Life Cycle Assessment as a tool for addressing proper ASR management

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Abstract

The objective of this paper is to analyse different ASR management strategies in order to assess the environmental impacts related to each scenario.

Life cycle assessment (LCA) according to ISO 14040/44 is applied to different strategies of ASR treatment and disposal in order to characterise and quantify the environmental impacts related to each strategy analysed. For the life cycle inventory, data were collected from a representative a full scale gasification plant (Lazio, Italy), from a full scale ASR Landfill (Sicily, Italy), from a landfill pilot scale plant (Sicily, Italy) in the Custonaci basin. In this small area of 69 km2, about 54 quarries and related cutting plants.

The benefits of partially substituting fuel with ASR in the cement production emerges clearly from the results as all impact categories considered are negative with the exception of Global warming, Terrestrial ecotoxicity and Eutrophication. Global warming and Terrestrial ecotoxicity impacts are lower for ASR Co-incineration in cement plant compared to the Gasification scenario. ASR Landfilling has the least impact on Global warming of the three treatment scenarios due to negligible associated biogas produced.

A clear conclusion on the environmental sustainability of gasification as a treatment technology for ASR is not likely with currently available data and understanding of the process. On the other hand, the use in cement kiln could be promoted as an actual solution of a more sustainable ASR management in those countries that have not achieved the EU recovery and recycling target yet

Keywords: Automotive shredder residue (ASR); Car fluff; Environmental assessment; Gasification, Material recovery; Recycling

1. Introduction

The mean age of vehicles has grown in the last decade as a consequence of the economic crisis. Starting from its end, estimated in late 2011, the registration of new vehicles has systematically increased in Europe (Figure 1) causing the consequent need for an increased End of Life Vehicles disposal. According to the European Union Directive 2000/53/EU for vehicles produced after 1980, a reuse and recovery target of 95% on a mass basis (recycling 85%) should have been achieved by January 2015 [1]. The EU ELV Directive also implies that the option of energy recovery from ELVs is limited 10% of ELV weight, by the same deadline. These targets have not been homogenously achieved in Europe (Figure 2) with Italy showing one of the lowest rate (Figure 3)

One of the main issue in achieving the EU recycling and recovery targets is the proper management the automotive shredder residue (ASR or car fluff), a highly heterogeneous material, mainly composed of plastics, rubber/elastomers, metals, glass [2] which constitute the remaining 20-25% of ELVs after shredding and sorting the vehicle to recover valuable metals.

A significant increase in the presence of plastics and composites as well as of light metals is expected as a consequence of actual lightweight car designs, aimed at emission reduction during the usage phase, in view of which it may prove additionally difficult in the future to achieve the required recycling quota of 95%.

ASR management is thus critical to achieve the targets set by European Regulation and for a fully environmentally sustainable management of ELVs.

In order to reach the 85% of recycling several actions could be implemented on ASR:

- Advanced metals recovery [3,4]: it consists in the recovery of nonferrous metals (e.g. aluminium, copper, brass) and of the residual iron fraction which could lead to an increase of recycling rate of about 1%.
- Advanced polymers recovery [3,5]. Technologies used in recovering valuable sub-streams from SR include heavy media separation, froth flotation, vibrating tables, optical sorting and air classification. The overall process is quite complex and requires a high energy input but could lead to an increase of the recycling rate of about 4 - 5% probably sufficient to reach the objective set by the EU Regulations. Concerns arise due to the high cost and complexity of the process affecting the overall sustainability of this option which is also strongly connected to the marketability of recycled polymers. Besides, the lower calorific value of the residual ASR is significantly reduced after plastic removal and therefore the waste suitability for incineration with energy recovery is diminished; this fact could lead to fail the 95% recovery target.
- Pyrolysis or gasification of ASR could specifically be designed to maximize gaseous products or focus on material recovery as a key design requirement. Potential users of pyrolysis char include iron, steel and cement industries. However, these industries apply restrictions on the presence of specific metals, and chlorine mainly from PVC and other plastics, and a reduction of these components may be required either prior to or following shredding.
- Direct use of ASR in the cement industry. The use in kilns may lead to reduced environmental impacts resulting from less mining, transportation and preparation of coal and mineral ores as well and reduced impacts of ASR landfill leachate. Remaining barriers to acceptance include demonstration that a full-scale system will consistently produce high value fuel with low concentrations of hazardous materials
- Direct use of ASR as secondary raw materials mainly in the construction industry [5,6] for the production of cement and asphalt. This option appears to be limited due to the possible low acceptability of the ASR based products by the market.
- Direct use of bottom ash and slag after incineration; this option is usually not carried out in most countries (e.g. Italy) due to excessive amounts of contaminants, especially metals [7].
- Metals recovery from slag after ASR incineration [7,8, 9]: various metals (especially iron, aluminium, copper, zinc, lead) can be removed from incineration bottom ash and slag by a combination of mechanical (e.g. crushing, sorting) and physical (e.g. magnetic and eddy-current separation) unit operations. The recovered materials can be used in metallurgic industry to produce metals with a market value [7]. This option is little effective in increasing the recycling rate of the ELVs (probably in the order of 0.3 – 0.5%). However, by reducing the metals content of ash and slag from ASR treatment, the process could make these waste complying with building materials standards thus increasing the potential for recycling of these materials in the construction industry [7,8,9]. Since bottom ash and slag from the incineration of ASR represent about 4% of the total weight of ELVs, their recycling is an important step towards the fulfilment of the standards set by the ELV Directive.

Thanks to the high calorific value of ASR [2,10] the thermal treatment with energy recovery appears a fundamental step for the appropriate management of this waste; often the incineration is carried out mixing ASR with other combustible waste.

The objective of this paper is to analyse different ASR management strategies in order to assess the environmental impacts related to each scenario while verifying if the recycling and recovery levels, set by European Regulation, can be reached.

The analysis was carried out by means of a Life Cycle Assessment (LCA) approach following the methodological framework and principles described in the ISO standards 14040 and 14044. LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. The LCA methodology allows the comparison of products or systems that provide the same function which in the case of the present study refers to the treatment of ASR waste. A preliminary investigation of the most diffused technologies of ASR treatment and disposal was carried out, aiming at selecting proper scenarios. Specifically, alternatives to the main current disposal solutions were analysed in terms of benefits resulting from the conservation of non-renewable resources and reduction of waste disposal [11,12].

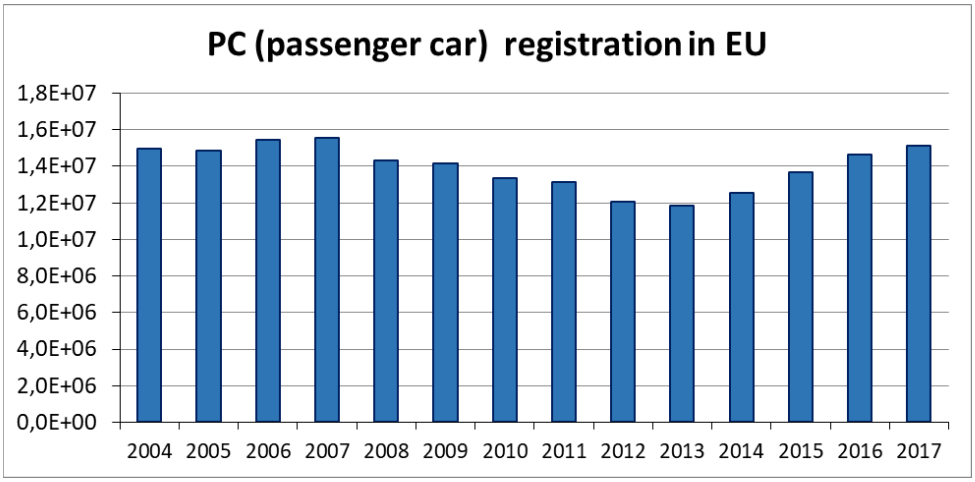


Figure 1 Passenger car registration in Europe

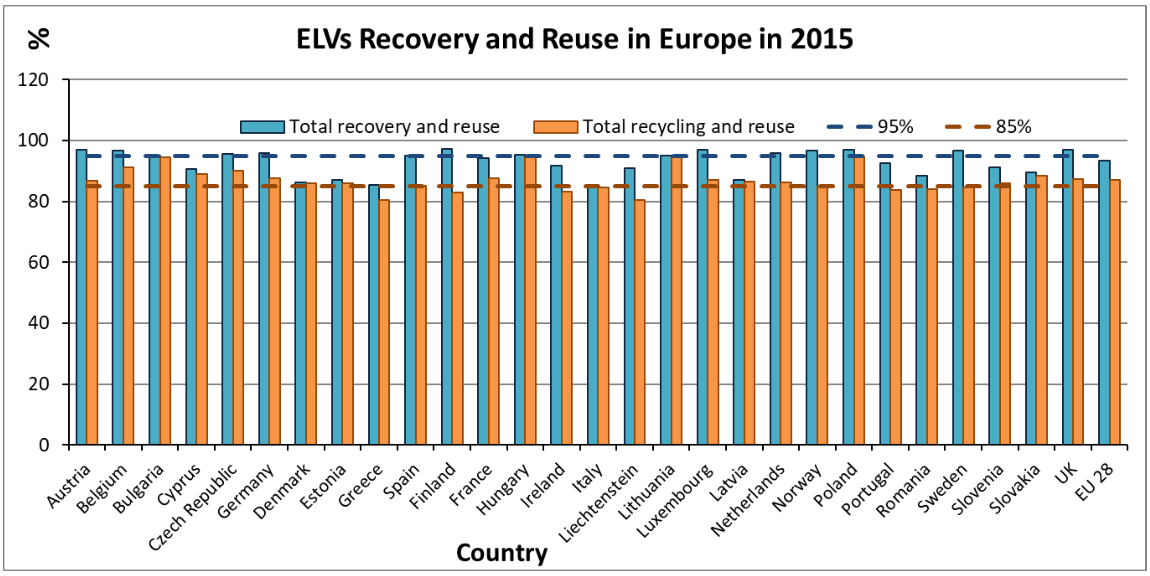


Figure 2 ELVs Recovery and reuse in Europe (2015)

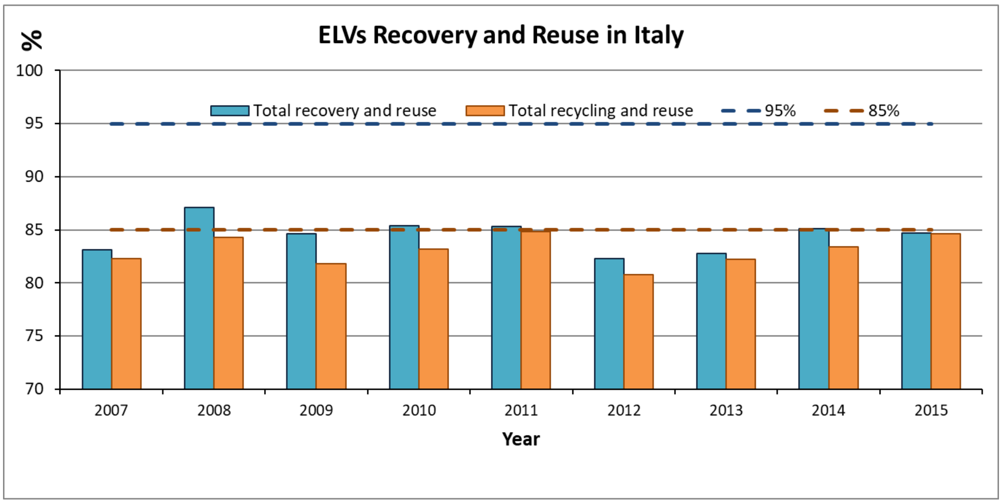


Figure 3 ELVs Recovery and reuse trend in Italy

2. Goal and Scope of the Study

2.1 Objective and scenarios

The objective of the LCA study is analysing different ASR management strategies in order to assess their relative environmental impacts. Furthermore, the implementation of each scenario will be used in verifying if the recycling and recovery levels, set by European Regulation, can be met.

2.2 System Boundaries and functional unit

The ASR management strategies chosen are those with a more solid industrial background in terms of process, machinery and marketability of recycled materials. For these reasons the following scenarios have been chosen:

- Scenario 1: Landfill disposal of ASR (used as benchmark);
- Scenario 2: Co-incineration in a cement kiln and use of ash and slag as cement manufacturing feedstock;
- Scenario 3: Gasification with energy recovery of ASR and landfilling of ash and slag

As a matter of fact, among of the analysed scenarios only one allows to reach both the recycling and recovery targets set by the EU Directive mentioned above. Table 1 shows the presumed recycling/recovery levels for each scenario calculated using the literature data presented above.

Table 1. Recycling and recovery rates as estimated for each scenario

ASR Scenarios	Recycling [%]	Recovery [%]
Scenario 1 (Landfill)	83	83
Scenario 2 (Gasification)	83	> 95
Scenario 3 (Cement Kiln)	86	> 95

To ensure comparability of the ASR treatment strategies a functional unit of 1,000 kg of ASR was adopted for this study. ASR, reported in Mancini et al., (2014) [13], was considered in this work as it is the same waste utilized in the gasification tests and disposed in the ASR landfill from which the data have been collected. As it can be easily observed in table 2, fines (0–20 mm fraction) represent almost the 35% of the total sample. For the fine fraction, a thorough composition analysis cannot be performed, because of the very small size of the materials included. Anyway, it is possible to identify glass pieces, plastics and metals, blended together with dust and dirt with a low Heat value which prevent their energy recovery [14].

The remaining fluff mainly consists of polymers, up to 48%, such as polyurethane (foam rubber), plastics and rubbers. Textiles accounts for about 17% on the total and together with polyurethane foam (PUF) are strictly related to car seats and carpeting.

Table 2. Materials contained in the two ASR feedstock and comparison with other references.

Material	Mamcini et al., 2014 [13	Galvagno ta l, (2001) [28	Mirabile et al (2002) [29	Fabrizi (2003)	Zolezzi (2004)	Pineau (2005)	Boughton (2006)	Forton (2006)	Nourreddine et al. (2007) [3	Osada (2008)	Hwang (2008)	Morselli (2010)	Fiore (2010)	Santini wt al, (2011) [2
fine material < 10 mm,	21.7	35	-				17.5						32.3	17
fine material < 20 mm^a	35.2											34.5		
foam	0.28	-		7	4.5	6.2		8.9		5	11		3.5	
fabric, fibbers	17	25	10	6	5	16.4			10	3.7	9	18	15.6	27
soft plastic,	0.47	20	41	22	20	14.2	25	14	41	29.3	37	7.5	21	23
hard plastic	32.9											24.5		
rubber/elastomers	15.9	20	21	23	38	8.9	15	2.3	21	9.4	13	13	6.6	9
wiring/ceramic and electric material	3.5	-	3			1.7		1.5	3	3.5	1			
ferrous metals	2.9	-	-	13	6	12	4.5	2.7		2.2	11	2.5	6.9	8
non-ferrous metals	1.4			1										
glass	0.09	-	16	13	16.5	1.5	7.5		16					
wood	2.07	-	-	4	10	5.1		0.8		1		3	0.4	1
paper, cardboard	0.4				1								0.4	
Others		9			2.2	15.5	16.5	26.55	4			30	18	

^{a}Including the < 10 mm fraction;

According to ISO 14040 and 14044 guidelines all life cycle stages of ASR are considered to ensure equivalence of the systems being compared. However, life cycle phases and related flows prior to the gate of the ASR treatment plant are identical for all scenarios considered and therefore excluded from the analysis. Hence, system boundaries begin with the physical and geographical boundaries of each ASR treatment plant and end with the landfill disposal of waste and residues, or with the benefits resulting from material and energy recovery processes.

The CML-IA (baseline) method was used for life cycle impact assessments (LCIA). The CML-IA method elaborates the problem-oriented (midpoint) approach and includes the category indicators most used in LCAs, namely:

- Abiotic depletion (elements, ultimate reserves) in kg Sb eq
- Abiotic depletion (fossil fuels) in MJ
- Global warming 100 years (GWP100), in kg CO_2 eq
- Ozone layer depletion (steady state) in kg CFC-11 eq
- Human toxicity, Freshwater aquatic ecotoxicity, Marine aquatic ecotoxicology and Terrestrial ecotoxicity in 1,4-dichlorobenzene eq
- Photochemical oxidation (high NOx) in kg C_2H_4 eq
- Acidification in kg SO_2 eq
- Eutrophication in kg PO4 eq

3. Life Cycle Inventory

The ASR treatment scenarios are modelled following the specific process flow diagrams provided in the sub-sections that follow. All relevant input and output material and energy flows are considered based on 1,000kg ASR fed into each treatment process. As mentioned above, a general cut-off criterion is applied to exclude life cycle stages prior to the gate of the ASR treatment plant as they are considered identical for all of the scenarios to be compared.

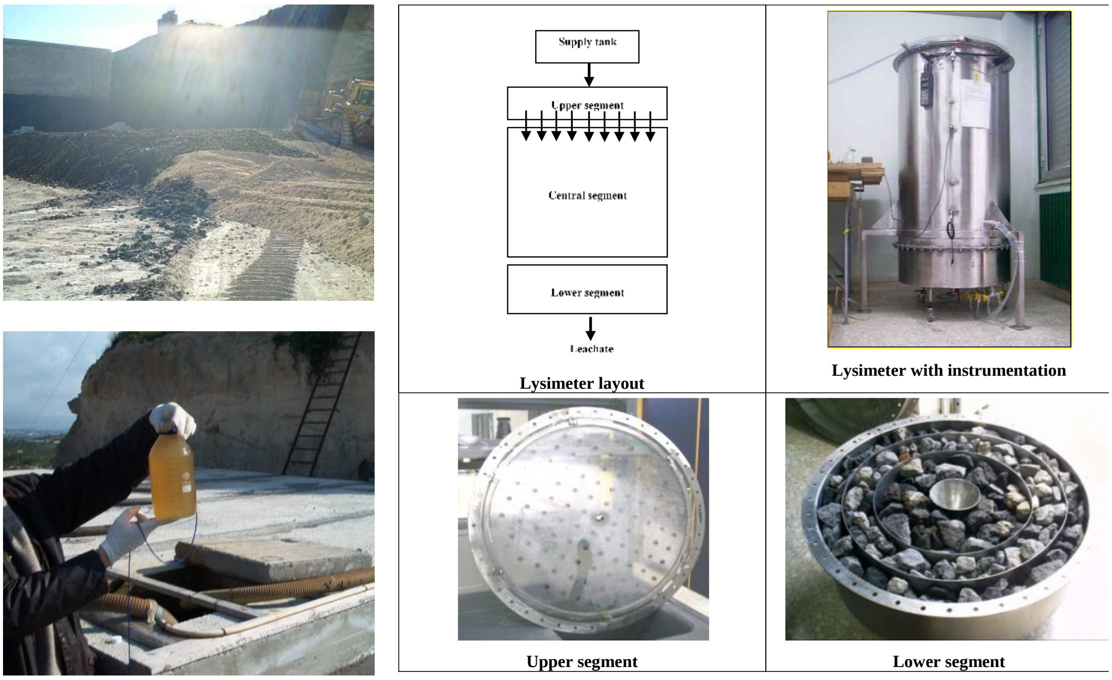
Material and energy flows including inputs and emissions were inventoried for each scenario prioritizing the use of primary data. In particular, the composition of ASR used for Scenarios 1 and 3 derives from primary data from previous work from the authors [10,13,15,16]. In the case where reliable and representative primary data were not available secondary data from Ecoinvent 3.4 European related processes were used and parameters adjusted to increase technological and geographical representativeness. Secondary data from similar treatment processes of prevalently plastic wastes were preferred due to high plastic content of ASR under study. However, primary data used in modelling the ASR treatment scenarios account for major impacts.

3.1 Scenario 1: Landfill disposal of ASR (used as benchmark).

Data on potential impact of ASR landfilling (i.e. leachate characteristics and potential biogas production) were collected both trough field and pilot plant (lysimeter) sampling as described in Mancini et al., (2018) [17]. Lysimeter geometry was defined to have a sufficiently large volume with respect to the waste characteristic size so ensuring higher equivalence to the landfill behavior with respect to traditional batch tests (Figure 4).

3.1.1 ASR for landfill simulation

The ASR was collected directly from a shredding plant of the steel factory (located in Sicily) sampled on several days (about 100 kilos for 10 samplings over 3 weeks) in order to get a material as independent as possible from the specific lot treated each day. Sampling for ASR characterization was carried out according UNI 10802. Analysis were carried on the fluff solid matrix to evaluate metals concentration as well as other anions and cations concentration, pH, electrical conductibility, moisture content, lower calorific power, apparent density, TOC, dioxins, free cyanides, phenols and PCB. Metals determinations were carried out by ICP after acid digestion while anions and cations were detected trough ionic chromatography. In accordance with Ciacci et al. (2010) [3], it was assumed that a negligible contribution derives to biogas production from this kind of waste, even if some reactions of polymeric degradations may take place [18, 19, 20, 21]. Finally, transport processes were inventoried on a distance of 150 km, which is the estimated average distance from shredding plants to landfills in Italy.



Lysimeter layout

Lysimeter with instrumentation

Upper segment

Lower segment

Figure 4: Landfill leachate sampling and lysimeter main design features.

3.1.2 Leachate characterization

Results obtained from the leachate sampled from the central sector of the lower segment of the lysimeter at the third month of the monitoring period are shown in Table 3. The same parameters are also shown, for the leachate sampled at the real fluff landfill where the examined fluff is disposed.

Table 3. Comparison between lysimeter (third month) and landfill (third year) leachate parameters.

Parameter	U.M.	Lysimeter	Landfill	Parameter	U.M.	Lysimeter	Landfill
As	mg/l	-	0,054	Fe	mg/l	-	2,662
Cd	mg/l	-	0,007	Ni	mg/l	-	0,127
Cu	mg/l	-	0,008	Pb	mg/l	-	0,040
Cr III	mg/l	< 0,050	< 0,050	2.3.7.8 TCDD	ng/l	< 0,005	<0,0001
Cr VI	mg/l	< 0,050	< 0,050	1.2.3.7.8 PeCDD	ng/l	< 0,005	<0,0002
Hg	mg/l	< 0,005	< 0,005	1.2.3.4.7.8 HxCDD	ng/l	< 0,005	<0,0002
Residual at 180°C	g/l	2,704	7,4	1.2.3.6.7.8 HxCDD	ng/l	< 0,005	<0,0003
pH	-	7,5	7,05	1.2.3.7.8.9 HxCDD	ng/l	< 0,005	<0,0002
eH	mS/cm	3,055	8,45	1.2.3.4.6.7.8.	ng/l	0,006	<0,0003
Chlorides	mg/l	72	2797	1.2.3.4.6.7.8.9	ng/l	0,029	<0,0004
Sulphides	mg/l	< 1	24,13	2.3.7.8 TCDF	ng/l	< 0,005	<0,0004
Ammonia	mg/l	10,4	137,99	1.2.3.7.8 PeCDF	ng/l	< 0,005	<0,0001
Organic Nitrogen	mg/l	21,2	47,70	2.3.4.7.8 PeCDF	ng/l	< 0,005	<0,0001
Nitrates	mg/l	< 1	0,69	1.2.3.4.7.8 HxCDF	ng/l	< 0,005	<0,0001
Fluorides	mg/l	1,28	13,36	1.2.3.6.7.8 HxCDF	ng/l	< 0,005	<0,0001
Free Cyanides	mg/l	< 0,1	< 0,1	2.3.4.6.7.8 HxCDF	ng/l	< 0,005	<0,0001
BOD$_5$	mg/l	270	250	1.2.3.7.8.9 HxCDF	ng/l	< 0,005	<0,0001
COD	mg/l	2860	550	1.2.3.4.6.7.8.HpCDF	ng/l	0,005	<0,0002
TOC	mg/l	835	439	1.2.3.4.7.8.9 HpCDF	ng/l	< 0,005	<0,0002
PCB	mg/l	< 0,001	<0,01	1.2.3.4.6.7.8.9	ng/l	< 0,005	<0,0006

3.1.3 Modelling details and assumptions

Due to the not-hazardous nature of ASR a sanitary landfill is modelled for this scenario. Primary data related to the running of the landfill [22] were used and it was considered that, leachate collected and treated satisfy Italian effluent discharge legal limits (D. Lgs 152/06). Given the low concentration of leachate produced compared to values of typical landfills, the leachate treatment material and energy inputs were assumed to be 50% less than that from available studies. Process specific burdens related to the incineration of sludge from leachate treatment and consequent landfilling of resulting residues are considered using secondary data from Ecoinvent 3.3. No emissions of Biogas is considered from the landfilling of ASR due to negligible amounts reported in previous studies.

3.2 Scenario 2: Co-incineration in cement kiln and use of ash and slag as cement manufacturing feedstock

3.2.1 Modelling of process and assumptions

ASR co-incinerated in cement plant is modelled taking into consideration the partial substitution of conventional fossil fuel combusted in Italian cement kilns as reported by the Italian technical and economic association of cement (AITEC). It is assumed that ASR is used to partial replace petcoke which is the major fossil fuel burnt in Italian cement plants. A substitution ratio of ASR to petcoke of 1:0.7 was applied taking into consideration the respective heat values and combustion efficiency differences. Energy and material inputs to handle the ASR in the plant are considered negligible.

Slag and ash resulting from the ASR is recycled in the cement process as raw material substituting quarried limestone. It is assumed that the concentration of chlorine in the ASR is low enough to avoid the production of by-pass dust/ash which would otherwise need to be disposed of with associated impacts. Data for emissions to air and water are based on Genon et al. (2008) [23] for the co-incineration of Refuse Derived Fuel (RDF) in cement plant and ecoinvent database for plastic waste treatment in Municipal solid waste incinerators (Table 4)

Table 4. Emissions to air from RDF co-incineration

Parameter	U.M.
Electricity	1.4 kWh
Diesel	0.814 l
Air emissions	Quantity (kg/t RDF)
CO_2	2.46E+03
CH_4	7.46E-01
SO_2	1.01E+00
N_20	1.53E-02
NO_x	6.85E+00
NH_3	6.16E-02
HCl	3.36E-02
HF	4.51E-03
NMVOC	3.63E-01

3.2.2 Scenario 3: Gasification with energy recovery of ASR and landfilling of ash and slag

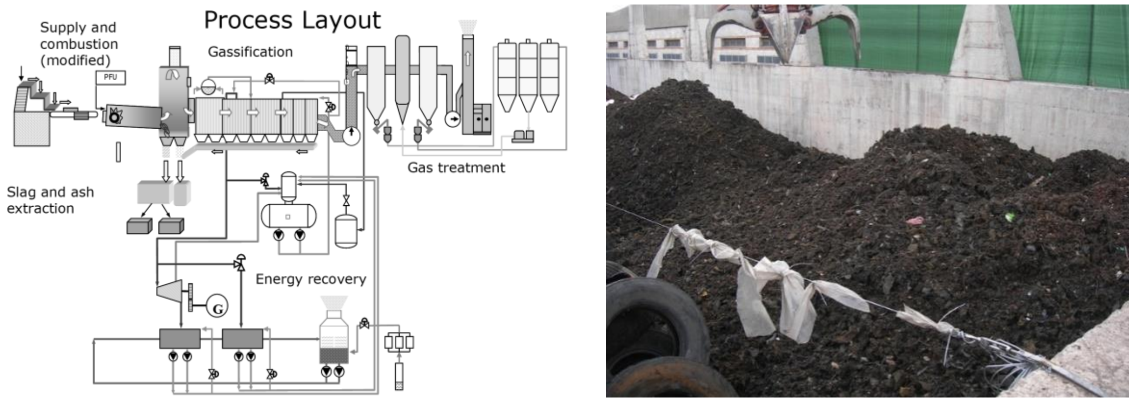
Data for emissions to air and water for ASR gasification-incineration are provided from a full scale experimental campaign carried out from the authors [14]. ASR gasification-incineration experiments were carried out on a full-scale tyre incineration plant, specifically modified to optimize combustion of car and waste-collection SRs.
The rotary kiln was made up of a slightly inclined pipe with an internal diameter of 2.7 meters and a length of approximately 14 meters lined with fire-proof material. Temperatures throughout the furnace varied from 850°C at the entrance to approx. 1120°C at exit. During the first phase, the stoichiometry (air factor) was maintained at less than 1, to enhance the conversion in the first chamber of solid fraction to gases, through volatilization, destructive distillation and partial combustion reactions. The secondary chamber was employed in completion of gas phase combustion reactions.
Inorganic waste components and metallic drum materials formed a melt that ran off at the lower end into a slag remover filled with water where it solidified and was discharged on a continuous basis.

The afterburner chamber is provided with auxiliary burners to ensure that regulatory incineration temperatures were reached. The slag running off the walls of the afterburner chamber is collected at the bottom of the chamber and removed at regular intervals.

The hot flue gases released from the afterburner chamber reach the boiler where their energy content is used to generate steam at an overpressure of approx. 43 bars and a temperature of around 430°C. This steam is used to drive a turbine in order to produce electricity.

During the subsequent multi-stage process, flue gases are cleaned to such an extent to ensure reliable compliance with legal limits, assuring an adequate safety margin.

The first cleaning device provided is a cyclone specifically introduced to eliminate flue gases dust. A fabric bag filter aimed at achieving removal of fly ash is located immediately after the cyclone, followed by a contact reactor where sodium carbonate is added prior to second stage filtration which occurs through a second bag filter. The latter ensures removal mainly of acid gases and sulphur oxides. A second induced draft fan is located downstream from the bag filter to draw off flue gases from the filter, subsequently releasing them into the atmosphere through the plant stack.



(a) (b)

Figure 5. Sketch of the full scale plant layout (a) and ASR used in the experimental campaign (b).

3.2.2.1 ASR feedstocks characterization

In the total, more than 500.000 kg of ASR were thermally treated during the experimental campaign. Plastics in ASR are above all polyolefins (PE, PP), PVC, PU (foam and rigid) nylon (poly amides, PA), polystyrene (PS) and several “blends” such as ABS (acrylonitrile-butadiene-styrene) and glass-fiber enforced polymers. Specifically, a high PVC content, up to 20 %-wt in some ASRs [24], is of concern for the consequential chlorine content increase. The high values variability is typical of fluff, depending on feed (ELVs, light iron, white goods) by the shredding system, the trammel sieves and other separation methods. Examples of the wide difference in values and categorization are provided in Table 1. ASR utilized in the gasification tests shows contents of ferrous metals, glass and wood generally lower than those reported in literature [25,26].

Table 5 shows, for the examined ASR, some of the more remarkable characteristics in terms of gasification/combustion process [27]. The results are presented as an average of the three samples. All results are presented on a dry-weight basis to provide consistency and for comparison to other fuels. Higher Heat value was about 5200 kcal/Kg. Galvagno et al. (2001) and Mirabile et al. (2002) [28,29] found Higher Heat Values of 4151 and 4013 kcal/kg respectively which are similar to that obtained. Kondoh et al. (2001) [30] found a Higher Heat Value of 6856. Density value was 2.7 kg/dm^3. Day et al. (1996) [31] found density values in the range 0.4-0.5 kg/dm3 while a broader range (0.28-0.56 kg/dm^3) was suggested by Roy and Chaala (2001) [32].

Chlorine levels were considerably high (> 1.7%) for the examined fluff. A high Chlorine content may cause some concern for the thermal processing of SRs for reasons of equipment corrosion risks by HCl, chlorine (Cl_2) and other chlorinated compounds as well as formation of dioxins/furans (PCCD/Fs). However, no significant correlation with plastic content was found.

Table 5. Combustion properties.

Parameters	U.M.	Mancini et al. (2014)
Ash	% s.s	27.22±4,03
Metallic coarse materials	%	14.05±13.24
Non-combustible materials	% s.s.	10.97±1.71
Moisture	%	6.69±0.58
Bulk density	kg/dm^3	0.27±0.02
High calorific value	kcal/kg s.s.	5596±78
S	mg/kg s.s.	2567±1405
Cl	mg/kg s.s.	17422±8684

3.2.4.2 *Mass balance and residues characterization*

Slag production corresponded, on an average, to approx. 18% of total fluff burnt with a mean bulk density of about 1000 kg/m^3, notably denser than the value of the initial ASR (range 270-420 kg/m^3). On this basis it can be calculated that ASR volume is reduced more than 10-fold following thermal treatment. Ashes from exhaust gas treatment represented approx. 3% of initial fluff mass (including sodium bicarbonate utilized to neutralize acid gases). The solid residues represent the major products of ASR gasification and were composed mainly by ferromagnetic metals, not ferrous metals, char and inorganics in the form of powder or granules. Based on the analytical results, slags from combustion process were classified as not hazardous waste with CER code 19 01 12 (bottom ash and slag other than those mentioned in 19 01 11). Leachability tests performed on bottom and fly ashes collected from several sections of the plant revealed the hazardous characteristics of most of these wastes.

3.2.4.3 *Atmospheric Emission from combustion*

Patterns of monitored parameters in the gas emission from the plant chimney, as extracted from Mancini et al., (2014a), are reported in table 6, table 7 and table 8. The emission values were comparable to those deriving from tyres combustion, in both the two experimental campaign being always substantially below the law limits due to the appropriate technology applied in the treatment of the flue gasses.

Table 6. Emissions characterization as extracted from Mancini et al., (2014a)

Parameter	Emissions (mg/Nm^3)
COD	5
Total dust	1 – 2
Organic substances	< 10
HCl	< 5
HF	< 1
SO_2	10
NO_x	80 - 100
Cd+Tl	< 0,01
Hg	< 0,02
Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V+Sn	< 0,1
PCDD+PCDF (ng/Nm3)	< 0,05
IPA	0,001

Table 7. Synthesis of stack emissions as extracted from Mancini et al., (2014a).

Day	Measured value	TOC	HCl	HF	SO_2	NOx	CO	NH_3
		mg/m^3	mg/m^3	mg/m^3	mg/m^3	mg/m^3	mg/m^3	mg/m^3
1	Max (0,5h)	5.21	1.27	0.13	150.06	136.6	11.10	nd
	Mean (24 h)	0.14	0.98	0.04	26.11	90.59	1.22	nd
2	Max (0,5h)	1.36	6.23	0.53	174.54	122.11	6.53	0.05
	Mean (24 h)	0.06	1.57	0.21	26.64	82.71	0.83	nd
3	Max (0,5h)	0.32	1846	1.37	103.14	33.56	6.10	0.06
	Mean (24 h)	0.03	6.86	0.68	21.56	2.60	0.60	nd
4	Max (0,5h)	1.31	13.74	0.49	2.94	121.94	0.39	0.07
	Mean (24 h)	0.08	4.39	0.21	1.21	105.36	0.18	nd
5	Max (0,5h)	3.25	40.39	1.16	6.55	134.50	40.39	0.06
	Mean (24 h)	0.10	1.58	0.83	2.75	114.47	1.58	nd
6	Max (0,5h)	0.10	14.04	0.83	4.27	124.95	11.42	nd
	Mean (24 h)	0.01	9.25	0.52	1.91	97.07	0.46	nd
7	Max (0,5h)	0.32	11.56	0.47	9.16	103.83	0.6	nd
	Mean (24 h)	0.01	5.07	0.27	3.89	78.11	0.12	nd
8	Max (0,5h)	nd	9.82	0.40	6.53	113.65	0.35	nd
	Mean (24 h)	nd	5.52	0.26	1.89	89.95	0.12 1	nd
9	Max (0,5h)	0.49	11.85	0.51	4.72	110.11	14.98	nd
	Mean (24 h)	0.01	6.77	0.32	1.66	90.23	0.42	nd
24 h average limit	Mean (24 h)	10	10	1	50	200	50	
0,5 h average 100%(1)	Max (0,5h)	20	60	4	200	400		
0,5 h average 95%	Max (0,5h)	10	10	2	50	200		

Table 8. Comparison of stack emissions with regulatory limits as extracted from Mancini et al., (2014a).

Parameter	Emission values	Italian emission limits
Total dust	0.7	10 (daily mean - 30 half-hour mean)
PM 2.5	1.7	
PM 10	1.2	
Cd+Tl	0.0095	0.05 (daily mean)
Hg	0.039	0.05 (daily mean)
Sb+As+Pb+Cr+Co+Cu+Mn +Ni+V+Sn	<0.130	0.5 (hourly mean sum)
PCDD+PCDF (ng/Nm3)	0.0039	0.1 ng/m^3 (sum on 8h)
IPA	0.000717	0.01 mg/m^3 (sum on 8h)

3.2.4.4 *Energy balance*

The energy efficiency parameter was evaluated by means of simulation software (Aspen Plus). The process was simulated, assuming 330 days of annual operation, disregarding fuel consumptions for start-up and shut down phases, and assuming no auxiliary fuel requirement during conventional operation. Simulation details are reported in Mancini et al. (2010) [10]. Taking into account an internal consumption of approx. 500 kW (as deducted from the full scale plant), the net power output was approx. 2,560 kW. The gross power efficiency was approx. 16.8%, while net power efficiency was 14%.

Energy Efficiency parameter was calculated as approx. 0.61. This value exceeds the lower limit laid down by the Directive 2008/98/EC, for installations in operation and authorized in accordance with applicable Community legislation before 1 January 2009, while being lower than that established for new plants. However, consumptions could be optimized and auxiliary fuel requirements reduced in order to achieve the energy parameter value for the process to be classified as full recovery.

3.2.4.4 Process modelling and assumptions

The gasification model is based on the full-scale tyre incineration plant modified to burn ASR waste. Process data from the plant were applied in the LCA model. In particular, 0.90 kWh net electricity is generated which is considered as an avoided product and stack emissions (Table 9). 20 kg ash resulting from the process are disposed of in landfills after pretreatment consisting in solidification in cement.

Table 9 : Main process data

Parameter	values
Energy	**MJ/t ASR**
Natural gas	
Avoided product	**kWh/t ASR**
Electricity generated (net)	0.90
Stack emissions	**kg/t ASR**
CO	0.66
SO_2	0.66
Nitrogen oxides	2.64
HCl	1.32E-1
HF	1.32E-2
Hg	5.15E-4
Cd	1.25E-4
Dioxins	5.15E-5
PM 10	1.58E-2
PM 2.5	2.24E-2
Sb,As,Cr,Co,Cu,Mn,Ni,V,Sn	1.72E-4

4 Results

The benefits of partially substituting fuel with ASR in the cement production emerges (table 10) clearly from the results as all impact categories considered are negative with the exception of Global warming, Terrestrial ecotoxicity and Eutrophication. In the case of Global warming (figure 6), the fossil carbon content in the plastic fraction of ASR has a high contribution to Global warming which is not counterbalanced by the fuel substitution aspect. However, Global warming and Terrestrial ecotoxicity impacts are lower for ASR Co-incineration in cement plant compared to the Gasification scenario. Of the three treatment scenarios landfilling has the least impact only for Global warming, due to negligible associated biogas produced. This is also the only impact category for which landfill performs better than the co-incineration option.

Table 10 : Life cycle impact assessment results

Impact category	Unit	Landfill	Co-incineration cement plant	Gasification
Abiotic depletion	kg Sb eq	5.92E-06	-7.65E-07	3.11E-05
Abiotic depletion (fossil fuels)	MJ	2.29E+02	-3.53E+04	1.40E+00
Global warming (GWP100a)	kg CO2 eq	1.72E+01	2.11E+03	1.18E+03
Ozone layer depletion (ODP)	kg CFC-11 eq	2.72E-06	-1.69E-07	1.07E-06
Human toxicity	kg 1,4-DB eq	5.22E+02	-2.02E+03	1.00E+05
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	1.46E+03	-7.68E+02	1.78E+03
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.36E+06	-2.73E+06	2.19E+06
Terrestrial ecotoxicity	kg 1,4-DB eq	7.52E-01	5.68E-01	1.52E+01
Photochemical oxidation	kg C2H4 eq	3.69E-03	-4.44E-01	4.72E-02
Acidification	kg SO2 eq	1.20E-01	-2.97E-01	1.95E+00
Eutrophication	kg PO4--- eq	4.80E+00	6.07E-01	4.85E-01

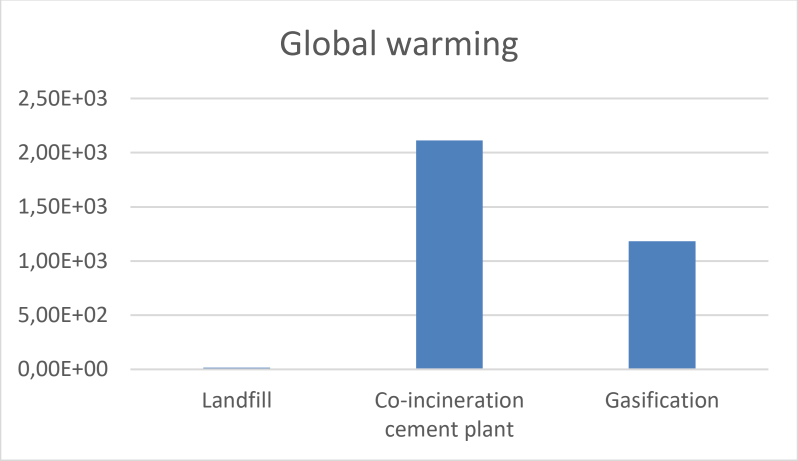


Figure 6. Comparison of the relative weights of global warming between the different scenarios

Similarly, low air and water emission values characterized by ASR sanitary landfills yield lower impacts on Photochemical oxidation, Acidification and toxicity related impacts compared to the Gasification option (figure7). In addition, Gasification contributes to higher values of abiotic depletion compared to landfilling resulting from the production of chemicals for flue gas and wastewater treatment. However, benefits of electricity generation in ASR Gasification is seen in the low values of Abiotic fossil fuel depletion compared to landfilling with no energy recovery features.

Among the two thermal treatments, there are more impacts avoided through the fuel substitution in the cement plant than the electricity generated in the gasification process (figure 8). This results in lower impacts, negative values in most cases, associated with co-incineration compared to gasification.

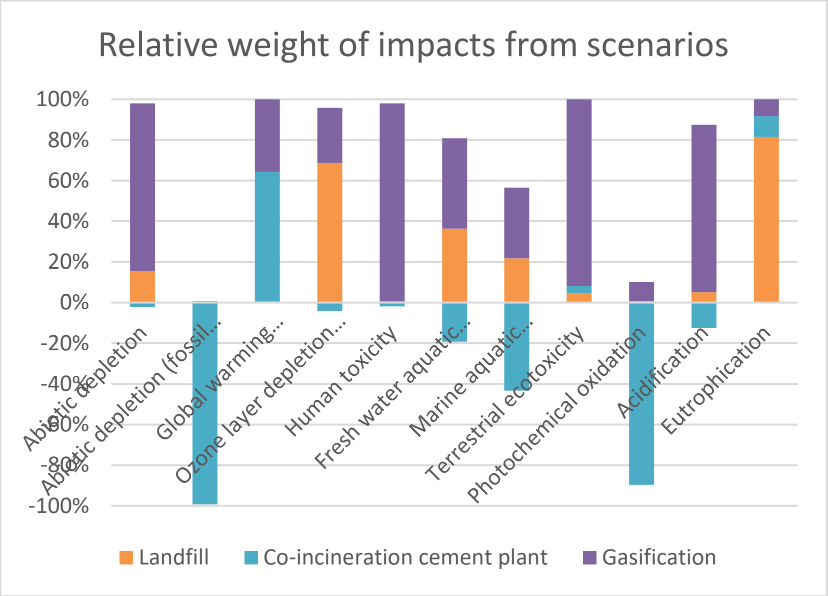


Figure 7. Comparison of the relative weights of all the impacts between the different scenarios

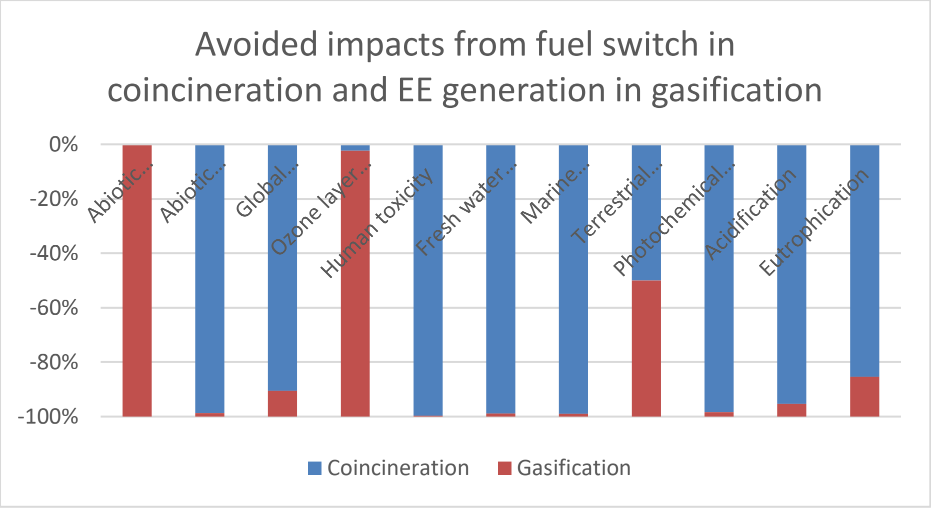


Figure 8. Avoided impacts from fuel switch in coinciniration and EE generation in gasification

Avoided impacts from electricity generated in gasification is higher than that from fuel substitution in co-incineration in Abiotic depletion, Ozone Layer depletion. However, co-incineration has lower overall values for these impacts due to the additional avoided impacts from the use of residual ash in substituting limestone needed in cement production. Furthermore, it is assumed that the co-incineration of ASR in cement plant does not require additional inputs of material than the normal cement process. So all inputs are allocated to the cement produced. On the other hand, the gasification process requires material and energy inputs which reduce the effect of avoided impacts from the related electricity generated.

5 Conclusions

The handling of SR according to Scenario 1 (landfill) shows overall savings for Global Warming, Photochemical Oxidant Formation and Terrestrial Eutrophication, mostly because of the rather low emissions to the atmosphere. For all non-toxic impact categories and within uncertainty, scenarios with increased energy recovery such as co-incineration in cement kiln, show significantly better environmental performance compared with the baseline landfill-based scenario (i.e. landfilling), indicating that increased energy recovery is a desirable option for the non-toxic categories.

The results for the gasification are however associated with significant uncertainty, mostly owing to the fact that the dataset for SR gasification refers only to one full-scale experimental campaign, showing a rather broad ranges of data. This suggests that a clear conclusion on the environmental sustainability of gasification as a treatment technology for ASR is not likely with currently available data and understanding of the process and the use in cement kiln could be promoted as an actual solution of a more sustainable ASR management in those countries that have not achieved the EU recovery and recycling target yet.

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