 3
Characteristics of the Plasmix (Rossi et al., 2010).

	% wet weight
Plastic	57
Paper and cardboard	10
Wood	3
Textiles	3
Inerts and others (incl. metals)	27
Total	100
Lower heating value (kJ/kg)	20,100
Ash (%)	20.5
Moisture (%)	9
C (%)	47.3
H (%)	7.1
Cl (%)	0.8
S (%)	0.2

- P1: Source separation only of bottles at 80% efficiency, leading to an overall plastic collection efficiency of about 22%. The bottles are mechanically separated into PET and HDPE and then recycled to PET flakes and HDPE granules that are used in substitution of primary PET and HDPE.
- P2: Source separation of all plastic (80% efficiency for bottles; 50% efficiency for the other plastic fractions), leading to an overall plastic collection efficiency of about 58%. The fraction is separated into PET, HDPE, a polyolefin fraction and a residue which, at least in the Italian context, is referred to as “Plasmix” (Rossi et al., 2010). Characteristics of the Plasmix are shown in Table 3. The Plasmix is used as fuel in cement kilns, replacing coal.
- P3: Plastic collection (80% efficiency for bottles; 30% efficiency for the other plastic fractions) according to a so-called “dry bin” scheme, together with metals. The overall plastic collection efficiency is then 43.5%. The subsequent mechanical separation yields 80% recovery for bottles and 20% recovery for the other plastic fractions.
- P4: No source separation for plastic, which is mechanically sorted from RW prior to incineration. The mechanical separation removes PET and HDPE bottles at high efficiency, which are sent to recycling, and other minor high calorific fluxes sent to energy recovery in cement kilns.

No allocation was done when the plastic management affected other waste streams (P2, P3 and P4). This means that the energy consumption of the MRFs is assigned exclusively to plastic management. In P2 the input to the MRF was source separated plastic and the energy use was therefore solely allocated to the plastic fractions. In P4 the waste was source separated for paper, glass and metal prior to arriving at the MRF and the energy use was therefore also allocated to the plastic fractions. This was not the case for P3 where mixed metal and plastic from a “dry bin” were sorted at the MRF, but as the focus of the investigation was on the plastic fractions, the energy was allocated in total to the plastic fractions. In contrast, the benefits from metal recycling resulting from the overall sorting process were not ascribed to plastic recycling.

2.4. Impact categories and characterisation method

The impact assessment was conducted according to the EDIP-method. EDIP is the Danish mid-point assessment method originally developed for LCA of industrial products (Wenzel et al., 1997). The emissions are aggregated into the following potential impact categories: global warming, acidification, nutrient enrichment (eutrophication), photo-chemical ozone formation and a number of toxic impact categories including eco-toxicity in water and soil and human toxicity via soil, water and air.

All emissions are quantified for each technology and process and aggregated within a plastic waste management scenario (e.g. kg CO_2 fossil, kg CH_4). Emissions contributing to an impact category are converted to the same unit via their characterisation factor (e.g. 1 kg CO_2 fossil = 1 kg CO_2-equivalent, 1 kg CH_4 = 25 kg CO_2-equivalent). The potential environmental impacts can subsequently be quantified in terms of person equivalent (PE) – by dividing the impact in each impact category by the yearly contribution by an average person to the impact category in question. This is called normalisation and the normalisation references for the different impact categories are those reported in Stranddorf et al. (2005) for EU-15. Weighting was not performed in the current research.

In the interpretation of the results, most emphasis will be on the standard non-toxic impact categories (global warming, acidification, nutrient enrichment, stratospheric ozone depletion, and ozone formation), since these are based on broadly accepted concepts and the characterisation factors are well established. On the contrary, the toxic impact categories are much more uncertain in their approach – in particular the fate and exposure modelling – and the characterisation factors highly variable.

2.5. Inventory

2.5.1. Plastic MRFs

The MRFs are material recycling facilities that sort and upgrade the received waste stream. In the present study, MRFs are utilised for plastic upgrading and/or separation prior to its recycling. Four different types of plastic MRFs were then defined specifically for this study, mainly based on information derived from existing plants. The four MRFs plants are then directly related to the four scenarios P1–P4.

The MRF module in EASEWASTE uses transfer-coefficients for each material fraction to route the waste fractions to the outputs. A residue waste output includes the mass not routed to a specific output in order to maintain the mass balance. The characteristics of the output streams are based on the characteristics of the input material fractions via mass-transfer coefficients.

2.5.1.1. MRF for scenario P1: targeted source separation of plastic bottles. The input to the sorting process is constituted by source separated bottles. It is assumed that plastic bottles are conferred in reusable containers, so that no bags enter the sorting plant. Thus the mechanical process is solely based on near infra-red (NIR) sorting, in order to separate PET bottles from HDPE bottles and then to split the flow of PET bottles in 3 flows (clear PET, light blue PET and mixed colours PET), as required by the subsequent recycling processes (Fig. 1).

A manual refining is to be considered for each output stream in order to reach the required purity for subsequent recycling. This step was obviously not modelled.

The energy consumption of a single NIR sorting step is 12 kWh per tonne of material input, calculated as an average of the values reported by Shonfield (2008). The total consumption of the sorting process results in 30 kWh per 1 tonne of plastic entering the sorting process, which corresponds to 6.5 kWh referred to 1 tonne of plastic waste in the gross waste.

The sorting efficiency of NIR machines was derived from Shonfield (2008), which gives the following average values: 75% for HDPE and 72% for PET. The subsequent manual refining allows to reach a 90% separation efficiency.

The complete mass balance is reported in Table SM2 of the Supplementary Material. The overall plastic collection is 22% and the plastic material recycling is 19% (151 kg PET and 43 kg HDPE sent to recycling). The residual fraction (784 kg) remains in the RW and is then treated accordingly as in scenario P0 (i.e. 90% to WTE and

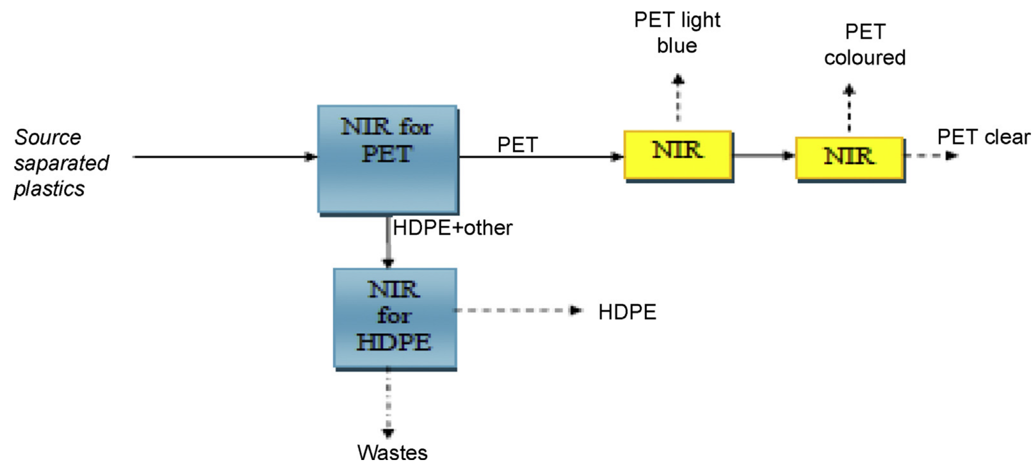

Fig. 1. MRF for scenario P1 (NIR = near infra-red separator).

Table 4
Electricity consumption of machineries utilised in plastic MRFs (expressed in kWh per tonne of input material).

Machinery	Electricity consumption (kWh/t)	Data source
Near infra-red (NIR) separator	12	Elaboration Shonfield (2008)
Film removing phase	5.7	Elaboration Shonfield (2008)
Sieves	1	CITEC (2004)
Magnets	0.75	CITEC (2004)
Eddy current separator (ECS)	0.95	CITEC (2004)
Bag trimmer	3	CITEC (2004)

10% to MBT). The plastic-reject (22 kg) is used as a fuel assumed to substitute for coal burning in a cement kiln.

2.5.1.2. MRF for scenario P2: source separation of all plastic. The input to the sorting process is source separated plastics, in a context where general and liberal source separation of all plastic is encouraged. This means that the material will include impurities, dirt and other items which will end up in the previously mentioned Plasmix.

An advanced sorting plant located in Northern Italy was taken as a reference for this scenario. The scheme of the sorting process is shown in Fig. 2.

The layout includes a bag trimmer, two sieves and film separation (ballistic sieve), and four NIR sorting steps. A manual refining on the outputs of the NIR separators allows to reach the required purity (90% for bottles, 80% for film). A magnet and an eddy current separator (ECS) allow to recover part of the iron and of the aluminium present in the Plasmix. According to information gathered from the plant, the recovered iron is about 4% of the total weight of Plasmix, while for aluminium the percentage is about 1%.

Based on the electricity consumption of each machinery (Table 4), the total consumption of the sorting process resulted in 29 kWh per one tonne of plastic entering the sorting process, which means 16.7 kWh per one tonne of plastic in the gross waste.

Mass transfer coefficients of non-plastic fractions from gross waste were adapted in order to have a composition of Plasmix similar to the one reported by Rossi et al. (2010) (Table 3). As a final result, assuming a 80% source separation for bottles and 50% for the other fractions, this yields 216 kg plastic bottles and 365 kg of mixed plastic. The mechanical separation is characterised by the transfer-coefficients shown in Table SM3 of the Supplementary Material. This yields 151 kg PET, 71 kg HDPE and 161 kg polyolefin mix, all sent to recycling. The Plasmix constitutes 347 kg, of which 198 is plastic. The Plasmix is used as a fuel assumed to substitute for coal burning in a cement kiln. The overall plastic collection is 58% and the plastic material recycling is 38%. The residual fraction (419 kg) remains in the RW and is then treated accordingly as in scenario P0 (i.e. 90% to WTE and 10% to MBT).

2.5.1.3. MRF for scenario P3: source separated plastic in the "dry-bin". Focus is on a "dry-bin" concept, with a targeted commingled source separation of plastic and metals. The composition of the dry bin (wet weight) is iron 21%, aluminium 6% and plastic 73%.

Metals are sorted in the plant thanks to magnets and ECS. Fig. 3 shows the hypothesised MRF for the P3 scenario.

By summing the energy consumption of each step, the total energy consumption of the sorting process results in 20 kWh per one tonne of material input (plastic and metals), which corresponds to 12 kWh referred to one tonne of plastic in the gross waste.

Assuming 80% source separation for bottles and 30% for the other plastic fractions, this yields 216 kg of plastic bottles (164 kg PET bottles and 52 kg HDPE bottles) and 219 kg of mixed plastic. The mechanical separation is characterised by the transfer-coefficients as shown in Table SM4 of the Supplementary Material. This yields 135 kg PET, 45 kg HDPE and 32 kg polyolefin mix, all sent to recycling. The residue (237 kg) is mainly constituted of plastic (223 kg), but a minor amount of iron and aluminium is also present, due to the sorting efficiency of magnets and ECS. This residue is used as a fuel, assumed to substitute for coal burning in a cement kiln. The overall plastic collection is 43.5% and the plastic material recycling is 21%. The residual fraction (565 kg) remains in the RW and is then treated accordingly as in scenario P0 (i.e. 90% to WTE and 10% to MBT).

2.5.1.4. MRF for scenario P4: mechanical separation of plastic from residual waste. In this scenario, separated collection is carried out for all materials but plastic, which is left in the RW. This is then pre-treated in a MRF facility located just ahead of the WTE plant, where the focus is on removing high quality plastic by mechanical process units for its subsequent recycling (Fig. 4). This scenario is based on a new approach proposed in the Netherlands, starting from the assumption that citizens might be annoyed by a further request of sorting plastic waste at their household.

The mechanical separation uses a first shredder, followed by a 150 mm trommel. Plastic is then separated by film separators and NIR separators for polymers identification. In the 150 mm trommel, the organic fraction is being removed (under sieve), so that it does not interfere with the sorting of the plastics; then at the end the remaining waste is reunited with the organic. As a result, the

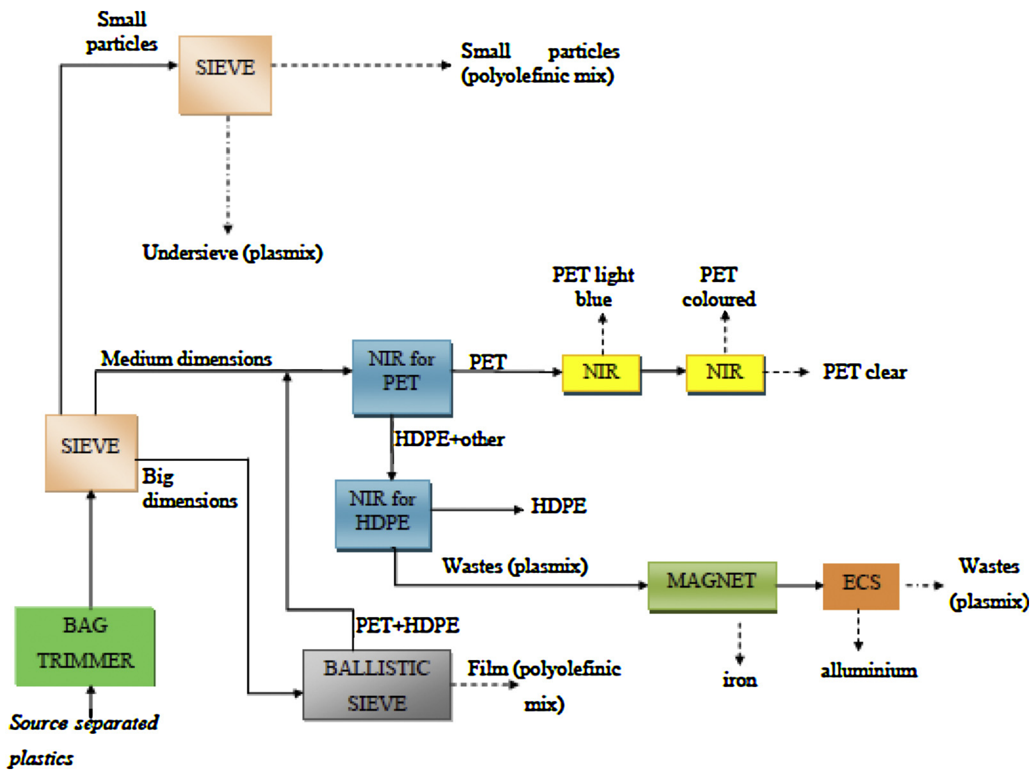

Fig. 2. MRF for scenario P2 (NIR = near infra-red separator; ECS = eddy current separator).

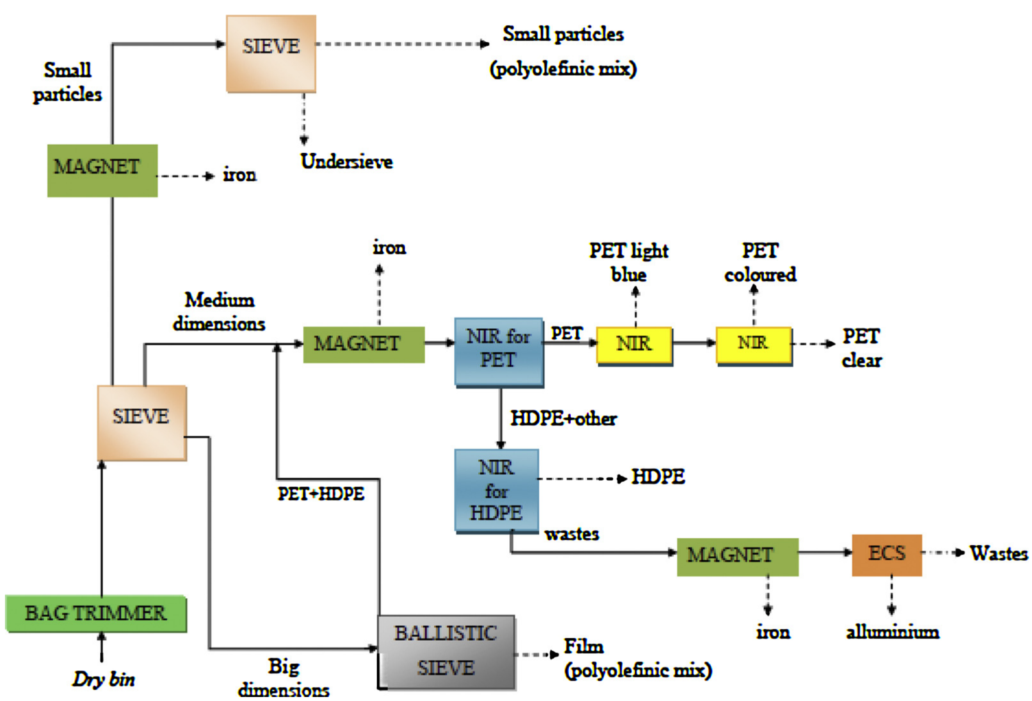

Fig. 3. MRF for scenario P3 (NIR = near infra-red separator; ECS = eddy current separator).

so-called “RDF” fraction destined to the WTE plant has a modest lower heating value (LHV), lower than the one of input RW (8.7 vs. 9.6 MJ/kg). This is because the plastic fraction is removed, while the organic fraction is still present in the waste.

The MRF uses 25 kWh per tonne of RW (i.e. 151 kWh per tonne of plastic waste in the gross waste) and is characterised by the transfer-coefficients as shown in Table SM5 of the Supplementary Material.

Starting from 1000 kg of plastic waste in the gross waste, this yields:

- 541 kg of RDF, which is sent to the WTE plant;
- 271 kg of plastic bottles, of which 205 kg is PET and 66 kg is HDPE, both sent to recycling;

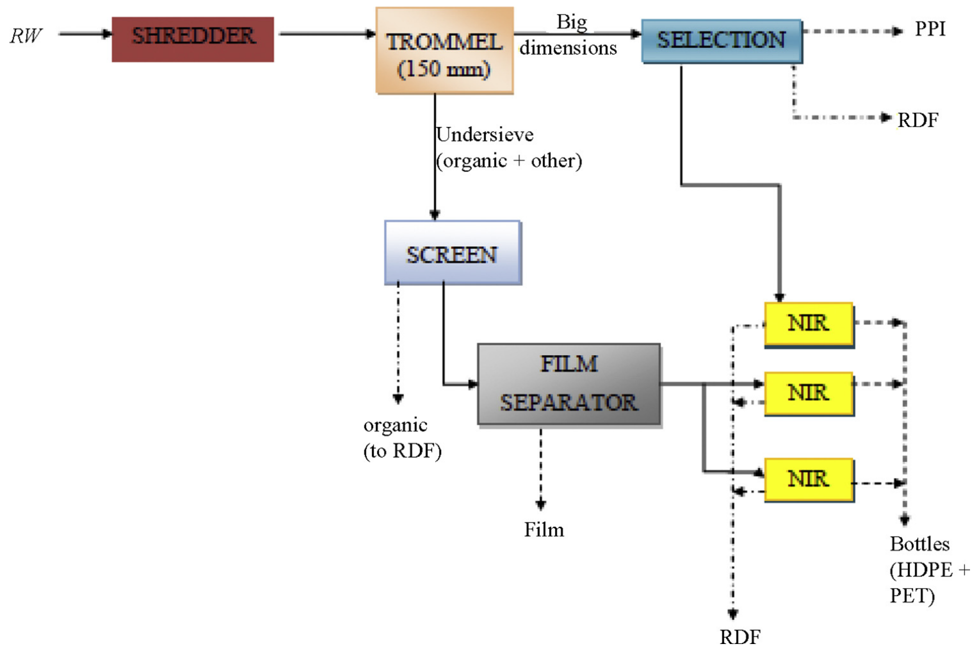

Fig. 4. MRF for scenario P4 (RW = residual waste; NIR = near infra-red separator).

- 139 kg of so-called "PP1", utilised as a secondary fuel in a cement kiln;
- 49 kg of foils in bales, also utilised as a secondary fuel in a cement kiln.

2.5.2. Plastic recycling

This study includes the recycling of different types of plastic: PET, HDPE and a polyolefin mix.

In EASEWASTE the material recycling module is used to model the recycling of a waste material into a new material/product. It is reasonable to assume that the recycled material is sold and can substitute for similar materials/products on the market. According to this approach, recycling leads to avoided production of other materials/products based on virgin resources which should be accounted for in the LCA. The recycling module requires a substituted amount to be entered, meaning that the amount of output is specified as a percentage of the amount of waste material input (i.e. the "technical substitution value"). This is required in order to take into account the material loss that occurs in the recycling process. In addition, a substitution percentage for the avoided production must be specified (i.e. the "market substitution value"), because the recycled material cannot always fully substitute a similar product on the market for several reasons:

- there might be a loss of quality (loss of material grade) during the reprocessing, meaning that the material cannot be recycled forever;
- the properties of the recycled material can differ from those of the virgin one;
- market elasticity, and thereby substitution ratio, might be different for recycled and virgin material.

The utilised recycling datasets are here below described.

2.5.2.1. PET. The recycling dataset used for PET recycling is based on a process from the Ecoinvent database for the primary production and on literature data for secondary production. The primary production is the process of Ecoinvent database: "Polyethylene terephthalate, granulate, amorphous, at plant/RER", that describes the primary production of amorphous PET. Data is based on the average unit process from the Eco-profiles of the European plastics industry. For the secondary production, consumptions of electricity, methane, water and sodium hydroxide were considered, which are summarised in Table 5.

According to Giugliano et al. (2011), the technical substitution value for recycled PET is 75.5% whereas Rigamonti et al. (2009) reported a 81% market substitution value.

2.5.2.2. HDPE. The recycling dataset used for HDPE recycling is based on a process from the Ecoinvent database for the primary production and on literature data for secondary production. The primary production is modelled according to the Ecoinvent module "Polyethylene, HDPE, granulate, at plant/RER". Data are from the Eco-profiles of the European plastics industry (PlasticsEurope). For the secondary production, consumptions of electricity, methane and water were considered, which are summarised in Table 6.

According to Giugliano et al. (2011), the technical substitution value for recycled HDPE is 90%, whereas Rigamonti et al. (2009) reported a 81% market substitution value.

2.5.2.3. Polyolefin mix. This study assumes that recycled polyolefins are used to manufacture products traditionally made of wood, for example outdoor furniture (fences, benches, facilities for children playgrounds). Hence the recycling and utilisation of waste polyolefin will save some wood that, being available, can instead be used to generate energy (cascading effect).

The recycling database for polyolefin mix recycling accounts for:

- Secondary production of polyolefin mix. It is assumed that it has the same material and energy consumption per tonne of recycled polyolefin as the secondary production of HDPE. According to Giugliano et al. (2011), the technical substitution value for recycled polyolefin is 60% and Rigamonti and Grosso (2009) reported a 50% market substitution value.
- Production of heat by saved wood, accounted as a load. To convert plastic into wood, it was assumed that 1 tonne of polyolefin mix means 1.029 m^3 of planks that can be used instead of 1.029 m^3 of wood (Rigamonti and Grosso, 2009). The following characteristics

Table 5
Input material for the secondary production of PET expressed per kg of recycled PET.

	Average value	Unit	Std. dev.	Min	Max	Reference
Electricity	0.32	kWh	0.10	0.24	0.47	Torregrossa et al. (2005) Arianna (2000) Visited plant Perugini et al. (2005) Franklin Associated (2010)
Methane	2.56	MJ	0.31	2.29	2.90	Visited plant Perugini et al. (2005) Franklin Associated (2010)
Water	2.96	kg	–	–	–	Perugini et al. (2005)
Sodium hydroxide	0.003	kg	–	–	–	Perugini et al. (2005)

Table 6
Input material for the secondary production of HDPE per kg of recycled HDPE.

	Average value	Unit	Std. dev.	Min	Max	Reference
Electricity	0.44	kWh	0.17	0.20	0.56	Arena et al. (2003) Perugini et al. (2005) Torregrossa et al. (2005) Franklin Associated (2010)
Methane	0.51	MJ	0.21	0.27	0.65	Arena et al. (2003) Perugini et al. (2005) Franklin Associated (2010)
Water	1.78	kg	–	–	–	Perugini et al. (2005)

of the wood were assumed: 20% humidity, density 540 kg/m^3 and lower heating value 15.7 MJ/kg.

- Avoidance of the heat production from natural gas, accounted as a saving.

2.5.3. MBT and WTE plants

Table 7 summarises the main characteristics of MBT and WTE plants that treat the RW, and consequently also the plastic which is not collected separately (Møller et al., 2012).

2.5.4. Collection and transportation

Waste collection is modelled as fuel consumption per tonne of waste. In the modelling, the following fuel consumptions were used: 3 l diesel per tonne of RW and 8 l diesel per tonne of separated plastic. The value for RW is based on several observations, while that for plastic is an estimate.

Transportation represents the fuel consumption for the transport of the collected waste to the point of unloading, e.g. at the treatment facilities. The fuel consumption is expressed in fuel consumption per tonne per km (on-way-distance). In the modelling, the following fuel consumptions related to the RW and the separated plastic were used: 0.10 l per tonne of RW per km and 0.20 l per tonne of separated plastic per km. The distances travelled were assumed to be: 15 km for the RW sent to WTE plant, 25 km for the RW sent to MBT plant, and 100 km for the separated plastic sent to recycling industry.

3. Results and discussion

3.1. Total potential environmental impacts

Fig. 5 shows the potential environmental impacts for the scenarios in the standard non-toxic EDIP impact categories “Global Warming”, “Acidification”, “Nutrient Enrichment”, “Photochemical Ozone Formation” and “Stratospheric Ozone Depletion”.

P0 contributed with direct savings for all impact categories but “Global Warming”, where it represents a net load to the environment, in clear contrast with the other scenarios. On the other hand, P0 performed best of all in “Acidification”. Scenarios P1–P4 had better results than P0 for “Global Warming” and “Nutrient Enrichment”, but with a different pattern. In “Stratospheric Ozone

Table 7
Main characteristics of MBT and WTE plants.

Main characteristics		
RW management (%)	WTE	90
	MBT	10
WTE (%) efficiency	Electricity	20
	Heat	20
Bottom ash management from WTE (%)	Iron recovery[a]	75
	Al recovery[a]	40
	Road construction	75
	Landfill	25
Air pollution control residues from WTE	Destination	Mines/hazardous landfills (50/50)
MBT	Technology	Single stream (bio-drying + mechanical refining)
	Iron recovery[a] (%)	94
	Al recovery[a] (%)	24
	Residue destination	Landfill
	RDF destination	Cement kiln
Displaced energy	Electricity	Coal
	Heat	Mix[b]

[a] These values are not applied to the plastic fraction contained in the RW.
[b] 20% district heating (coal and gas), 14% hard coal, 2% lignite, 8% oil, 42% natural gas, 13% wood.

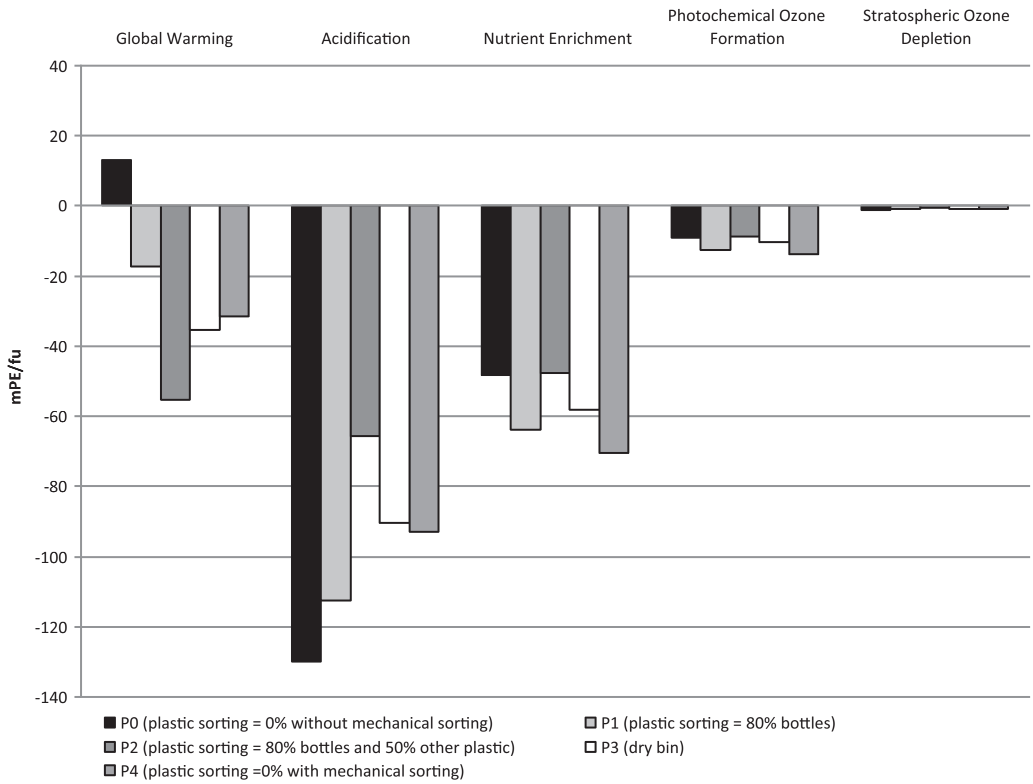

Fig. 5. Potential environmental impact in the non-toxic impact categories.

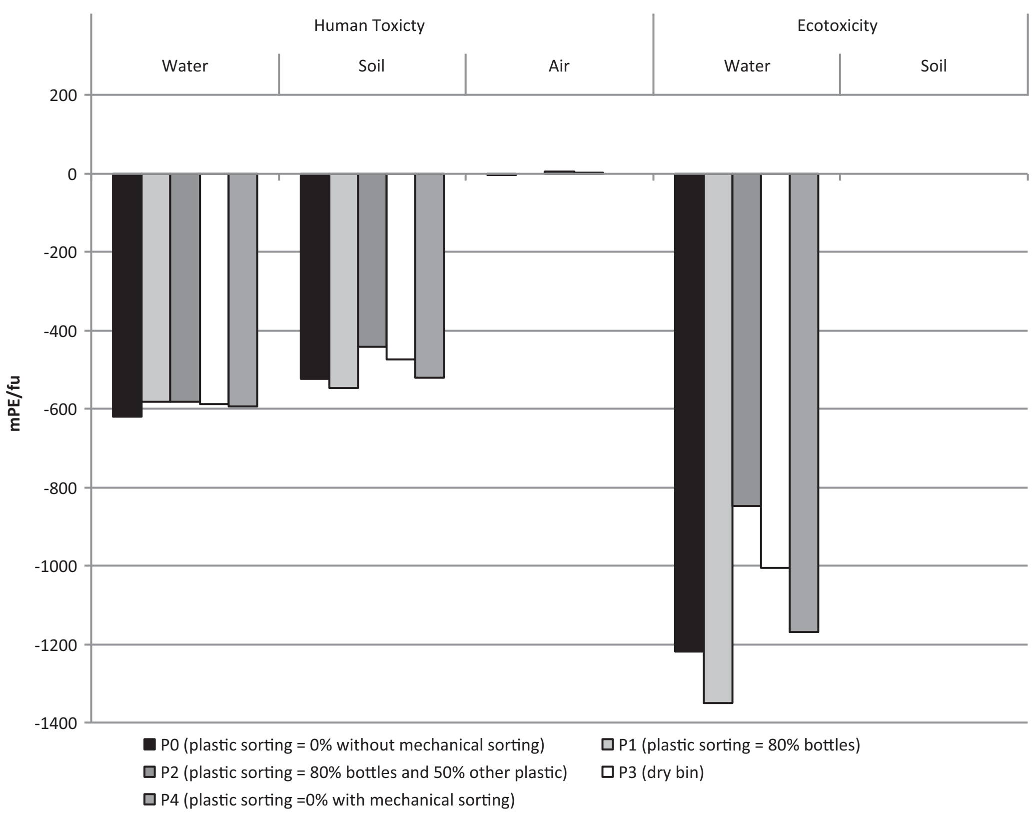

Fig. 6. Potential environmental impact in the toxic impact categories.

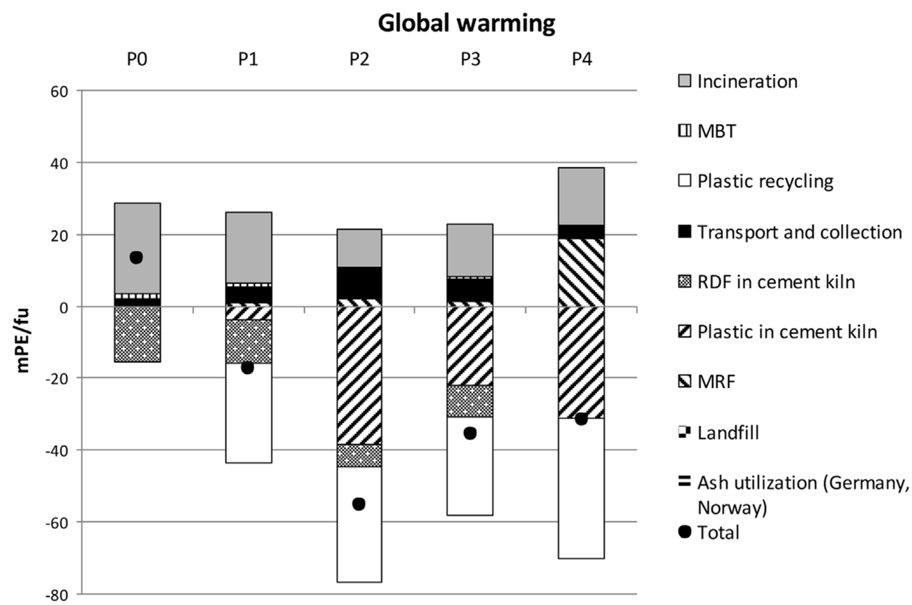

Fig. 7. Potential environmental impacts in the impact category Global Warming (100 years) related to lifecycle stages and processes.

Depletion" absolute impacts in milli Person Equivalents are very modest, as well as the variation among scenarios.

As a general consideration, none of the examined scenarios emerged as the best option for all non-toxic impact categories.

Fig. 6 shows the potential environmental impact for the scenarios in the EDIP impact categories of toxicity towards humans and ecosystems. Huge impact savings are observed for all of the scenarios in the categories "Ecotoxicity in Water", "Human Toxicity via Water" and "Human Toxicity via Soil". On the contrary, "Ecotoxicity in Soil" and "Human Toxicity via Air" had negligible impacts or loads in terms of milli Person Equivalents. Differences among scenarios are generally modest, with the sole exception of "Ecotoxicity in Water". Focussing on the latter, which is also the one which gives the highest savings, P1 performed best of all, while P2–P4 resulted worse than P0.

As for the non-toxic impact categories, none of the examined scenarios emerged as the best option for all toxic impact categories.

3.2. *Potential environmental impacts from lifecycle stages and processes*

The potential environmental impacts were divided into the different lifecycle stages of the scenarios to identify the most important of them. The total impacts of each scenario, i.e. the sum of all the categories, are represented by black dots.

The impacts were divided into the following categories: "Incineration", "MBT", "Plastic recycling", "Transport and collection", "RDF in cement kiln", "Plastic in cement kiln", "MRF", "Landfill", "Ash Utilisation (Germany, Norway)". The category "Incineration" includes process specific emissions, waste specific emissions and energy substitution. The plastic recycling stage represents the net impact of the secondary production and the avoided primary production. The categories "RDF in cement kiln" and "Non-recyclable plastic in cement kiln" include waste and process specific emissions minus the avoided utilisation of hard coal.

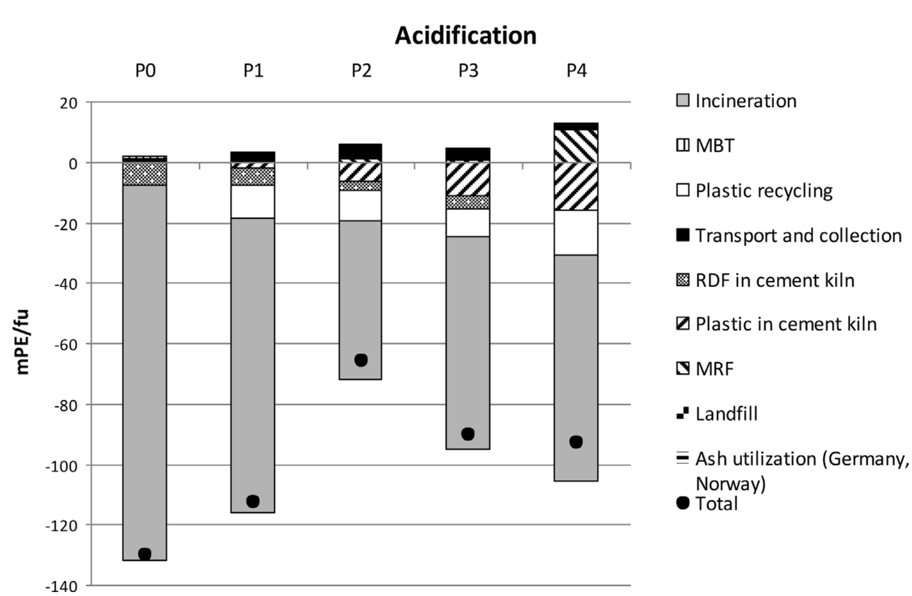

Fig. 8. Potential environmental impacts in the impact category Acidification related to lifecycle stages and processes.

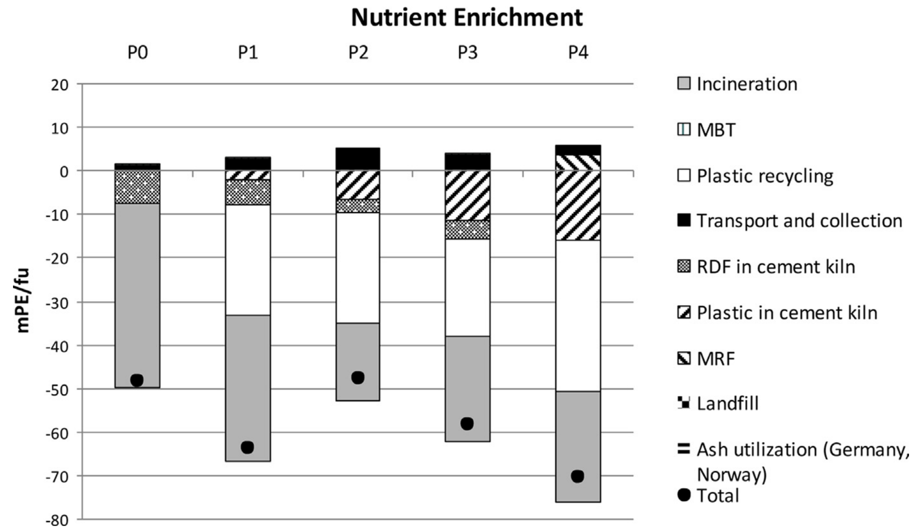

Fig. 9. Potential environmental impacts in the impact category Nutrient Enrichment related to lifecycle stages and processes.

Figs. 7–9 show as an example global warming, acidification and nutrient enrichment divided into the different lifecycle stages.

The maximum contributions to the savings on "Global Warming" impact category are related to plastic co-combustion in cement kiln and plastic recycling. Plastic in the residual waste ending up in RDF co-combusted in cement kiln also plays a role, despite the modest amount of material following that path. Incineration always represents a load due to the fossil CO_2 emissions from plastic combustion. It is then easy to understand why for this impact category the P0 scenarios performs worst, giving a net load to the environment, while all the other scenarios where a certain amount of plastic is recycled or co-combusted result in a net saving.

A completely different picture compared to "Global Warming" is obtained for "Acidification", where incineration of plastic contained in the residual waste plays a major role in determining the savings. This is due to the balance of SO_2 emissions between plastic combustion and substituted coal combustion, the latter being much higher because of the higher content of sulphur. Plastic recycling and plastic co-combustion in cement kiln give a modest saving in P1–P4 scenarios, while in P4 the operation of the MRF for plastic sorting prior to incineration constitutes a load. This is due to its energy consumption which, as explained, in the modelling of the scenarios was fully allocated to the plastic content of the residual waste.

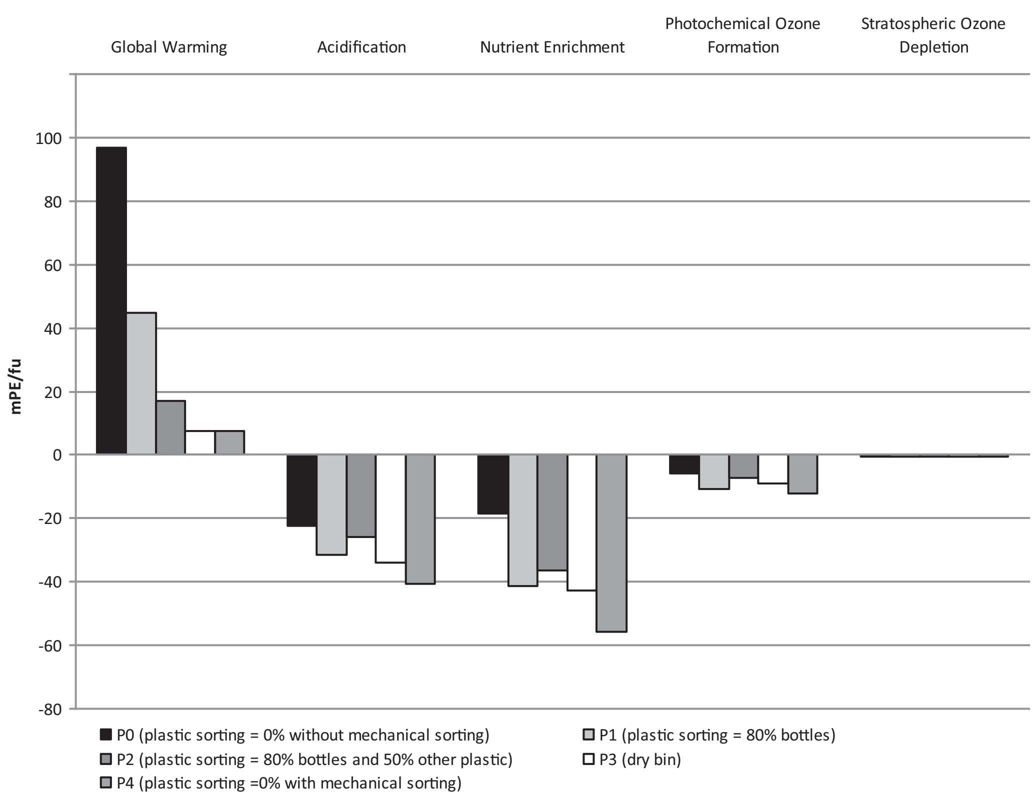

Fig. 10. Potential environmental impact in the non-toxic impact categories when the marginal energy is based on natural gas.

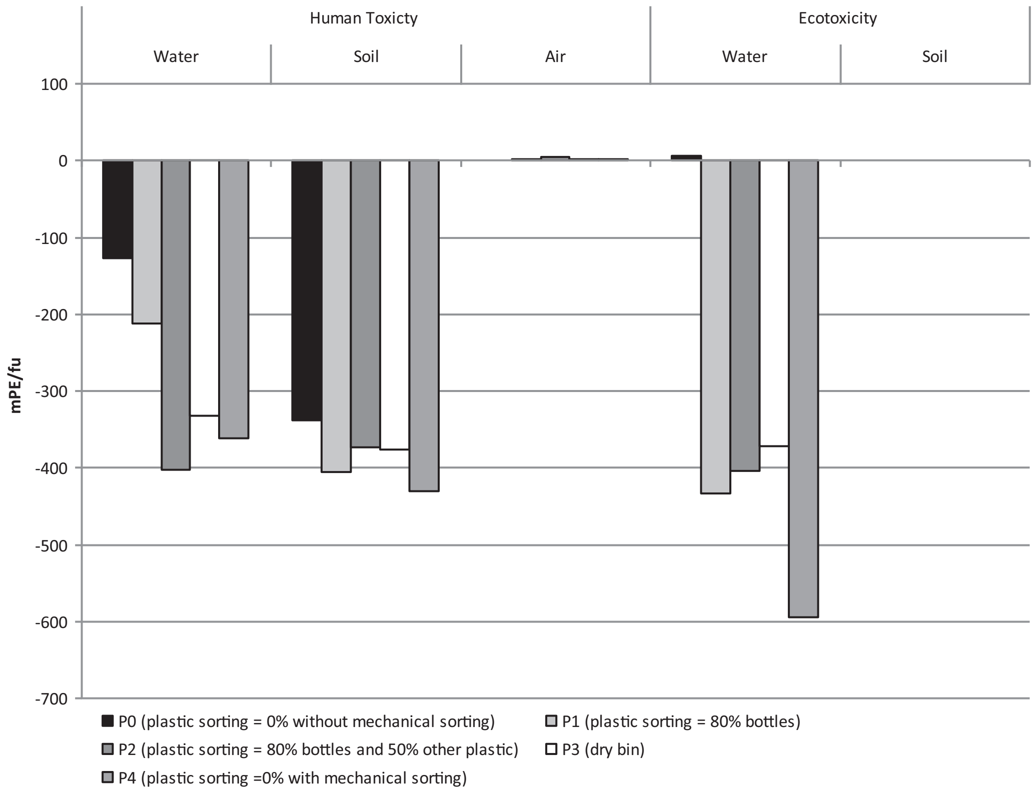

Fig. 11. Potential environmental impact in the toxic impact categories when the marginal energy is based on natural gas.

For “Nutrient Enrichment”, incineration of plastic in the residual waste is very relevant in determining the overall savings for scenario P0, while for scenarios P1–P4 it gives savings of similar order of magnitude as plastic recycling. A similar picture was obtained for “Photochemical Ozone Formation” and “Stratospheric Ozone Depletion”.

For the toxic categories, not shown here for reason of space, the largest savings were related to the energy substitution from incineration, with plastic recycling and plastic co-combustion in cement kilns also playing a role.

3.3. Sensitivity analysis

The robustness of the LCA was tested through a sensitivity analysis about the marginal energy, which was assumed based on natural gas for both electricity and heat, instead of coal and a mix of fuels as in the baseline scenarios.

Fig. 10 shows the potential environmental impacts for the scenarios in the standard non-toxic EDIP impact categories. All the scenarios contributed with direct savings for all impact categories but “Global Warming”. Scenario P4 is the best option for “Acidification” and “Nutrient Enrichment”, whereas the best options for “Global Warming” are P3 and P4. In “Stratospheric Ozone Depletion”, absolute impacts in milli Person Equivalents are very modest, as well as the variation among scenarios.

Fig. 11 shows the potential environmental impact for the scenarios in the EDIP impact categories of toxicity towards humans and ecosystems. Huge impact savings are observed for all of the scenarios in the categories “Ecotoxicity in Water”, “Human Toxicity via Water” and “Human Toxicity via Soil”. On the contrary, “Ecotoxicity in Soil” and “Human Toxicity via Air” had negligible impacts or loads in terms of milli Person Equivalents. Scenario P2 performed best of all in “Human Toxicity via Water”, whereas P4 is the best option for “Human Toxicity via Soil” and “Ecotoxicity in Water”.

As a final consideration, none of the examined scenarios emerged as the best option for all impact categories. Scenario P0 is the worst option for all impact categories, whereas P4 is the one performing best in the highest number of impact categories.

When the potential environmental impacts were divided into the different lifecycle stages of the scenarios to identify the most important of them, the main conclusions are as follows:

- for “Global Warming”, the same considerations made in Section 3.2 are valid, with plastic co-combustion in cement kiln and plastic recycling being the most relevant contribution to the savings;
- for “Acidification”, “Nutrient Enrichment”, “Photochemical Ozone Formation” and “Ecotoxicity via water”, plastic recycling is very relevant in determining the overall savings in scenarios P1–P4, more than incineration of plastic in the residual waste;
- for “Human toxicity via soil”, incineration of plastic contained in the residual waste plays a major role in determining the savings, together with plastic recycling in scenarios P1–P4;
- for “Human toxicity via water”, the largest savings were related to plastic co-combustion in cement kilns.

4. Conclusions

Management of the plastic waste fraction contained in municipal solid waste was assessed with the definition of a number of scenarios, in order to address the challenges associated with such a critical material.

In the baseline scenario (P0), plastic is treated together with the residual waste and routed to WTE and MBT. A range of potential improvements in plastic management is introduced in scenarios P1–P4. Out of the total plastic present in the gross waste, a certain amount is sent to recycling:

- P1: Source separation only of bottles at 80% efficiency, which leads to a plastic material recycling of 19%;
- P2: Source separation of all plastic (80% efficiency for bottles; 50% efficiency for the other plastic fractions), which leads to a plastic material recycling of 38%;
- P3: Plastic collection (80% efficiency for bottles; 30% efficiency for the other plastic fractions) in the "dry bin" together with metals; this leads to a plastic material recycling of 21%;
- P4: No source separation for plastic, which is mechanically sorted from residual waste prior to incineration; this leads to a plastic material recycling of 27%.

When moving from the P0 treatment strategy to the other scenarios, substantial improvements can be obtained for "Global Warming". For the other impact categories, results are strongly affected by the assumption about the marginal energy. When marginal electricity is based on coal and marginal heat on a mix of fuels, moving from the P0 treatment strategy to the other scenarios implies small improvements for "Nutrient Enrichment" and an increase of the impact in the category of "Acidification" (in terms of a lower saving and not of an actual load to the environment), whereas in the remaining impact categories the changes are relatively small. When marginal energy is based on natural gas, moving from the P0 treatment strategy to the other scenarios implies significant improvements in "Human toxicity via water" and "Ecotoxicity in water" categories and minor improvements in the other impact categories. Scenario P0 is the worst option for all the impact categories, whereas P4 is the one performing best in the highest number of impact categories.

When lifecycle stages and processes are considered, for global warming the co-combustion of the non-recyclable fraction of plastic and of the sorting residues in cement kiln gives the largest savings per tonne of plastic, followed by plastic recycling. On the contrary, incineration gave a load due to the fact that all of the CO_2 emitted from the combustion of plastic together with the residual waste is of fossil origin. For the other impact categories, results are affected by the assumption about the marginal energy. When marginal electricity is based on coal and marginal heat on a mix of fuels, the largest savings was caused by electricity substitution from incineration; plastic recycling and sorting residues co-combustion in cement kiln also play a role. When marginal energy is based on natural gas, plastic recycling is very relevant in determining the overall savings in scenarios P1–P4, more than incineration of plastic in the residual waste, for the majority of the impact categories.

As a final consideration, none of the examined scenarios emerged as the best option for all impact categories. But irrespective of the assumptions on marginal energy, scenario P4 turned out to be the best option in most impact categories thanks to the contribution of PET and HDPE recycling.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2013.12.012.

References

ADEME. La composition des déchets ménagers et assimilés en France, résultats de la campagne nationale de caractérisation – 2007 [*Composition of municipal solid waste in France, results from the national characterisation campaign 2007*]; 2009.

Al-Salem SM, Lettieri P, Baeyens J. Recycling and recovery routes of plastic solid waste (PSW): a review. Waste Management 2009;29:2625–43.

Arena U, Mastellone ML, Perugini F. Life cycle assessment of a plastic packaging recycling system. International Journal of Life Cycle Assessment 2003;8:92–8.

Arianna. Analisi ambientale della Filiera Petrino – Relazione Analisi Ciclo di Vita (Life Cycle Assessment, LCA); 2000 [in Italian] www.ariannambiente.it

Astrup T, Fruergaard T, Christensen TH. Recycling of plastics: accounting of green house gases and global warming contribution. Waste Management & Research 2009;27(8):763–72.

CITEC. Guidelines for the design, production and running of high technology plant for the disposal of urban waste. GEVA Edizioni; 2004.

Corepla-Italian consortium for plastic recycling. Personal communication from Mr. Petriglieri about plastic waste composition; 2011.

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, et al. Recent developments in life cycle assessment. Journal of Environmental Management 2009;91(1):1–21.

Franklin Associated. Life cycle inventory of 100% postconsumer HDPE and PET recycled resin from postconsumer containers and packaging. Final report prepared for The Plastics Division of the American Chemistry Council; 2010.

Frees N. Miljømæssige fordele og ulemper ved genvinding af plast [Environmental advantages and disadvantages the recycling of plastics]. Examples based on specific products. Environmental Report No. 657. Copenhagen: Danish Environmental Protection Agency; 2002.

Giugliano M, Cernuschi S, Grosso M, Rigamonti L. Material and energy recovery in integrated waste management system. An evaluation based on life cycle assessment. Waste Management 2011;31:2092–101.

IEA. International Energy Agency: electricity information. IEA Statistics; 2010.

Kirkeby JT, Hansen TL, Birgisdóttir H, Bhander GS, Hauschild MZ, Christensen TH. Environmental assessment of solid waste systems and technologies: EASEWASTE. Waste Management & Research 2006;24:3–15.

Lazarevic D, Aoustin E, Buclet N, Brandt N. Plastic waste management in the context of a European recycling society: comparing results and uncertainties in a life cycle perspective. Resources, Conservation & Recycling 2010;55(2):246–59.

Mathiesen BV, Münster M, Fruergaard T. Energy system analyses of the marginal energy technology in life cycle assessments. In: SETAC Europe 14th case studies symposium-extended abstracts. LCA of energy – energy in LCA. SETAC; 2007. p. 15–8.

Møller J, Grosso M, Rigamonti L, Martinez Sanchez V, Clavreul J, Barahona Ramirez KL, et al. SEWAS (Sustainable European Waste Systems) life cycle assessment of prospective integrated waste management schemes. In: Proceedings Venice 2012, fourth international symposium on energy from biomass and waste; 2012.

Perugini F, Mastellone ML, Arena U. A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes. Environmental Progress 2005;24(2):137–54.

Rigamonti L, Grosso M. Flaccovio D, editor. Riciclo dei rifiuti – Analisi del ciclo di vita dei materiali da imballaggio, Palermo, settembre 2009; 2009, ISBN 978-88-7758-897-5, 286 pp. [in Italian].

Rigamonti L, Grosso M, Sunseri MC. Influence of assumptions about selection and recycling efficiencies on the LCA of integrated waste management systems. International Journal of Life Cycle Assessment 2009;14(5):411–9.

Rossi G, Spreafico C, Bonvino S, Casula A, Cossu R, Simion F, et al. Residues from the mechanical sorting of source segregated plastics: management and LCA of different utilisation scenarios. In: Proceedings Venice Symposium; 2010.

Shonfield P. LCA of management options for mixed waste plastic. London: Waste Resource Action Programme (WRAP); 2008.

Stranddorf HK, Hoffmann L, Schmit A. Impact categories, normalization and weighting LCA, updated on selected EDIP 97-data. Environmental News No. 78. Copenhagen, Denmark: Danish Environmental Protection Agency, Danish Ministry of the Environment; 2005.

Torregrossa M, Lanza PA, Nicosia S, Sammartino O. Materie plastiche nei rifiuti. I fabbisogni di energia e di acqua per il recupero: caso studio. In: Proceedings Ecomondo 2005: Tecnologie innovative per l'industrializzazione del sistema ambiente, 26–29 October. Maggioli editore; 2005. p. 518–25.

Wenzel H, Hauschild M, Alting L. Environmental assessment of products. Vol. 1: Methodology, tools and case studies in product development. Hinghamm MA, USA: Kluwer Academic Publishers; 1997.