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Strategies for the enhancement of automobile shredder residues (ASRs) recycling: Results and cost assessment

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A B S T R A C T

With reference to the European regulation about the management of End-of-Life Vehicles (ELVs), Directive 2000/53/EC imposes the achievement of a recycling target of 85%, and 95% of total recovery by 2015. Over the last few years many efforts have been made to find solutions to properly manage the waste coming from ELVs with the aim of complying with the targets fixed by the Directive.

This paper focuses on the economical evaluation of a treatment process, that includes physical (size and density), magnetic and electrical separations, performed on the light fraction of the automobile shredder residue (ASR) with the aim of reducing the amount of waste to dispose of in a landfill and enhancing the recovery of valuable fractions as stated by the EU Directive. The afore mentioned process is able to enhance the recovery of ferrous and non-ferrous metals of an amount equal to about 1% b.w. (by weight) of the ELV weight, and to separate a high energetic-content product suitable for thermal valorization for an amount close to (but not higher than) 10% b.w. of the ELV weight.

The results of the economical assessment led to annual operating costs of the treatment ranging from 300,000 €/y to 350,000 €/y. Since the considered plant treats about 13,500 metric tons of ASR per year, this would correspond to an operating cost of approximately 20–25 €/t. Taking into account the amount and the selling price of the scrap iron and of the non magnetic metal recovered by the process, thus leading to a gain of about 30 €/t per ton of light ASR treated, the cost of the recovery process is balanced by the profit from the selling of the recovered metals. On the other hand, the proposed treatment is able to achieve the fulfillment of the targets stated by Directive 2000/53/EC concerning thermal valorization and reduce the amount of waste generated from ELV shredding to landfill.

1. Introduction

With reference to the European regulation concerning the management of End-of-Life Vehicles (ELVs), in 2000 the EU enforced the ELV Directive (2000/53/EC) with the purpose of reducing wastes generated by ELVs and enhancing their collection and recycling. Directive 2000/53/EC imposed the achievement of a recycling target of 85% and a total recovery of 95% by 2015. By that time only 5% of a vehicle will be admitted into a landfill and no more than 10% will undergo thermal recovery.

In order to improve the environmental sustainability of the overall automotive productive process and meet the targets stated by the EU Directive, over the last few years a lot of efforts have been made to find solutions to properly manage the waste coming from ELVs. In particular the actions undertaken included the improvement in the logistics for the ELV's collection and dismantling (Mahmoudzadeh et al., 2013), mainly in emerging countries, the design for recycling (i.e. the disassemblability of the automotive components) (Galvagno et al., 2001; Go et al., 2011), the complete depollution prior to shredding (i.e. the removal of the engines and of a increased number of plastic parts) (Ferrão and Amaral, 2006; Forton et al., 2006; Schmid et al., 2013) and the pretreatments devoted to rise the amount of an ELV suitable for material or energy recovery (Granata et al., 2011; Santini et al., 2012; Viganò et al., 2010).

This waste, named automobile shredder residue (ASR) or car fluff, is generated from ELVs after shredding and sorting valuable ferrous and non ferrous metals and it counts for about 20–25% b.w. (by weight) of a vehicle's total weight (Fiore et al., 2012). ASR represents up to 10% b.w. of the whole amount of hazardous wastes produced per year in the EU and about 60% b.w. of the EU's total shredding wastes (Rossetti et al., 2006).

The composition of the ASR was reported by several authors (Fiore et al., 2012; Morselli et al., 2010; Santini et al., 2011; Zorpas and Inglezakis, 2012) as a mixture of plastic, rubber, light and heavy fiber materials in varying proportions and an abundant fraction (40–50% b.w.) which includes fine particles (<10 mm) that are usually very rich in metals. The exact composition and the

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characteristics of the ASR waste depend on the quality of the feed (combination of ELVs, white goods and ferrous waste), the grade of de-pollution operated in the shredding plant, the specific shredder equipment employed and the post shredder separation processes operated.

Due to the high complexity of the waste, the development of technologies for the enhancement of the recycling of ASRs is quite complicated. In addition, there are some factors preventing the total recovery of ASRs that include its physical nature, frequent contamination, poor development of secondary markets and substantial processing costs (Simic and Dimitrijevic, 2012; Simic and Dimitrijevic, 2013).

According to Nourredine (2007), the conventional route for the recovery and recycling of an ELV is made up of standard practices aimed at metal recycling. The process includes the phases of de-pollution (e.g. removal of tires, batteries, lubricants and fuel), shredding and sorting ferrous and non ferrous metals, by using magnetic and electrostatic separation, to be recycled in foundry plants. Such a process proved capable of achieving a recovery rate (RR, as defined in ISO 22628) equal to 75.9% b.w. of an ELV (Fiore et al., 2012). This value may rise to 78.6% b.w. if the phase of de-pollution, other than tires, batteries, lubricants and fuel, includes the removal of bumpers, fuel tanks and alloy wheels (Fiore et al., 2012).

So, in order to further improve the RR value, in the same work (Fiore et al., 2012) several post-shredding processes were tested by the authors at lab scale. The focus of those tests was only on the ASR light fraction because, according to the usual ASR classification (Fiore et al., 2012; Vermeulen et al., 2011), ASR consists of three parts: light ASR, heavy ASR and soil/sand, the first of which is the most abundant, accounting for about 90% b.w. of the total ASR produced in a shredding plant (Fiore et al., 2012). The lab-scale post-shredding tests were carried out on the light ASR deriving from ELVs only, without white goods or light collection items, which are usually shredded together with ELVs but whose amount is very variable and difficult to quantify.

The post-shredding processes tested in Fiore et al. (2012) had the aim of reducing the amount of waste to be disposed of in landfill and trying to meet the goals stated by Directive 2000/53/EC. Among the processes tested at lab scale, the authors demonstrated that the treatment, named T2 and recalled in the following sections, based on the physical (size and density), magnetic and electrical properties of the ASR waste, was able to recover fractions suitable for both material and energy recovery, thus contributing to fulfilling the targets stated by Directive 2000/53/EC, concerning the share of an ELV that can undergo thermal valorization, and appreciably reducing the amount to be disposed of in landfill.

In this paper, after having recalled and described the results obtained in the T2 post-shredding treatment with more detail than in the previous paper, the hypothesis of transposing those lab-scale outcomes to a full scale treatment was made. The main objective of this paper is then to perform a rigorous and complete economical assessment of an hypothetical industrial recovery process of light ASR, obtained by transferring the results gathered at lab-scale to full-scale, by taking into account, on the one hand, the costs connected to the operations that make up the process and, on the other hand, the trade of ferrous and non-ferrous metals recovered from the treatment and the saving due to the reduction in the ASR amount destined for disposal.

2. Materials and methods

2.1. Light ASR origin and characterization

In order to carry out a complete economic assessment of an industrial post shredding treatment which performs the same unit operations of the T2 process tested at lab-scale (Fiore et al., 2012), it was hypothesized that such a process treats an ASR amount equal to that generated by an Italian medium-size shredding plant (ELV shredding capacity: 50,000–80,000 t/y), like those described in Fiore et al. (2012). In particular, the economic assessment presented in this paper was carried out on a hypothetical post-shredding process capable to treat about 13,500 t/y of light ASR. This is the amount of light ASR generated by an ELV shredding plant with a capacity of 65,000 t/y.

The full-scale process will treat a light ASR material having similar characteristics in term of particle size distribution and product composition of that employed in the lab-scale post shredding tests. The ASR undergone the lab scale tests described in Fiore et al. (2012) was generated and collected in a shredding plant that is composed of a grinding phase, handled by a hammer mill, coupled with an air separator which separated the light fraction of ASR coming from the shredding of the hulks. Magnetic and dimensional separators follow the grinding phase. The dimensional separator generates three fractions with dimensions of <10 mm, 10–50 mm and >50 mm, respectively. The 10–50 mm fraction undergoes subsequent electrostatic and densimentric (at 2 and 3 kg/dm^3 density values) separation.

As already described in Fiore et al. (2012), the light ASR, undergone the post-shredding tests at lab-scale, was collected according to a standardized procedure (Italian norm UNI 10802:2004) in a 20-kg sample following sequential quartering operations of the heap generated during the performance of an industrial shredding test. The test involved about 300 t of ELVs, less than 10 years old, that came from an enhanced phase of de-pollution with the removal of bumpers, fuel tanks and alloy wheels.

The characterization of the sample included the product composition, manually performed, the elemental analysis, the content of metals, the heating value and the leaching behavior.

The elemental analysis (C, H, N, S) was carried out using a CHNS Flash 2000 ThermoFisher Scientific analyzer. The content of metals was determined on samples ground to sizes of less than 4 mm, that underwent an acid digestion in microwave oven (Milestone 1200 Mega) in the presence of sulfuric acid (97%) and nitric acid (65%), using a Perkin Elmer Optima 2000 spectrometer (ICP-OES). The leaching behavior was assessed by submitting the samples to elution test UNI 10802:2004 (that acknowledges EN 12457/2). Metals, Dissolved Organic Carbon (DOC), Chemical Oxygen Demand (COD), chloride, sulfate, nitrate and fluoride in the eluate were determined in accordance to reference methods (APHA, AWWA, WEF, 2005). The heating values (HHV, higher heating value and LHV, lower heating value) were determined by the combustion of 1 g of sample, ground to <4 mm sizes, in a Mahler calorimeter according to UNI 9903-5:2004 rule for HHV, and from a mass balance on the hydrogen content, for LHV (Ruffino et al., 2010).

2.2. Treatment process description and cost evaluation

According to the results of the lab-scale tests presented in Fiore et al. (2012) and here resumed (see Section 3), a treatment process able to recover both material and energy from the light fraction of ASR should include the four unit-operations of 4-mm sieving (A), magnetic separation (B), electrostatic separation (C) and a two-phase (2 kg/dm^3 and 1 kg/dm^3 density values) densimetric separation (D), as shown in Fig. 1. At a lab scale, the phases of sieving, magnetic separation and densimetric separation at 1 kg/dm^3 density value were carried out on the 20-kg light ASR sample collected and characterized as described in Section 2.1. The outcomes of the phases of electrostatic separation and densimetric separation at 2 kg/dm^3 density value were hypothesized on the basis of the characteristics of the materials in terms of sizes and product composition.

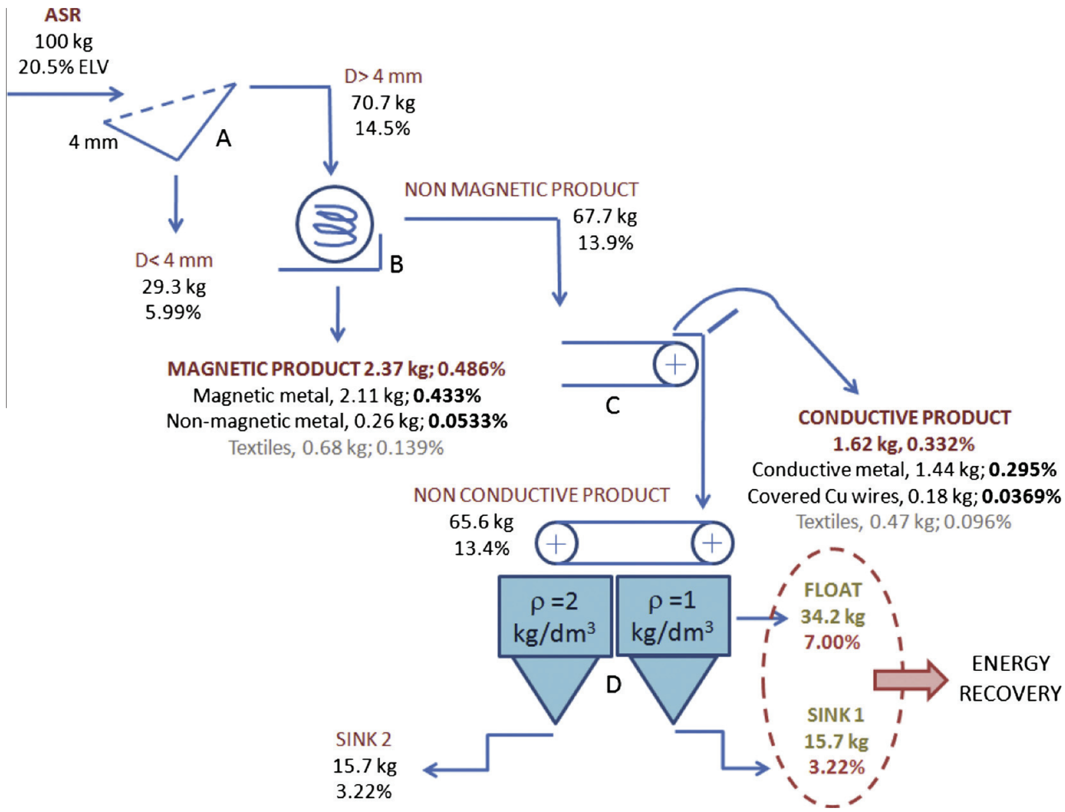

Fig. 1. Flow sheet of the hypothetical industrial recovery treatment (adapted from Fiore et al. (2012)).

Moving from the lab-scale to the hypothetical full-scale process, the cost evaluation of the recovery treatment, including the afore-mentioned unit-operations, was performed by referring to a procedure used in previous works (Ruffino and Zanetti, 2007; Ruffino and Zanetti, 2008; Ruffino et al., 2009, 2011) and here described in detail (see also Fig. 2). This procedure returned the unit cost of the ASR which had undergone the treatment as the ratio of the annual operating costs of the plant, where the treatment is carried out, and the amount of the processed ASR. In turn, the plant annual operating costs were assessed as the sum of four cost items: investment, utilities (i.e. the energy and the raw materials employed for the plant operation), maintenance and labor.

For the evaluation of the afore mentioned cost items some hypotheses concerning the plant working time were made. In particular it was assumed that the plant worked 220 days per year and on one shift (8 h per day).

The annual installment of the investment (R) was calculated with reference to the initial total fixed cost (TFC) according to the French amortization system, the most diffused amortization method at fixed rates. It is also known as "progressive amortization system" because the principal repayments increase in geometric progression with ratio $i+1$ (Janssen et al., 2013). The calculation of the annual installment was performed by hypothesizing an interest rate (i) of 6% and a useful life (n) of 5 years:

$$R = TFC\frac{i}{1-(1+i)^{-n}}$$

The TFC is the sum of the direct costs (TPDC, total plant direct costs, so purchase costs of the machines, instrumentation and electrical facilities and installation costs) and indirect costs (TPIC, total plant indirect costs, so design engineering and construction).

With reference to the TPDC, the purchase costs of the machines installed in the plant were evaluated by means of the JavaScript Equipment Cost Estimating Aid software. In order to calculate the purchase cost of the machines, the afore mentioned software employs the scale-factor method described in Turton et al. (2008). The scale factor method relates the ratio between the cost of the considered machine or piece of equipment (C) and the cost of a similar reference machine (C_0), with the ratio of a characteristic parameter (F) of both as in the following equation:

$$\frac{C}{C_0} = \left(\frac{F}{F_0}\right)^n$$

TPDC items were estimated, with the exception of the costs of the machines, which were evaluated as previously described, by multiplying the total purchase cost (PC) of the machines by the coefficients suggested by Turton et al. (2008) and listed in Table 4. TPIC was then derived from TPDC by multiplying it by 0.10 for design engineering and by 0.20 for construction.

Utility costs were calculated as the sum of the costs of the electric energy employed for the sieve, the magnetic, electrostatic and densimetric separators (equal to 0.1 €/kW h, Eurostat, 2012) and for non-listed pieces of equipment (fixed equal to 20% of the afore-mentioned electric costs).

Maintenance costs were estimated as 10% of the equipment purchase cost (Turton et al., 2008).

Labor costs were fixed at 36000 €/year, a real value referred to Italian workers employed in factories, assuming one operator dedicated to the ASR recovery process.

3. Results and discussion

3.1. Treatment test performances

In this paragraph the characterization of the light ASR waste subjected to the post-shredding recovery treatment, the efficiency

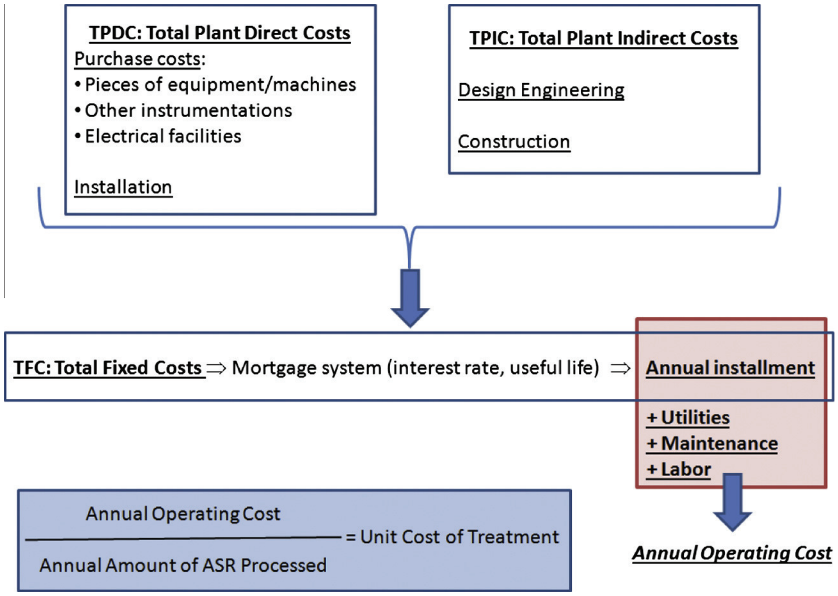

Fig. 2. Procedure for cost evaluation.

obtained in each step (simulated at lab-scale) and the materials resulting from each separation process are recalled to better understand the performances of the hypothetical post-shredding industrial recovery process.

As shown in Fig. 3, the results of the product composition analysis carried out on the light ASR sample revealed a relevant fraction (about 30% b.w.) with sizes lower than 4 mm, 20% b.w. of plastic, 13% b.w. of a miscellaneous material with sizes from 4 to 10 mm, and percentages variable from 6% to 8% b.w. of rubber, textiles and metal. More precisely, the material named "metal" is composed of 33.7% b.w. of magnetic metal, 6.6% b.w. of non-magnetic metal having the appearance of aluminum, 17.9% b.w. of uncoated copper wires and 41.8% b.w. of rubber-covered copper wires (respectively, 2.34%, 0.46%, 1.24% and 2.91% b.w. of the light ASR fraction that underwent the characterization process).

The results of the elemental analysis, and of the determination of the metal content, heating value and capacity to release chemicals in water according to the UNI 10802:2004 elution test are shown in Table 1. Among the results listed in Table 1, the two values of LHV and DOC deserve to be discussed in detail. In fact,

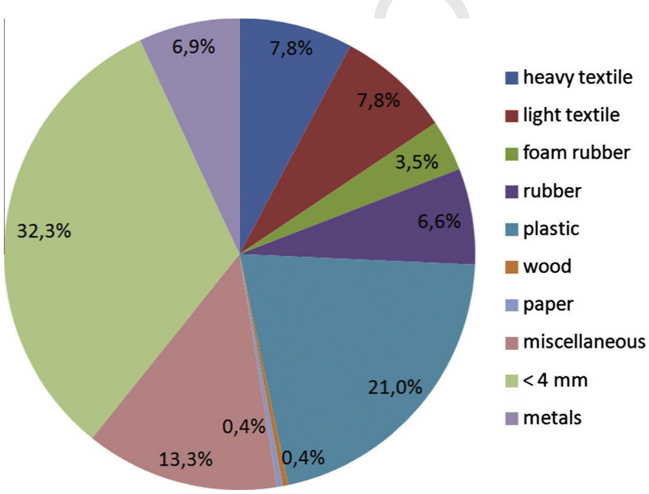

Fig. 3. Results of the product composition analysis of the light ASR.

according to the Italian regulation DLgs 36/2003, which acknowledges European Directive 1999/31/EC, wastes having an LHV higher than 13,000 kJ/kg must not be disposed of in any category of landfill. After the reduction of waste LVH below 13,000 kJ/kg, ASR fractions not otherwise valorizable and not exceeding the amounts fixed by Directive 2000/53/EC, may be disposed of either in non-hazardous waste landfills or in hazardous waste landfills according to the characteristics of the leachate given by the UNI 10802:2004 procedure. In this case DOC is the critical parameter. So, both in order to comply with Directive 2000/53/EC, and for the above mentioned reasons, it is necessary to find alternative management solutions to landfilling.

According to Fiore et al. (2012), due to the physical (size and density), magnetic and electrical properties of the light ASR fraction, the treatment process capable at recovering materials to be valorized as both secondary raw materials and combustible should include the four unit-operations of 4-mm sieving (A), magnetic separation (B), electrostatic separation (C) and a two-phase (2 kg/dm^3 and 1 kg/dm^3 density values) densimetric separation (D), as shown in Fig. 1.

The experimental tests demonstrated that the sieving phase (A) was able to separate the fraction with sizes of less than 4 mm with an efficiency of 90.6% (Ruffino et al., 2010). Making the hypothesis that the efficiency value obtained at lab scale may be transferred at the real scale, the consequence is that 29.3% of the light ASR (this values may be obtained by multiplying the amount of light ASR with sizes <4 mm, 32.3% b.w., by the efficiency of the sieving phase, about 90%), or about 6% of the weight of a whole ELV, is separated by the sieve as <4 mm fraction. As well as eliminating the fraction with very fine sizes that could disturb the subsequent phases of the treatment, the sieving phase also contributed to opening the fluff heaps, improving the efficiency of the following magnetic and electrostatic separations.

The chemical composition and the leaching capacity of the fraction that passed through the sieve (*D* <4 mm) are reported in Table 2. It had, on the whole, a content of metals (see for example aluminum, 2.48% b.w., copper, 1.42% b.w., iron, 4.27% b.w. and zinc, 0.66% b.w.) higher than that of the original sample, thus demonstrating that metals tended to concentrate in the finest fraction (Gonzalez-Fernandez et al., 2008). The *D* <4 mm fraction showed a low LHV, equal to 6800 kJ/kg, due to its low carbon content

Table 1
Characterization and leaching capacity of the light ASR. Comparison with the Italian threshold values for landfilling.

Undisturbed sample characterization		Eluate (UNI 10802) characterization		Threshold values for the admission in a landfill (DM 27/09/2010)		
				Inert	Non hazardous	Hazardous
Al (%)	0.763	NO_3^- (mg/l)	12.9	–	–	–
As (mg/kg)	3.44	F^- (mg/l)	<0.1	1	15	50
Ba (mg/kg)	36.6	$SO_4^=$ (mg/l)	97.8	100	5000	5000
Cd (mg/kg)	15.2	Cl^- (mg/l)	21.9	80	2500	2500
Co (mg/kg)	13.6	Ba (μg/l)	78.6	2000	10,000	30,000
Cr (mg/kg)	226	Cu (μg/l)	210	200	5000	10,000
Cu (%)	3.35	Zn (μg/l)	1820	400	5000	20,000
Fe (%)	3.26	Co (μg/l)	3.76	–	–	–
Mn (mg/kg)	311	Ni (μg/l)	37.0	40	1000	4000
Ni (mg/kg)	111	As (μg/l)	<5.3	50	200	2500
Pb (mg/kg)	410	Cd (μg/l)	6.20	4	100	500
Zn (%)	0.314	Cr tot. (μg/l)	7.01	50	1000	7000
N (%)	1.68	Pb (μg/l)	175	50	1000	5000
C (%)	46.0	Al (μg/l)	46.7	–	–	–
H (%)	5.89	Fe (μg/l)	83.3	–	–	–
S (%)	0.386	Mn (μg/l)	152	–	–	–
HHV (kJ/kg)	18,300	pH	6.67	–	–	–
LHV (kJ/kg)	17,000	DOC (mg/l)	282	50	100	100

(16% b.w.). The concentrations in the eluate of some heavy metals (copper, nickel, cadmium and lead) and COD prevented this fraction from being employed in reuse activities, according to DM 5/02/1998 (the Italian law concerning the reuse of non hazardous wastes). Due to its characteristics, the fate of the <4 mm fraction can only be the disposal in landfills for non hazardous wastes derogating from the DOC content.

The fraction held back by the sieve ($D > 4$ mm) underwent first magnetic and then electrostatic separation.

The magnetic separation, that, according to the results obtained in lab-tests, could have an efficiency equal to 89.9%, was able to separate a product (named "magnetic product") which accounted for 2.37% b.w. of the light ASR sample (see Fig. 1), and 3.35% b.w. of the fraction undergone the magnetic separation. This last value was obtained by diving the amount of magnetic product recovered (2.37 kg over 100 kg of light ASR) by the amount (70.7 kg) subjected to magnetic separation.

According to the outcomes of the product composition analysis performed on the magnetic product separated in the lab-scale magnetic separation test, the magnetic product recovered by the full-scale process would be made up of 69.2% b.w ferromagnetic metal, 8.52% b.w. non ferromagnetic metal and the remaining 22.3% b.w. of light textile rolled up on the metallic scraps. As shown in Fig. 1, the clean ferromagnetic metal recovered in the magnetic stage accounted for 2.11% b.w. of the light ASR sample and for 0.433% b.w. of the weight of a whole ELV.

It was then hypothesized that the non magnetic product (67.7% b.w. of the original light ASR sample, see Fig. 1) underwent an electrostatic separation process. As shown in Fig. 1, the product recovered by the electrostatic separation (named "conductive product") was 1.62% b.w. of the light ASR sample and 2.39% b.w. of the fraction undergone the electrostatic separation. This last value was obtained by diving the amount of conductive product recovered (1.62 kg over 100 kg of light ASR) by the amount (67.7 kg) subjected to the electrostatic separation.

According to the outcomes of the product composition analysis performed on the product recovered in the lab-scale test, the conductive product was made up of the effective products of the electrostatic separation (non-magnetic metal like aluminum and uncovered copper wires) as well as foreign bodies like rubber-cov-

Table 2
Characterization and leaching capacity of the < 4 mm fraction. Comparison with the Italian threshold values for landfilling.

Undisturbed sample characterization		Eluate (UNI 10802) characterization		Reuse threshold values DM 5/2/98	Threshold values for the admission in a landfill – DM 27/09/2010		
					Inert	Non hazardous	Hazardous
Al (%)	2.48	NO_{3-} (mg/l)	13.6	50	–	–	–
As (mg/kg)	14.6	F^- (mg/l)	<0.1	1.5	1	15	50
Ba (mg/kg)	34.5	$SO4^=$ (mg/l)	93.5	250	100	5000	5000
Cd (mg/kg)	25.4	Cl^- (mg/l)	21.3	100	80	2500	2500
Co (mg/kg)	21.9	Ba (μg/l)	100	1000	2000	10,000	30,000
Cr (mg/kg)	169	Cu (μg/l)	340	50	200	5000	10,000
Cu (%)	1.42	Zn (μg/l)	1504	3000	400	5000	20,000
Fe (%)	4.27	Co (μg/l)	4.25	250	–	–	–
Mn (mg/kg)	547	Ni (μg/l)	50.8	10	40	1000	4000
Ni (mg/kg)	197	As (μg/l)	<5.3	50	50	200	2500
Pb (mg/kg)	504	Cd (μg/l)	6.46	5	4	100	500
Zn (%)	0.661	Cr tot. (μg/l)	3.21	50	50	1000	7000
N (%)	0.468	Pb (μg/l)	279	50	50	1000	5000
C (%)	16.3	Al (μg/l)	52.7		–	–	–
H (%)	1.80	Fe (μg/l)	273		–	–	–
S (%)	0.404	Mn (μg/l)	214		–	–	–
HHV (kJ/kg)	7200	pH	7.75	5.5–12	–	–	–
LHV (kJ/kg)	6800	DOC (mg/l)	209		50	100	100
		COD (mg/l)	410	30			

ered copper wires and light textile. The clean non-ferromagnetic metal recovered by the electrostatic separation accounted for 1.44% b.w. of the light ASR sample and 0.295% of the weight of a whole ELV. Unfortunately, the electrostatic separation process should show very scarce effect on the rubber-covered copper wires that remained in the waste product generated by the three in-series processes of sieving, magnetic and electrostatic separation. It was verified that the process of electrostatic separation determined the recovery of only 0.18 kg (see Fig. 1) of rubber-covered wires over 2.91 kg present in 100 kg of light ASR.

The results of the densimetric separation at 1 and 2 kg/dm^3 density values, performed at lab scale, are shown in Figs. 4 and 5. The material subjected to densimetric separation was split into the three classes (<1 kg/dm^3; 1–2 kg/dm^3; and >2 kg/dm^3) according to a b.w. ratio of about 2:1:1.

As shown in Fig. 5, almost the total amount of the textiles (light and heavy), foam rubber, wood and paper passed into the light product (<1 kg/dm^3), whereas plastic was divided between the two classes <1 kg/dm^3 and 1–2 kg/dm^3 according to a b.w. ratio equal to about 1:1. The fraction having sizes lower than 4 mm (this is the fraction that was not removed by sieving and on which neither magnetic separation nor electrostatic separation had effect) was divided into the two classes <1 kg/dm^3 and 1–2 kg/dm^3 approximately according to the same ratio. Metals, miscellaneous material (4–10 mm) and rubber were mainly found in the >2 kg/dm^3 class. With reference to rubber, many rubber parts or components employed in the manufacture of a vehicle are made of steel-reinforced rubber, that is the reason why rubber was found in the >2 kg/dm^3 density class.

To sum up, the treatment process described in Fig. 1, yet the performance of which were only evaluated at lab-scale, is able:

- to reduce the amount of waste to be disposed of in a landfill from 20.5% b.w. to about 6% b.w. of an ELV weight, under the hypothesis that, with reference to Fig. 1, the only fraction to send to landfill is that with particle size <4 mm;
- to separate a product, with density <2 kg/dm^3, whose amount is slightly lower than 10% of an ELV weight, as stated by the EU Directive, with high calorific content (LHV about 25,000 kJ/kg) and purity (containing about 85% b.w. of combustible materials) that can be sent to thermo-valorization processes;

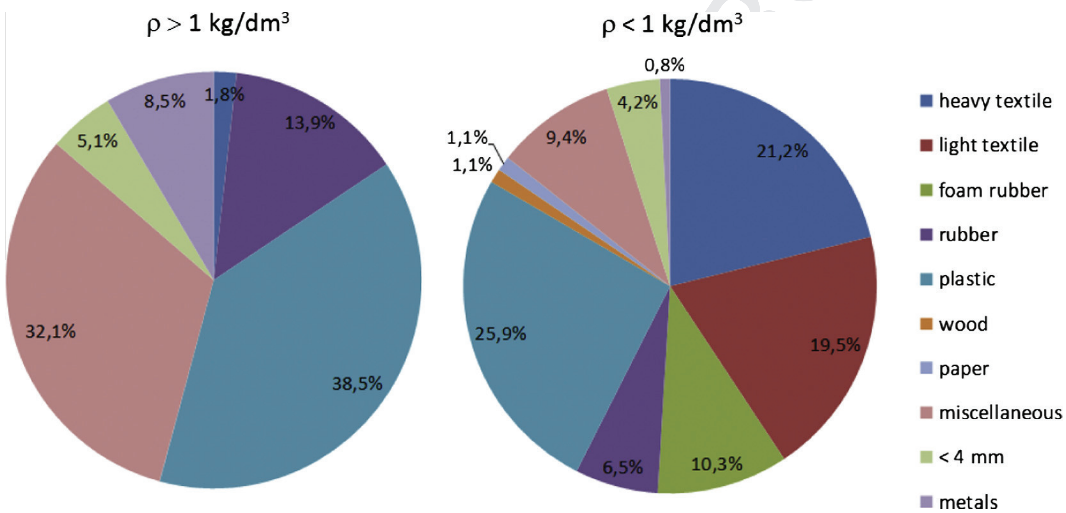

Fig. 4. Results of the product composition analysis of the two fractions coming from the densimetric separation at 1 kg/dm^3.

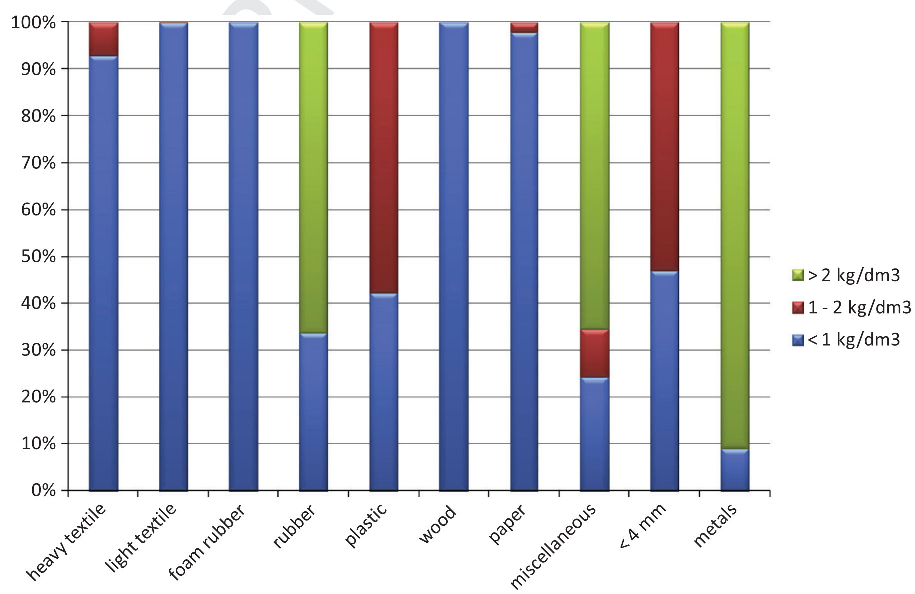

Fig. 5. Partition of each product among the three densimetric classes (<1 kg/dm^3; 1–2 kg/dm^3; and >2 kg/dm^3).

Table 3
Characteristics and costs of the machines composing the plant.

Type	Mass flow rate (t/h)	Characteristic dimension	Material	Electric consumption (kW)	Price (€)
Sieve (1-deck large)	9.2	$A = 6\ m^2$	Carbon steel	30	29,300
Magnetic separator conveyor	2–5	$W/D = 40$ $L = 8.5$ m	Carbon steel	10	51,500
Electrostatic separator conveyor	2–5	$W/D = 40$ $L = 8.5$ m	Carbon steel	10	51,500
Densimetric separator screw classifier	5	$D = 1.4$ m	Carbon steel	2 × 2.25	73,400
Other pieces of equipment					205,700

A, surface; W, width; D, diameter; and, L, length.

Table 4
Total fixed costs (detail).

TPDC		
Purchase cost of the listed machines (LMPC)		205,700 €
Non-listed equipment purchase costs	1.00 × LMPC	205,700 €
Total PC		411,400 €
Installation	0.40 × C	164,540 €
Instrumentation	0.10 × PC	41,140 €
Electrical facilities	0.25 × C	102,850 €
Total TPDC		719,950 €
TPIC		
Engineering	0.10 × TPDC	71,995 €
Construction	0.20 × TPDC	143,990 €
Total TPIC		215,985 €
TPDC + TPIC = TFC		935,935 €
Annual installment (R) ($i = 6\%, n = 5$)		222,190 €

– to enhance the metal separation, already performed on the shredded hulks in other section of the shredding plant, by sorting about 21 kg of scrap iron, per ton of treated ASR, and 19 kg of a mixture of copper, brass, aluminum and magnesium, per ton of treated ASR.

3.2. Cost evaluation of the full-scale recovery plant

With reference to the economical assessment of a hypothetical industrial recovery process of light ASR, obtained by transferring the results gathered at lab-scale to full-scale, the characteristics and costs of the machines in the full-scale plant are shown in Table 3.

Referring to the pieces of equipment, the sieve dimensions were established by dividing the mass flow rate (9.2 t/h, obtained considering the annual capacity of the plant, 13,500 t, and the working time, 1760 h, by increasing the mass flow rate per hour by 20%) by a coefficient Q defined as:

$$Q = Q_0 \cdot d^{0.7}$$

where Q_0 is equal to 1 t/(h m^2 mm) for 1-deck vibrating sieves.

Magnetic, electrostatic and densimetric separators were sized by taking into account the amount and the dimensional characteristics of the processed mass flow.

The cost of the item "other pieces of equipment" was assumed to be equal to the total cost of the machines processing the four unit-operations (see Table 4). TPDC (with the exception of the machine costs) and TPIC items were calculated using the coefficients listed in Table 4. Their end-values were respectively equal to 719,950 € and 215,985 €. From the sum of these values, equal to 935,935 €, the annual installment of the investment was calculated to be equal to about 222,200 €.

As mentioned in Section 2.2, the utility costs were calculated as the sum of the costs of the electric energy employed by each piece of equipment (sieve, magnetic, electrostatic and densimetric sorters), under the hypothesis that each machine works 8 h per day, 220 days per year. The price of the electric energy was set at 0.1 €/kW h (Eurostat, 2012). The energy cost of non-listed pieces

Table 5
Summary of the costs per year of the recovery plant.

Depreciation (annual installment)	222,200 €
Labor	36,000 €
Maintenance	41,100 €
Utilities	14,400 €
Total	313,700 €

of equipment was fixed as being equal to 50% of the utility costs of the listed machines (Turton et al., 2008).

The maintenance costs were estimated at 10% of the equipment purchase cost and then equal to 41,140 €. Labor cost was fixed at 36,000 €/year, assuming one operator dedicated to the ASR recovery plant. The summary of the cost items per year of the recovery plant is listed in Table 3.

As a consequence of both the calculations summarized above and the hypotheses made, the annual operating costs of the plant were estimated at a value ranging from 300,000 €/y to 350,000 €/y. Since the plant was to treat about 13,500 tons of ASR per year, this corresponds to a processing cost of approximately 20–25 €/t.

Under the hypothesis that the price of the recovered scrap iron (about 21 kg per ton of treated ASR) could be 150 €/t and the price of the recovered non magnetic metal (as a mixture of copper, brass, aluminum and magnesium, about 19 kg per ton of treated ASR) is equal to about 1200–1500 €/t (Simic and Dimitrijevic, 2012), thus leading to a gain of about 30 €/t per ton of ASR treated, it is possible to conclude that the cost of the recovery process (20–25 €/t) can be balanced by the profit from the selling of the recovered metals. Because of the small difference (from 5 to 10 €/t of ASR treated) between the gain deriving from the selling of the recovered metals and the unit cost of the recovery process, other tests, at an intermediate scale between lab and full, should be performed in order to evaluate the real quality of the recovered products. In fact it has to be taken into account that the quality of the products deriving from the industrial process could not satisfy market standards, thus lowering their full price as well as the profit from selling.

Moreover, a potential weakness of the method for the economical assessment of the post shredding recovery process lies in the employment of several coefficients, gathered from literature, for the estimation of the costs of pieces of equipment and, above all, for the estimation of plant direct and indirect cost items (as listed in Table 4).

In the end, it has to be considered that the economical balance did not consider the reduction, from 20.5% b.w. to about 6% b.w. of an ELV weight, in the amount of the waste to be disposed of in a landfill. With reference to a metric ton of light ASR, with a landfill cost of approximately 150 €, the treatment of the waste performed in the plant shown in Fig. 1 would allow a money saving of about 100 €/t ASR (Table 5). Q2

4. Conclusions

In this paper, after having recalled and detailed the results obtained at lab-scale in the T2 post-shredding treatment, a

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performance and economic evaluation of an industrial treatment carried out on the light fraction of the ASR was made. The proposed recovery process, translated at the full-scale, had the aim of reducing the amount of waste to dispose of in a landfill and contributing to meeting the goals stated by Directive 2000/53/EC that forces the achievement of a recycling target of 85%, and 95% of total recovery, by 2015. According to the EU Directive, in fact, by that time only 5% of a vehicle will be admitted into a landfill and no more than 10% will undergo thermal recovery.

This treatment process, that includes four unit-operations based on the physical (size and density), magnetic and electrical properties of the ASR waste, is able:

- to enhance the recovery of metals of an amount approaching 1% b.w. of the ELV weight; this amount is the sum of the magnetic metal (and incidental non magnetic metal) recovered by the magnetic separation device (about 0.49% b.w. of an ELV) and of the conductive product recovered by the electrostatic separator (about 0.33% b.w. of an ELV);
- to separate a high energetic-content product, suitable for thermal valorization, for an amount close to (but not higher than) 10% of the ELV weight, as stated by the EU Directive, and
- to reduce the amount of waste from the ELV shredding to dispose of in landfill by about 2/3.

The results of the economical assessment performed on the recovery plant led to annual operating costs of the treatment ranging from 300,000 €/y to 350,000 €/y with a subsequent cost of approximately 20–25 €/t per ton of ASR processed.

Considering the amount and the selling price of the scrap iron and non magnetic metal recovered, thus leading to a gain of about 30 €/t per ton of ASR treated, it is possible to conclude that the cost of the recovery process is balanced by the profit from the selling of the recovered metals. On the other hand, the proposed treatment is able to reduce the amount of waste to dispose of in a landfill by 2/3 with a subsequent money saving of about 100 €/t ASR, and to contribute of achieving the fulfillment of the targets stated by Directive 2000/53/EC concerning the amount of an ELV that can undergo thermal valorization.

5. Uncited reference

Q3 Anon. (2013).

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