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ORIGINAL PAPER

A Circular Approach for Recovery and Recycling of Automobile Shredder Residues (ASRs): Material and Thermal Valorization

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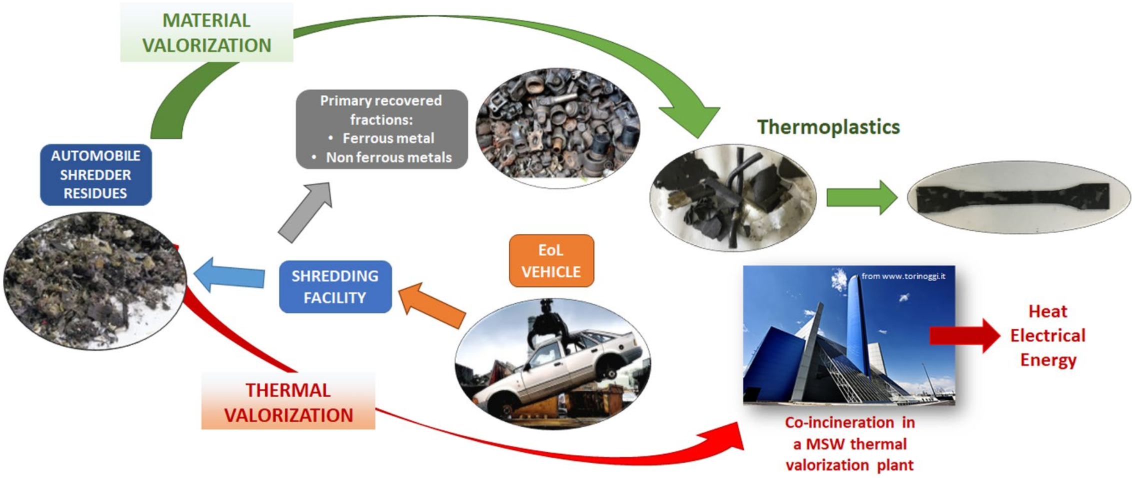
Abstract

The transition of the automotive industry towards a circular economy requires viable solutions for end-of-life vehicle (ELV) reuse, recycling and recovery. This study tested the feasibility of two recycling processes intended, the first, to produce recycled plastic composite goods from selected plastic fractions extracted from ASRs, through a conventional mechanical process; the second, to use the remaining ASRs as a solid recovered fuel (SRF) to saturate the residual treatment capacity of the local (Turin, NW Italy) municipal solid waste (MSW) incineration plant. Samples of light (CER code 191004) and heavy (CER code 191204) ASRs were collected from an ELV authorized treatment facility, subjected to a complete characterization and tested for the two recycling options. The results demonstrated that selected fractions of thermoplastic polymers could be employed in a molding process for the production of recycled plastic composite goods. This fraction, equal to 2660 t/a, was more than 2% b.w. of the original ELV and 7.6% of the whole ASR waste product. The remaining ASR, after plastic extraction and recycling, had lower heating values (LHVs, 24 or 31 MJ/kg, depending on the original product) and chlorine content (< 50 mg/kg) that made it suitable to assume the status of SRF. In the present operating conditions, the Turin MSW incineration plant has a residual treatment capacity of at least 45,000 t/y, for waste with a LHV of 30 MJ/kg, that is approximately 30% more than the annual amount of ASRs produced in the Turin area. The application of mass and energy balances to the thermal process demonstrated that the addition of ASRs as an extra fuel to the incineration plant did not worse the quality of flue gases in terms of acid compound (HCl, SO_2) concentration and allowed the annual net electrical energy production to be increased from 31 to 38 MW.

Graphic Abstract



Keywords End-of-life vehicles · Plastic scraps · Circular economy · Solid recovered fuel · Co-incineration

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Statement of Novelty

The circularity of the management of ELVs can be increased only if processes for ASRs valorization are implemented in the same geographical area where the waste is generated, without perturbing the regular operating conditions of the plants that will receive the ASRs. If the characteristics of the ASRs comply with the parameters for the cessation of the waste status of certain types of solid recovered fuels (SRFs), ASRs can be considered no longer as a waste and its use as a substitute fuel contributes to reach the target of 85% reuse and recycling. The application of mass and energy balances to the thermal process carried out in the Turin waste thermal valorization plant demonstrated that the addition of ASRs to the MSW did not adversely affect the quality of the flue gases and allowed the annual net electrical energy production to be increased by 23%.

Introduction

From the early 2000s the final phase of the lifecycle of a vehicle has been ruled by Directive 2000/53/EC. After the publication and enter-into-force of that Directive, the industrial sector devoted to the management of end-of-life vehicles (ELVs) has changed significantly, evolving from the old scrapyards to the authorized treatment facilities (ATFs) [1, 2]. This Directive had fixed clear objectives of reuse, recycling and recovery of ELVs, with the aim of reducing negative impacts to the environment. Specifically, starting from January 1st 2015, the reuse and recovery of ELVs had to be increased to a minimum of 95% of the vehicle weight. Within the same time limit, the re-use and recycling had to be increased to a minimum of 85% of the vehicle weight, thus meaning that only 10% of the ELV mass could be thermally treated for energy recovery and 5% could be finally disposed in an authorized landfill. During the last few years, huge efforts have been made to achieve the goals stated by the EC Directive on ELVs. It has been demonstrated that breakthrough treatment technologies could increase the recovery rates of materials and improve the environmental benefits gained from recycling ELVs [3–5].

Recently (June 2018), the European Union released the European Circular Economy Package (CEP), the intent of which was to ensure the European Union's transition to a circular economy. As opposed to the typical linear economy, in which resources are created, used, and disposed, a circular economy is one in which resources are used for as long and as productively as possible and, at the end of their useful life, their products and materials are recovered and regenerated. Among others, the European CEP includes Directive 2018/849 of May 30, 2018 amending the Directives that regulated waste electrical and electronic equipment (2012/19/EU), new and spent batteries and accumulators (2006/66/EC) and ELVs (2000/53/EC). Specifically, for what concerns ELVs, the amendment Directive requires Member States to take the necessary measures to ensure that all ELVs are stored (even temporarily) and treated in accordance with the waste hierarchy. However, the amending Directive did not change the targets for reuse, recycling and recovery of ELVs and their components originally stated by Directive 2000/53/EC.

The compliance to a circular approach requires that the value embedded in ELVs' components and materials is recaptured through reuse, recycling and recovery, in this order. Specifically, reuse and remanufacture of parts must be preferred to the recycling of materials in "close" or "open" loop processes. Recycling must be placed before energy valorization through chemical or thermal processes and only very useless residues can be left for landfill disposal [6]. The results of the latest studies concerning ELV management demonstrated that rates of material recycling and recovery from ELVs were greatly influenced by the vehicle design trends [7, 8]. Vehicle manufacturers are designing lightweight vehicles to reduce the overall vehicle mass while retaining the safety performance and structural strength. This is achieved by changing ferrous metals with high strength-to-weight ratio materials, such as aluminum, magnesium, plastics, and composites. Consequently, conventional ELV sorting processes that recover ferrous metals efficiently, such as metal shredder and magnetic separator, no longer would cater well for newer vehicle designs [9]. In this view, a big challenge remains the separation of ASRs into its main components, for which technologically simple and low cost processes should be applied. The different material combinations and their respective joining methods play an important role in determining the potential of full material separation in a closed-loop system [10]. For example, the recovery of distinct types of plastics from ASRs requires complex treatments, because of the large variety of polymers in vehicles and number of variations in filler contents, additives, and colorants. Furthermore, a large proportion of the recoverable components are contaminated with metal chips, screws, labels and foams, all of which should be removed before reusing [11].

Processes for the separation and recovery of plastics based on various techniques are currently under development, even because the proportion of plastics in future car design is expected to increase from the current 6–8% to 10–15%, mainly to meet the requirements for carbon dioxide emission reduction during the usage phase [12]. The most recent developed techniques for plastic separation use, for example, differential emissivity of distinct plastic types after infrared energy irradiation [13], froth flotation after surface conditioning [14], sensors based on eigen-frequency response of impact acoustic emission [15].

In the case a complete separation of plastic polymers cannot be achieved, mixtures of fine particles of thermoplastic nature can be used as a reinforcement in thermoplastic injection processes. For this purpose, it is of capital importance keeping separate thermoplastics from thermoset materials because of their chemical incompatibility. The mechanical recycling route of plastics offers the advantage of high production rate, complex shaped manufactured parts and low scrap material in the production line. However, the injection process is generally limited to a reinforcement volume fraction below 40%, implying large amounts of virgin material input [16, 17]. Selected non-metallic fractions from ELVs were used to produce inert granules for conventional aggregate substitution in concrete production [18].

According to the environmental protection hierarchy, fractions left from reuse and recycling operations, for no more than 10% of the weight of the original ELV, in compliance with Directive 2000/53/EC, can be involved in energy valorization processes. Waste materials are becoming attractive resources to be used in fuel production to cope with the fast-growing energy demand. Recently, Garrido et al. [19] added low quality and cheap materials, such as plastics from WEEE and ASRs, to woody biomass to obtain fuel blendstock briquettes. Evangelopoulos et al. [20] studied low-temperature pyrolysis of the ASR fraction under the assumption that a low temperature and an inert environment would enhance the metal recovery, i.e. the metals would not be further oxidized from their original state and the organic material could be separated from the metals in the form of volatiles and char. Ippolito et al. [21] suggested the thermal valorization of car-fluff samples as carbon sources to reduce the zinc, found in zinc–carbon and alkaline spent batteries, to metallic Zn so permitting its volatilization by thermal desorption and subsequent recovery.

One of the main limitation for ASR energy valorization is the lack of extensive information on the quality of emissions from thermal degradation processes of ASRs [2]. In fact, toxic pollutants, such as polychlorinated dioxins and furans (PCDD/Fs) and polychlorinated biphenyls (PCBs), can be generated as by-products during thermal processes, if operational conditions and gas cleaning systems are not carefully controlled [22, 23]. However, if the characteristics of the ASRs comply with the parameters fixed by Italian Decree 14/02/2013, n. 22, namely the regulation that states the cessation of the waste status for certain types of solid recovered fuels (SRFs), ASRs can be considered no longer as a waste. In this case its use as a substitute fuel, for example in cement factories, is a real recycling process and contributes to reach the target of 85% reuse and recycling.

The aim of the present work was to test the feasibility of two solutions aimed at enhancing recycling and recovery of ASRs in compliance with both the statements of Directive 2000/53/EC and the main requirements of a circular approach. ASR samples were collected from an authorized treatment facility (ATF) and subjected to a complete and thorough characterization. Selected plastic fractions underwent a mechanical recycling process in order to produce recycled plastic composite goods, thus boosting the valorization of ASRs in the form of material. Subsequently, the suitability of the residual fractions for a thermal valorization process in the incineration plant of the Metropolitan Turin Area (the TRM plant, Gerbido, Turin, NW Italy) was assessed, even verifying the possibility of attributing the status of solid recovered fuel to the residual ASRs. This study wanted to demonstrate that these forms of recycling and recovery of waste products from ELVs are important steps in the gradual transition of the automotive industry towards a circular economy, even because the proposed solutions permit the valorization of ASRs in the same area where they are produced.

Materials and Methods

Description of the ELV Authorized Treatment Facility

The samples of ASRs employed in this study were collected from the Centro Recuperi e Servizi ELV ATF of Settimo Torinese (Metropolitan Turin Area, NW Italy). The plant shreds and sorts both ELVs and metal scraps coming from old pieces of equipment (refrigerators, washing machines and other white goods) with an annual capacity of treatment of 123,200 t (70 t/h). The flow sheet of the dismantling, shredding and sorting operations carried out at the ATF is shown in Fig. 1.

Before entering the shredding and sorting plant, ELVs undergo the treatments of dismantling and depollution. In the phase of dismantling, ELVs are deprived of bumpers, tires and gas containers; in the phase of depollution, all fluids are removed from the vehicles. After these operations, ELVs, together with white goods scraps, are introduced in a preliminary grinder and, subsequently, in the main shredder (a hammer mill).

An extractor fan located over the hammer mill aspirates dusts and light pieces produced by the shredding operation. The power of the extractor fan is such to aspirate most of the light materials that derive from the car shredding. This waste product is known as “light fluff”. After the main shredding, two in-series magnetic separators separate iron and steel from a non-magnetic waste product.

The non-magnetic waste product enters a rotating sieve that separates three fractions on a size basis, from 0 to

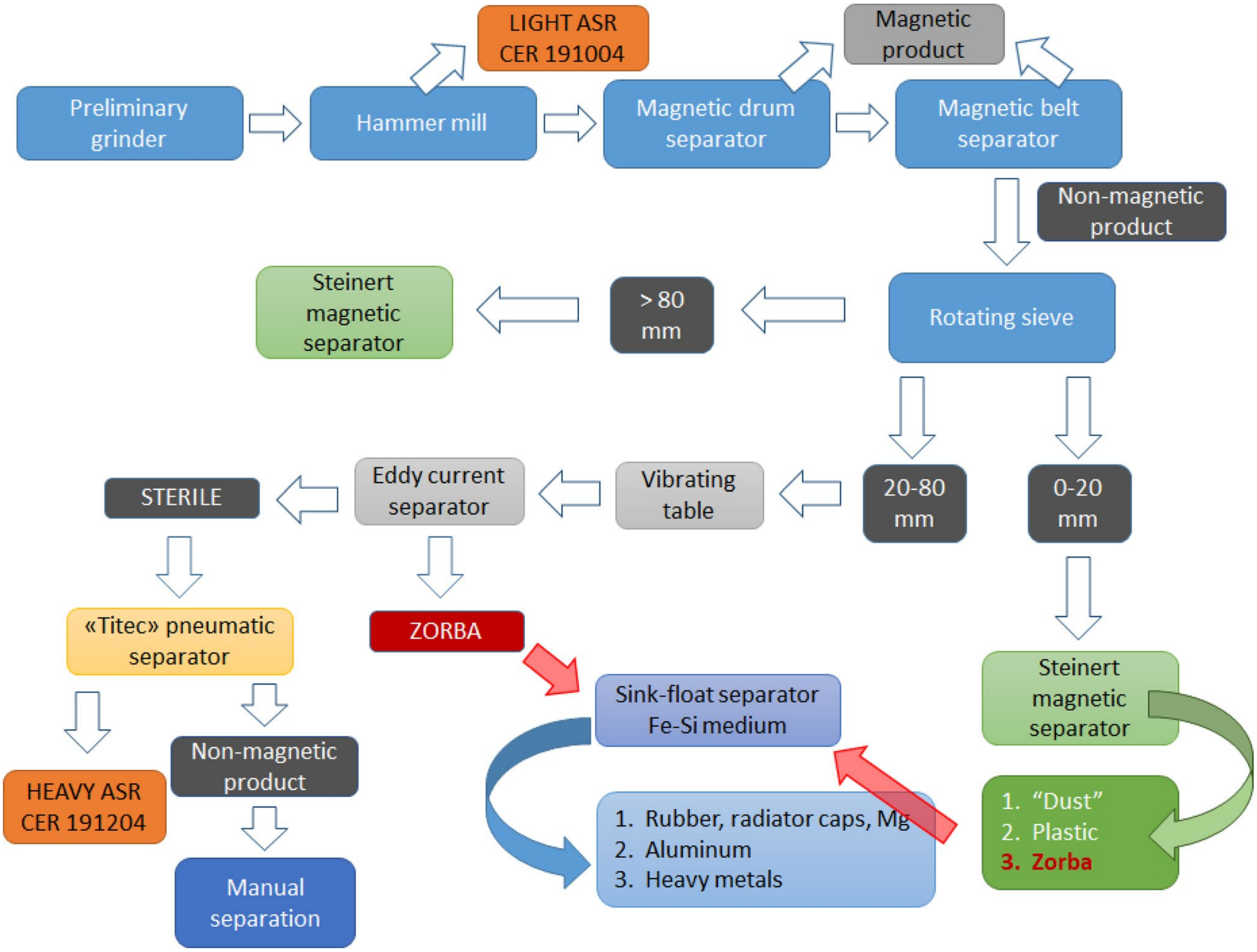

Fig. 1 Flow sheet of Centro Recuperi e Servizi authorized treatment facility and location of sample collection

20 mm, from 20 to 80 mm and more than 80 mm. The finest fraction (0–20 mm) enters the Steinert magnetic separator that separates the waste product into three fractions. The first of the three is mainly made of fine dust, the second of plastic and the third is rich of metal. Due to its composition, this last fraction is finally sent to a sink-float separator that uses media made of an aqueous mixture of iron and silicon to separate rubber and magnesium ($\rho < 2$ kg/dm^3), aluminum ($2 < \rho < 3$ kg/dm^3) and heavy metals ($\rho > 3$ kg/dm^3). The medium size fraction (20–80 mm) is preliminary sent to a vibrating table, that spreads the grains thus avoiding overlaying, and subsequently sent to an eddy current separator. This separation phase generates two products, with different amounts of metals. The product rich in metal is sent to the sink-float separator; the poorer product enters a pneumatic separator where non-magnetic metals concentrate in a product that is sent to a phase of manual separation. The remains from the pneumatic separator are a mixture of rubber and plastic, that constitutes that waste product known as "heavy fluff", CER 191204. Finally, the largest-size fraction (> 80 mm) is sent to the Steinert magnetic separator.

Sample Collection, Product Composition Analysis, Determination of the Calorific Value

As reported in "Description of the ELV Authorized Treatment Facility", the ATF considered in this study has a maximum annual capacity of ELVs/white goods treatment of 123,200 t, to which corresponds an average ASR generation in the order of 35,000 t/y. With reference to the different locations in the ATF where ASR waste products are separated, it is important to underline that the light ASR fraction accounts for approximately 85% b.w. of the whole waste production, while the fraction of the waste product (heavy fluff) separated by the pneumatic separator is approximately 10% b.w.

For this study, two samples of ASRs were collected from the ATF of Settimo Torinese in the plant locations shown in Fig. 1 and thoroughly characterized. One sample was collected from the pile of waste products generated by the extractor fan located over the main shredder. Because of its origin and main composition, the waste product found in this pile is usually known as “light fluff” (CER 191004, fluff-light fraction and dust other than those mentioned in 191003*). The second sample was collected from the waste product generated from the refinement of the non-magnetic metal product in the pneumatic separator. Because of its composition, this waste product is usually named as “heavy fluff” (CER 191204, plastic and rubber). The sampling campaigns carried out for the collection of the two waste products were repeated twice, in April and July 2017, thus originating four samples that were used for the study.

Each whole sample of ASRs underwent a product composition analysis and the assessment of the calorific value according to the methods used in previous works [24, 25]. Briefly, the product composition analysis was handmade on the overall mass (approximately 2 kg) of the four samples. The aim of the product composition analysis was to partition each ASR sample into its main components (light and heavy textile, rubber, foam rubber, plastic, metals, miscellaneous (4–10 mm), fine (< 4 mm), etc.) and quantify each of them.

Because of the high heterogeneity of the light and heavy ASR samples, the calorific value of each whole sample was obtained by evaluating the calorific value of each fraction (i.e. textiles, rubber, plastic, etc.) that composes the ASR samples and, subsequently, reconstructing the original value as a weighted average of the calorific values of each single product. The calorific value of each product was obtained by combusting 1 g ground samples in a calorimeter bomb. The analysis was carried out in triplicate.

Plastics Characterization—Polymer Separation and Chlorine and Sulfur Determination

In the view of a possible valorization of the plastic shredders extracted from the two couples of light and heavy ASR samples, in terms of material or energy recovery, a series of analytical determinations were carried out.

First of all, the four fractions of plastics extracted from the ASR samples underwent a densimetric analysis, with the aim of separating plastic materials with density lower and higher than 1 kg/dm^3. Water at 20 °C was used as a separating medium. The densimetric test was carried out in a tank with a volume of approximately 10 l.

Secondly, a temperature-based approach was used to identify the type of polymers contained in the samples of light and heavy plastic materials separated with the densimetric analysis. According to ASTM D 1525 rule (Vicat softening temperature; ASTM [26]), each polymer softens at an exact temperature value. By making use of this kind of indication, all the plastic scraps were placed on a flat ceramic surface inside a stove and subjected to temperature ramps in order to correlate the softening point with the typology of polymer. Specific temperature ramps were selected for light (< 1 kg/dm^3) and heavy (> 1 kg/dm^3) plastic samples as in Fig. 2.

Specifically, this test was carried out with the aim of separating thermoplastic materials from thermoset materials, because only the first are suitable to be reused to mold recycled plastic composite goods. Conversely, thermoset plastics are unwanted products in the recycling process because they negatively affect the strength and robustness of the recycled plastic composite goods.

Finally, in the view of a thermal valorization of the remaining ASRs, plastic extracted from both light and heavy ASR samples underwent the determination of chlorine and sulfur content. The determination of the two elements was limited to the plastic fraction because the main origin of chlorine were chlorinated polymers (PVC) from ASRs and the information on sulfur content was useful to complete the plastic characterization. The content of chlorine and sulfur was obtained by oxidizing the organically bound chlorine and sulfur contained into the plastics to chloride and sulfate, respectively. The oxidation was obtained by contacting the samples with concentrated nitric acid and hydrogen peroxide and by exposing the mixture to an irradiation of microwave at high energy.

Plastic scraps from light and heavy fluff were granulated in order to obtain a mixture suitable for molding operations. Granules of plastic obtained from the granulation process (with size in a range from 100 µm to a few mm) were used for the determination of chlorine and sulfur. The analysis was carried out on the following samples:

- a ground piece of heavy plastic, made of the high-temperature softening material, coming from the heavy fluff sample collected in July;
- a mixture of light plastic from the heavy fluff samples collected in April and July;
- a mixture of both light and heavy plastic coming from the light fluff samples collected in April and July;
- small slices of PVC and PET (from a mineral water bottle) as a control.

Samples of minced or ground plastics of 100 ± 10 mg were put in six microwave vessels (Milestone MLS-1200 Mega) together with 5 ml of nitric acid (HNO_3, 65%) and 1 ml of hydrogen peroxide (H_2O_2, 30%). Chloride and sulfate in the digestates were determined with spectrophotometric methods after filtration (Whatman 542) and dilution of the samples to 50 ml.

The Turin Incineration Plant for MSW

The local incineration plant (TRM, Gerbido, Turin, NW Italy), which began operation in the year 2014, is authorized to treat

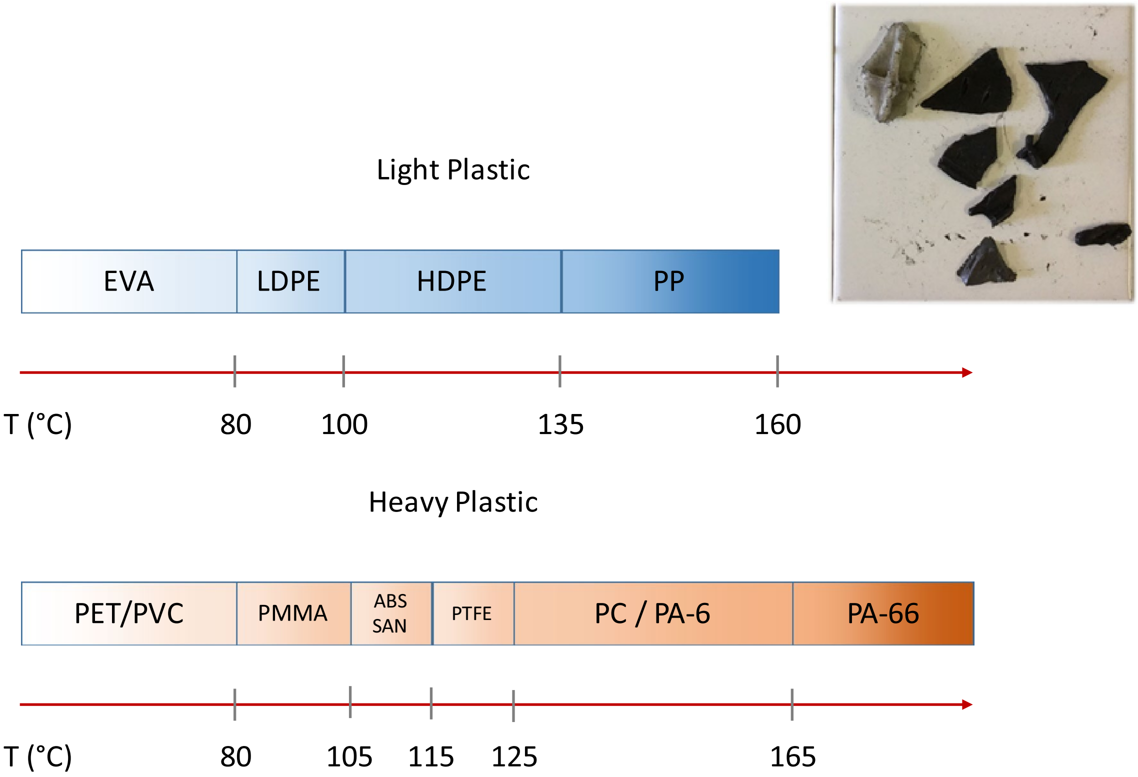

Fig. 2 Ranges of softening temperatures considered in this work (according to ASTM D 1525 rule). (Color figure online)

the fraction of municipal solid waste (MSW) that remains after a separate collection [27]. This residual fraction has a lower heating value (LHV) in the order of 11 MJ/kg. The plant operates for 7800 h/year and has three equal lines, each of them includes a combustion zone, an energy recovery section and, finally, a section for the treatment of flue gas. The combustion zone operates with a moving grate system,the energy recovery section is provided with a boiler and a steam turbine. At present, the incineration plant operates in an electricity-only configuration. The section for the treatment of the final flue gas consists of an electro filter for dust removal, a dry scrubber (with injection of sodium bicarbonate and activated carbon) for the removal of acid gases as well as organic and inorganic micro pollutants, a baghouse filter for the removal of residual and generated dust, and a final selective catalytic system for the reduction of NOx [28]. The combination of the afore-mentioned treatments allows the concentration of pollutants in the output flue gas to comply with the threshold values fixed by the national law concerning the emission of gaseous effluents into the atmosphere (D. Lgs. 133/2005).

Results and Discussion

Sample Characterization—Product Composition Analysis and Calorific Value

The results of the product composition analysis carried out on the samples of light ASRs (CER 191004) collected in April and July are shown in Fig. 3.

A very good reproducibility in the types and relative abundance of the products found in the samples could be observed, even if they were collected at a distance of several months. This evidence guarantees the representativeness of the two analyzed samples in describing the composition of the light ASR waste product. Both samples of light ASRs contained approximately 40% b.w. of textile products (that includes the categories of light and heavy textile and foam rubber), 20–25% of miscellaneous and fine residues with sizes of less than 10 mm, 15% plastics, 10–15% foam rubber, 6–8% metals and very small

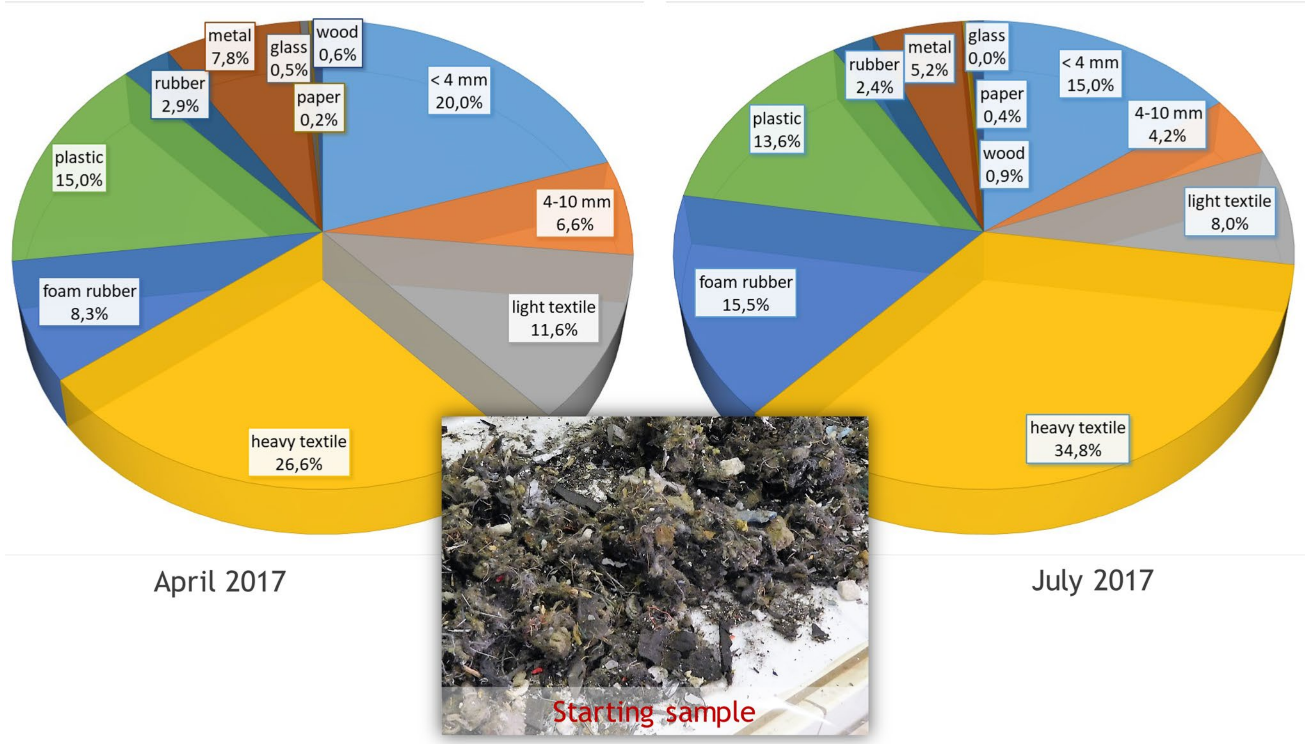

Fig. 3 Results of the product composition analysis of the light ASR sample (CER 191004). (Color figure online)

amounts, in the order of few percentage points, of rubber, paper, wood and glass. A comparison with the samples collected from the same location in the same ATF and used for a previous study [25] showed a reduction for miscellaneous (4–10 mm) and fine (< 4 mm) products (− 50%) and for plastic (− 30%) and an evident increase in the amount of textile products (+ 100%).

As it can be seen from Fig. 4, the two main products found in the heavy ASR samples (CER 191204) were rubber and plastic. In both samples rubber accounted for approximately 70–80% and plastic for a percentage in the order of

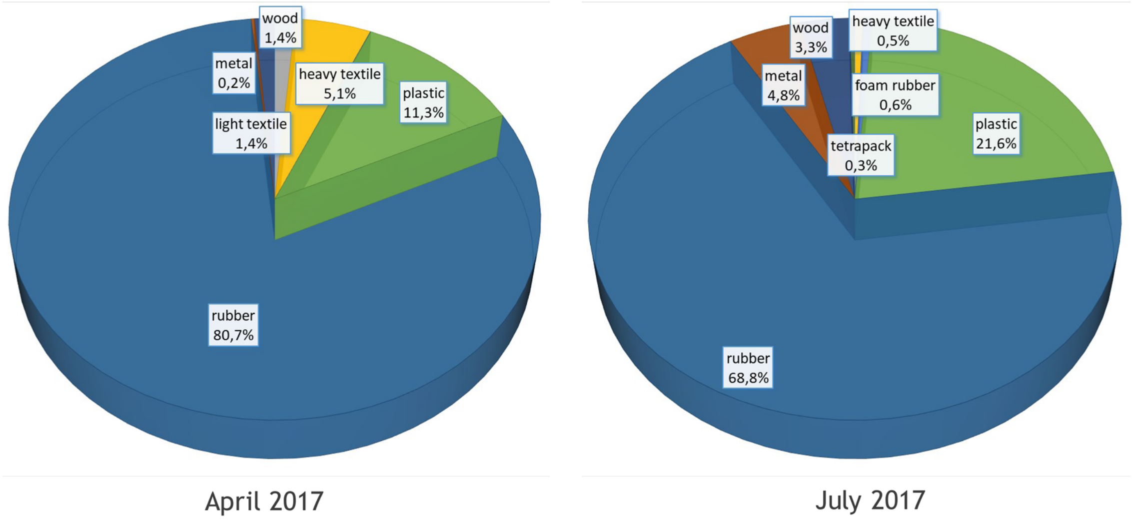

Fig. 4 Results of the product composition analysis of the heavy ASR sample (CER 191204). (Color figure online)

Table 1 Lower heating values (LHVs) of the products found in the ASR samples

Type of product	LHV (kcal/kg)
Light textile	6440
Heavy textile	7390
Foam rubber	7850
Plastics	8760
Rubber	7500
Metals	0
Wood	3570
Glass	0
Paper	4080
Miscellaneous (4–10 mm)	5030
Fine product (<4 mm)	2370

10–20%. Even in this case, the results of the analysis showed a good reproducibility between the two samples collected in April and in July. The first sample was richer in rubber than the second (80.7% vs. 68.8%), conversely, the amount of plastic increased from the first sampling to the second.

The LHVs of the products separated from the samples of light and heavy ASRs is shown in Table 1.

Starting from the data of Table 1 and the amounts of each product found in the samples (as in Figs. 3 and 4), the overall LHV of the two samples of light ASR was calculated and resulted of 5720 kcal/kg (23,920 kJ/kg) and 6300 kcal/kg (26,310 kJ/kg) for the samples collected in April and July respectively. The LHV of the two samples of heavy ASRs, collected in April and July, were of 7550 kcal/kg (31,570 kJ/kg) and 7450 kcal/kg (31,140 kJ/kg) respectively.

Plastics Characterization

The results of the densimetric analysis carried out on the plastics extracted from the ASR samples are shown in Fig. 5. Plastics from the two samples of light ASRs partitioned between light and heavy materials in the measure of approximately 1:1 b.w. Conversely, the two samples of heavy ASRs contained approximately 30% of light plastics and 70% of heavy plastics, b.w. In both cases (light and heavy ASR samples) a very good reproducibility in the distribution of light and heavy plastics was observed between the samples collected in April and July.

The softening test revealed the presence of LDPE, HDPE and PP in the low-density plastic materials ($\rho < 1$ kg/dm^3) coming from the samples of light ASRs, as shown in Fig. 6. It is of interest to note that PP represented the main plastic polymer in these samples (60–90%) and that scraps of an undefined material (with density of less than 1 kg/dm^3 and softening point of above 160 °C) were

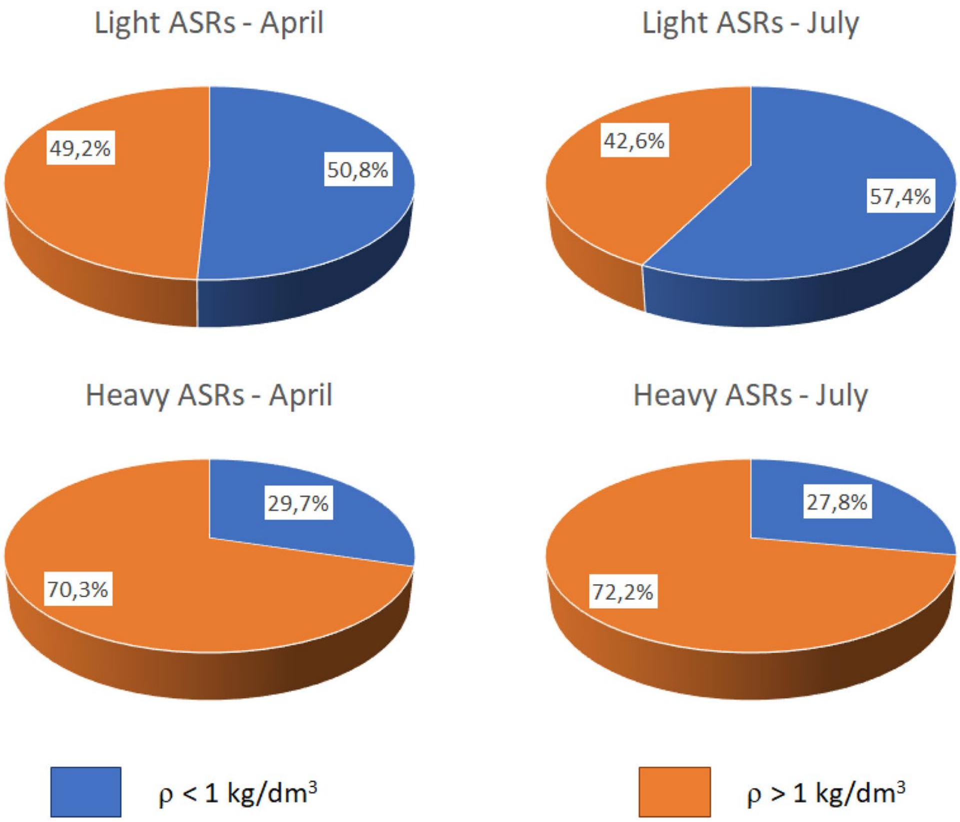

Fig. 5 Results of the densimetric analysis carried out on the plastic fractions extracted from the ASR samples. (Color figure online)

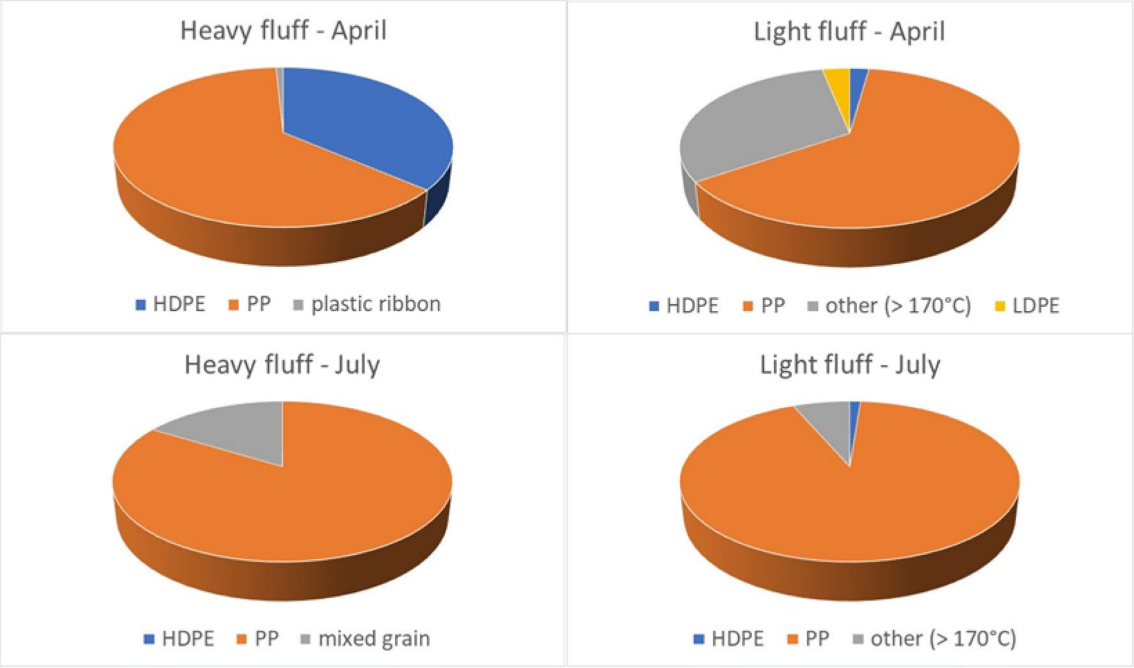

Fig. 6 Results of the softening test, according to ASTM D 1525 rule, for light ($\rho < 1$ kg/dm^3) plastics. (Color figure online)

also found. Even the light ($\rho < 1$ kg/dm^3) plastic scraps coming from the samples of heavy ASRs contained PP as the main polymer (60–80%). Scraps of HDPE were also identified in the sample collected in April. No pieces softening at high temperature values ($T > 160$ °C) were found in the light plastics from the heavy ASR samples.

As shown in Fig. 7, among the heavy plastics, the main polymers identified from the test were PC/PA-6 and one material (probably PA-66) that softens at temperature

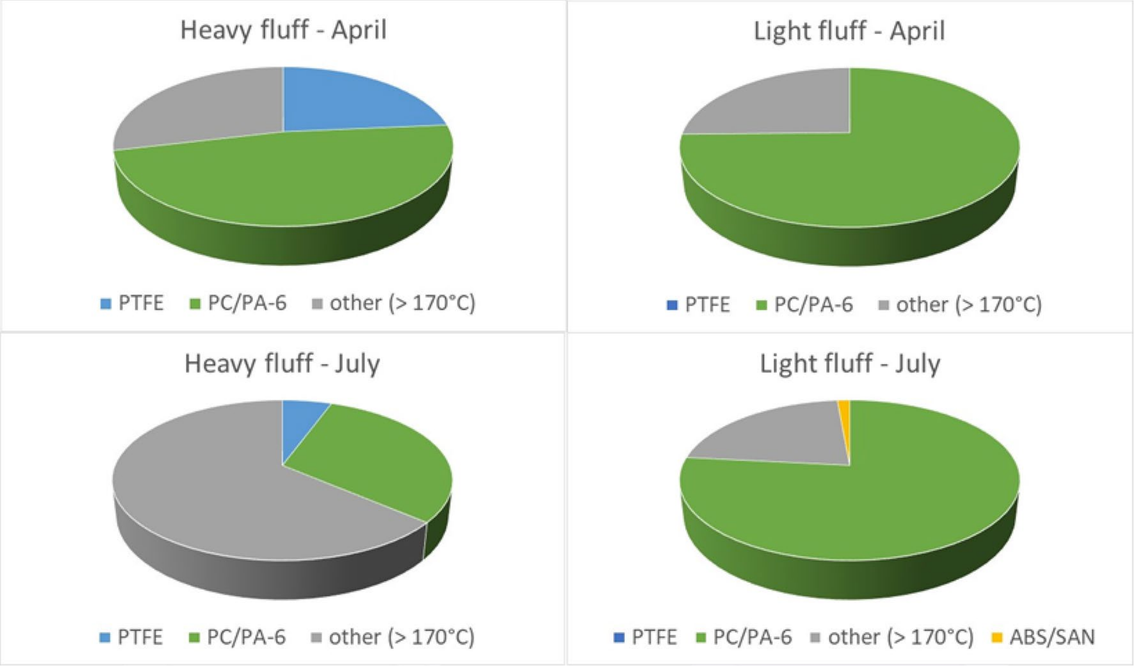

Fig. 7 Results of the softening test, according to ASTM D 1525 rule, for heavy ($\rho > 1$ kg/dm^3) plastics. (Color figure online)

values of more than 180 °C. It was not possible to distinguish between PC and PA-6 because the two polymers soften at very close temperature values (158 and 160 °C, respectively). Samples of heavy plastics ($\rho > 1$ kg/dm^3) coming from the light ASRs contained approximately 70–75% of PC/PA-6 and 25% of the material with high softening temperature. The samples of plastics coming from the heavy ASRs contained the same materials (PC/PA-6 and the high-temperature softening polymer) found in the samples from the light ASRs plus some scraps of PTFE (a very high density, aluminum-like polymer). In these last samples, the distribution of the plastic polymers was quite different between the samples of April and those of July.

Hypothesis Concerning the Plastic Recycling in Molding Processes

The two most employed techniques for the production of recycled plastic composite goods from plastics scraps are through molding or injection processes. The employment of these two techniques requires that plastic pieces of thermoplastic nature are not contaminated by thermoset polymers [29]. Unwanted polymers have density higher than 1 kg/dm^3 and very high softening temperature (> 170 °C) [30]. Specifically, the performances of the goods obtained with molding processes are highly affected by the capacity of scrap plastic granules to be involved in diffusion processes able to bind each granule to the others. However, the typical durations of molding processes, that is in the order of few minutes, made the generation of an adequate inter-granular adhesion possible only in the presence of a homogeneous distribution of granules (i.e. with the same size and shape) [16]. Heterogeneous granules make the whole specimen weak, with a high probability of inter-granule fractures in random positions. Conversely, plastic goods obtained with an injection process have a higher strength and durability, but the piece of equipment used for the injection can suffer serious damages in the presence of even small particles of thermoset polymers.

The results of the analysis aimed at polymer identification showed that samples of both light and heavy ASRs contained high-density ($\rho > 1$ kg/dm^3) materials that were not possible to identify by using the Vicat temperature approach. In the absence of a more accurate and reliable method for polymer identification, all the fractions made of high-density polymers were discarded in the view of a possible ASR material valorization, in order not to damage the final quality of the recycled plastic good. As mentioned in Sect. 3.2, high-density plastics accounted for approximately 40–50% in light ASR samples and 70% in heavy ASR samples.

Starting from the maximum annual capacity of the ATF (123,200 t), the consequent approximate ASR generation (35,000 t/y) and the amount of light plastic in the two more representative waste products separated in the plant and considered in this study, it could be concluded that 2500 t/a of plastic, coming from the light ASR product (85% b.w. of the whole ASRs, 15% b.w. plastic, 55% b.w. light plastic) and 160 t/a of plastic, coming from the heavy ASR product (10% b.w. of the whole ASRs, 15% b.w. plastic, 30% light plastic), could be employed and valorized for the production of recycled plastic composite goods. This amount, equal to 2660 t/a, was more than 2% b.w. of the original ELV and 7.6% of the whole ASR waste product.

Preliminary tests carried out by using a molding process to produce recycled plastic specimens demonstrated the limitation connected to the use of geometrically heterogeneous plastic granules. Plastic specimens with a useful length of 10 cm were obtained from PP and HDPE pieces extracted from heavy ASR samples and granulated for the purpose. Most of the specimens obtained from both PP and HDPE mixtures generated fractures in random positions when they were subjected to tensile tests. This result suggested that, if the molding process is chosen for the valorization of plastics coming from ASRs, improvements in the granulation of the plastic residues and in the setting of the operating conditions of the molding process are undoubtedly necessary.

Thermal Valorization of ASRs

The very basic approach, shown in Sects. 3.2 and 3.3 and based on densimetric separation and differential softening temperature, allowed the recovery of an amount of ASRs in the order of only 7–8%. According to that solution for material valorization, the separated plastic materials coming from ASRs could be subsequently reused as an ingredient for recycled plastic composite goods. However, in order to fully comply with the re-use and recycling targets, other solutions are inevitably necessary for the remaining part of ASRs.

According to European Directive 2000/53/EC, that regulates the management of ELVs, an amount equal to 10% of the ELV weight can be treated in incineration plants for energy recovery. However, if the characteristics of the ASRs comply with the parameters fixed by Italian Decree 14/02/2013, n. 22, namely the regulation that states the cessation of the waste status for certain types of solid recovered fuels (SRFs), ASR can be considered no longer as a waste and its use as a substitute fuel, for example in cement factories, is a real recycling process and contributes to reach the target of 85% reuse and recycling.

At this scope, Italian Decree 14/02/2013 n.22 fixes three reference parameters for the cessation of the waste status, that is a commercial parameter, the LHV; a process parameter, the chlorine content of the waste and, finally, an environmental parameter, that is the mercury (Hg) content. The threshold values of the reference parameters are shown in Table 2.

Table 2 Threshold values of the reference parameters for Italian Decree 14/02/2013 n.22

Parameter	Statistic measure	Units	Threshold values for class				
			1	*2*	*3*	4	5
LHV	Average	MJ/kg	*≥ 25*	*≥ 20*	*≥ 15*	≥ 10	≥ 3
Cl	Average	% SS	*≤ 0.2*	*≤ 0.6*	*≤ 1.0*	≤ 1.5	≤ 3.0
Hg	Median	% SS	*≤ 0.02*	*≤ 0.03*	≤ 0.08	≤ 0.15	≤ 0.50
	80°percentile	% SS	*≤ 0.04*	*≤ 0.06*	≤ 0.16	≤ 0.30	≤ 1.00

Only combinations of italic values are admitted for the status of SRF

In fact, the use of ASR as an additional fuel in a thermal process remains a controversial issue, because chlorine generates corrosive compounds which can damage the facilities and it can also be precursor of toxic chlorinated pollutants, such as polychlorinated dioxins and furans (PCDD/Fs) and polychlorinated biphenyls (PCBs), if operational conditions of the incineration process and gas cleaning systems are not carefully controlled [22]. Because of these potential issues, the Italian regulation (22/2013) states that waste products labelled with CER codes 191001 and 191002, coming from operations of ELV management, cannot obtain the status of SRF. That is not the case of the waste products considered in this study, that are labelled with other CER codes (191,004 and 191,204).

Both waste products considered in this study had a LHV higher than that required by Decree 22/2013, even after the deprivation of the plastic fraction that could be destined to molding process for material valorization. In fact, the calculated LHVs of the remaining ASRs was of 24 and 31 MJ/kg for the light and heavy product respectively. Also the content of chlorine was below the threshold values (see Table 2), while the determination of mercury was not performed. In the case of the chlorine assessment, the comparison of the difference in chloride concentration between the digestates generated from all the ASR plastic samples and the control samples (mixture of nitric acid and hydrogen peroxide subjected to microwave irradiation) and the difference between the digestates generated from the PET samples and the same control samples was below the experimental error. It could be concluded that the chlorine concentration in the solid samples was below 50 mg/kg. The potential of acid gas releases from the thermal process, and consequent issues for equipment and gas conducts, was fully quantified by taking into account also the presence of sulfur. The concentration of sulfate (that is the product of sulfur oxidation) in all the digestates was under the detection limit (0.1 mg/l). Consequently, the amount of sulfur in the samples was < 50 mg/kg.

The results of the above-mentioned determinations demonstrated the compliance of the ASR products with the requirements of the Italian law for the cessation of the waste status. Consequently, from the regulation point of view, ASRs could be accepted in a thermal valorization plant or in a cement factory as a SRF. Therefore, the technical feasibility of the thermal valorization of ASRs in the local MSW thermal valorization plant has been assessed.

The thermal valorization plant for MSW treatment located in the Metropolitan Turin Area has an authorized capacity of 421,000 t/y for waste with an average LHV in the order of 11 MJ/kg. In fact, each specific technology used for thermal treatment (fluidized bed, rotary kiln, moving grate or others) can receive and treat an amount of waste that depends on their calorific value. Figure 8 shows the chart of the grid capacity for one of the three equal grates used in the Turin thermal valorization plant. According to the chart (Fig. 8), the plant can correctly operate only when both the amount of fed waste and their calorific value fall into the grey area, that is the zone where the two parameters are well balanced. Specifically, the Turin thermal valorization plant can treat waste with a LHV that ranges from 6 to 16 MJ/kg.

After the enter-into-force of Decree 133/2014 (known as "Decreto sblocca Italia"), the plant was allowed to operate at its maximum treatment capacity, that is 580,000 t/y (for an average LHV = 11 MJ/kg). Thanks to the permission of Decree 133/2014, during the first three years of operation (2014–2016) the Turin thermal valorization plant has received and treated a yearly average amount of MSW in the order of 450,000 t, that was approximately 7% more than the authorized value. The average LHV of the waste fed to the plant in 2014–2016 was in the order of 8500–9000 MJ/kg. On the grounds of these facts, it can be seen that the plant had an important residual treatment capacity. Specifically, making reference to the grid chart shown in Fig. 8, it can be calculated the overall amount of waste that can be admitted to the plant depending on their LHV.

Table 3 shows that, in the case of waste products with a LHV of 11 MJ/kg, an extra capacity of 132,000 t/y could be obtained. The same approach returned a residual treatment capacity in the order of 42,000 t/y for waste with an average LHV of 13 MJ/kg. This residual treatment capacity could be used to provide an energy valorization of ASRs. The amount of ASRs that could be safely treated in the plant, that is without damaging the combustion system, was calculated by considering the actual amount of incinerated waste (at their highest calorific value, that is 450,000 t/y with a calorific value of 11 MJ/kg) and the highest calorific value of the ASRs. In the case of the heavy fraction of ASRs, with

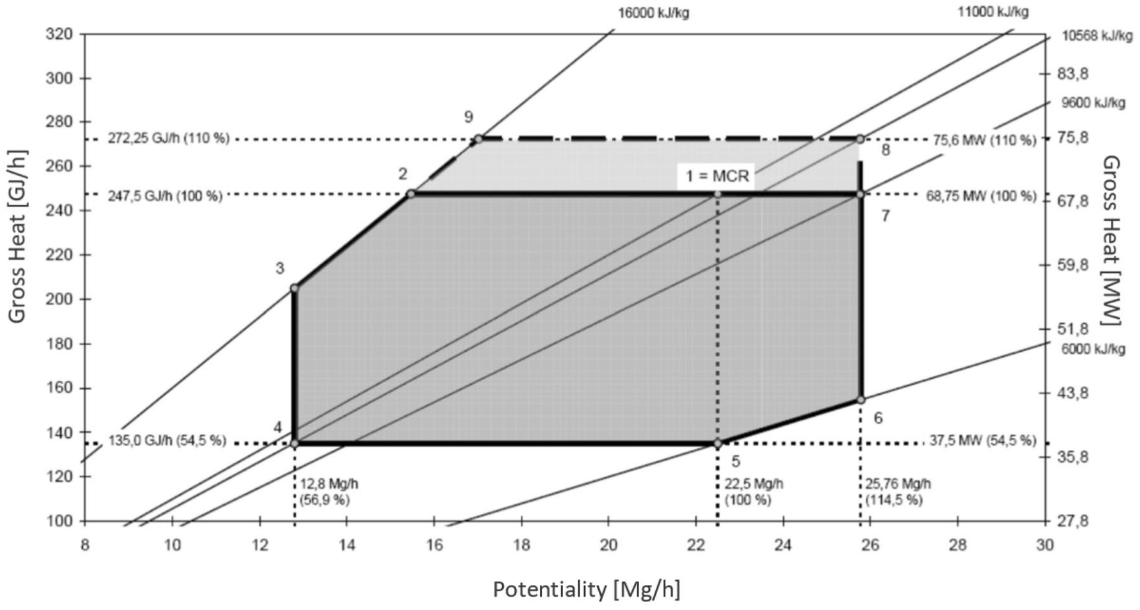

Fig. 8 Chart of the grid capacity for one of the three equal grates used in the Turin thermal valorization plant

Table 3 Residual capacity of the Turin thermal valorization plant as a function of the waste calorific value

LHV (MJ/kg)	Amount (t)	Residual amount (t)
11.0	580,000	132,000
11.5	560,000	112,000
12.0	530,000	82,000
12.5	510,000	62,000
13.0	490,000	42,000

Table 4 Average composition of the MSW collected in the Metropolitan Turin Area and treated in the Turin thermal valorization plant

Paper	32%
Cardboard	9%
Textiles	7%
Wood	1%
Plastics	25%
Inert and glass	13%
Metals	4%
Organic waste	2%
Fine particles (< 10 mm)	7%

a calorific value in the order of 31 MJ/kg, the amount that could be treated in the plant was in the order of 45,000 t/y. It can be highlighted that the residual thermal capacity of the incinerator was of the same order of magnitude, and even more, of the amount of ASRs (35,000 t/y) produced by the ATF considered in this study.

The addition of ASRs to the base stream of MSW processed by the thermal valorization plant could cause an increase in the concentration of acid gases (HCl and SO_2) and possible organo-chlorinated compounds in the exhaust gas streams. The approach of mass balances was used to obtain information concerning the exhaust gas stream composition in the new working scenario of the thermal valorization plant.

First of all, it was considered that the thermal valorization plant treats a base stream of MSW of 450,000 t/y, to which a yearly amount of ASRs of 45,000 t was added. The average composition of the MSW collected in the Metropolitan Turin Area and treated in the thermal valorization plant was provided by the plant manager and it is listed in Table 4.

The concentration of acid gases (HCl and SO_2) in the exhaust gas streams was calculated considering the amount of elemental chlorine and sulfur in the feedstock and the volume of effluents generated by the combustion. Chlorine in the both feedstock (MSW and ASRs) was due to the presence of PVC. In the case of MSW, according to the literature and the information provided by the TRM plant manager, the average amount of PVC in the plastic scraps was in the order of 14%. Chlorine in the PVC polymer accounts for approximately 57%. Consequently, the amount of chlorine in the MSW feedstock was in the order of 9 t/y.

According to the results of the characterization phase of ASR samples carried out in this study, the amount of chlorine from the PVC found in the plastic scraps was of very small extent, that is of less than 50 mg/kg. For this reason, in order to quantify the contribution of the ASR addition to the quality of exhaust gas streams, a mass balance involving chlorine was carried out by using an estimated chlorine concentration into the ASRs equal to 1.3% b.w., that could

Table 5 Flow rate and characteristics of the flue gases that result from the combustion of MSW only or MSW + ASRs

	Primary air (Nm^3/h)	Secondary air (Nm^3/h)	Overall air (Nm^3/h)	HCl (mg/m^3)	SO_2 (mg/m^3)
MSW only	232,156	163,788	429,943	1716	345
MSW + ASR	287,426	200,309	525,812	1465	433
MSW + ASR (Cl 1.3%)	287,849	200,604	526,585	1518	434
MSW + ASR (Cl + 15%)	287,840	200,603	526,584	1539	434
MSW + ASR (Cl -15%)	287,858	200,604	526,586	1498	434

be obtained by averaging different values found in the most recent literature studies [31, 2]. For the subsequent calculations, this amount (1.3%) was increased and decreased by 15%. Table 5 reports the volume of primary (stoichiometric) air needed for the combustion process, the volume of the secondary air necessary to guarantee an oxygen concentration in the wet exhaust gas streams of 8% (v/v) and the concentration of HCl and SO_2 that resulted from the combustion process.

As expected, the increase in the amount of feedstock from 450,000 t/y to 495,000 t/y determined an increase in the demand of both stoichiometric and secondary air. Specifically, the demand of the overall air increased by 22%. Furthermore, in all scenarios the excess of air was in the order of 41%. As it can be seen from Table 5, the extra volume of air necessary to support the combustion diluted the concentration of chlorine into the exhaust gas streams. Consequently, the apparatus currently used for the abatement of acid gases and organo-chlorine compounds, specifically a dry treatment with the injection of powdered activated carbon and sodium bicarbonate and a subsequent filtration on a battery of fabric filters, could cope also with a new scenario where ASRs were co-incinerated with MSW.

The new scenario could also provide a benefit for what concerns the electrical energy produced in the Turin thermal valorization plant. At present the plant operates with a layout according to which only electrical energy is produced from the heat of combustion (that is, it operates only in an electrical mode/configuration), with a net electrical efficiency in the order of 20%. In this case, the addition of ASRs to MSW would increase the annual net electrical energy production from 31 to 38 MW.

Conclusions

This study demonstrated that material and thermal valorization were both viable solutions to increase the circularity of the management of a vehicle through all its life phases. However, the feasibility and the success of the proposed solutions inevitably depend on the availability of recovery plants / facilities in the area where ASRs are generated.

For what concerns the material recovery, this study devoted a special focus to plastics in the view of using plastic scraps from ASRs to cast recycled plastic composite goods. Plastic was found in both light and heavy ASR samples, in an average amount of approximately 15% b.w. However, only light plastics ($\rho < 1$ kg/dm^3) were found suitable for molding processes because they were not contaminated by thermoset polymers, that are strongly unwanted in this type of processes. The fraction of ASRs generated in the Turin area that could be recycled in plastic composite goods resulted of 2660 t/a, that is more than 2% b.w. of the original ELV weight and 7.6% of the whole ASR waste product.

The LHV (24–31 MJ/kg) and chlorine content (< 50 mg/kg) that resulted after light plastic extraction, made the remaining ASR fraction suitable to assume the status of SRF. However, the feasibility of the energy route depends on the presence of suitable thermal plants with a residual thermal capacity. The technical feasibility of using the remaining ASR product as an extra fuel for the local incineration plant was assessed. In the present operating conditions, the Turin MSW incineration plant has a residual treatment capacity of at least 45,000 t/y, for waste with a LHV in the order of 30 MJ/kg, that was approximately 30% more than the amount of ASRs yearly produced in the Metropolitan Turin Area. The application of mass and energy balances to the thermal process demonstrated that the input of ASRs to the incineration plant did not adversely affect the quality of the flue gases, for what concerned the concentration of acid gases (HCl, SO_2), and allowed the annual net electrical energy production to be increased from 31 to 38 MW. Therefore, the recovery of materials and heat undoubtedly determined strong environmental benefits in ELV dismantling and recycling processes, even because the proposed solutions allowed the valorization of the ASRs in the same area where they are produced.

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