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Article

# End-of-Life Tyres: Comparative Life Cycle Assessment of Treatment Scenarios

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**Featured Application:** This work can support the scientific community and the waste sector in the identification of the most suitable treatments for end-of-life tyres.

**Abstract:** Waste tyres and their accumulation is a global environmental concern; they are not biodegradable, and, globally, an estimated 1.5 billion are generated annually. Every year around 350,000 tons of end-of-life tyres (ELT) are managed in Italy, collected from cars, two-wheeled vehicles, trucks, up to large quarry vehicles and agricultural vehicles. ELTs are collected and sent for material or energy recovery, in line with the circular economy principles. This paper investigates the environmental impacts of two common scenarios of ELT treatments. Specifically, it is analysed the recycling of crumb rubber (CR, deriving from the tyre shredding) for the composition of bituminous mixtures for the wearing course of roads. This scenario is compared with the energy recovery route in a dedicated incinerator. To this aim the standardised methodology of Life Cycle Assessment (ISO 14040-44) is employed. Results shows that for most part of the impact categories analysed, the material recovery presents higher environmental benefits if compared with energy recovery.

**Keywords:** waste tyres; crumb rubber; LCA; recycling; incineration



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## 1. Introduction and State of the Art

It is estimated that the annual generation of waste tyres amounts to 1.5 billion whole-tyres worldwide [1], contributing to the huge number of tyres already placed in landfill and stockpiles. Due to recent global recognition and strong environmental awareness, many authorities have imposed strict rules and regulations regarding this waste product to prevent excessive stockpiles and landfill operations [2].

According to the European Tyre and Rubber Manufacturers' Association (ETRMA), every year more than three million tonnes end-of-life tyres (ELTs) are collected and treated. The rate of ELTs treated for material recycling and energy recovery has significantly increased in the last two decades and already in 2009, 95% of ELTs arising on the EU market were successfully diverted from landfill. In most European nations, the handling of ELTs is managed by an Extended Producer Responsibility, a principle that gives to the tyres producers and importers the responsibility for a correct ELT management. In Italy this principle has been ratified with the Dlgs 152/20,006 and the ministerial decree n. 82/2011. Currently, every year around 350,000 tons of ELTs are managed in Italy, collected from cars, two-wheeled vehicles, trucks, up to large quarry vehicles and agricultural vehicles. Producers guarantee the collection and the sending to materials/energy recovery programs for 100% of the ELTs legally placed on the spare parts market. The management of ELTs is therefore in line with the circular economy principle, aiming at avoiding or, at least, reduce waste and manage raw materials' scarcity through the continual use of resources.

According to the hierarchy adopted in the EU for waste management (Directive 2008/98/EC), the tyre retreading offers high potential for circularity, through direct reuse

of part of worn tyres and a lifetime extension. However, the retreading market is in decline, down by 20% since 2010 [3]. When it is not possible to avoid the waste, the directive suggests that generally the priority should be given to the recovery of materials (recycle and/or reuse). Currently, in Italy, the 56% of ELTs is sent to material recovery. Specifically, according to Ecopneus [4], secondary raw materials from ELTs currently finds employment in sport flooring (especially as synthetic grass for soccer fields, surface coats for tennis, basketball and horse-riding), children's playgrounds, acoustic insulation, rubber articles (e.g., shoe soles) and civil works (e.g., asphalts). The other 44% is sent to energy recovery through co-incineration in existing cement kilns (using scrap tyres as replacement of traditional fuels) or dedicated incineration.

In this context, this paper aims to analyse and compare the environmental impacts of two common scenarios of ELT treatments: the recycling of ELT for the realisation of Rubber Asphalt (RA) and the incineration for energy recovery. Impact calculations will be carried out according to the standardised [5,6] methodology of Life Cycle Assessment (LCA).

Life cycle assessment (LCA) applied to these materials has rapidly expanded over the last few years as a tool able to capture and handle complexities and interdependencies typically characterizing modern integrated waste management systems [7–9]. With reference to the European situation and the most recent legislation published by the European Commission (EC), i.e., the Waste Directive 2008/98/EC (EU, 2008), LCA is used to rationalize technological choices and to define management strategies; in less advanced regions, with a similar approach, LCA is used to develop measures required to implement more integrated solid waste management systems, and to reach EU directives [10]. The LCA methodology according to ISO 14,040 is worldwide accepted and appreciated because it allows an objective evaluation of the environmental performances of products and processes [11].

Literature on ELTs management is quite abundant and environmental assessments have been performed for different tyre treatments and recovery methods. However, results are often difficult to compare or are scarcely reproducible because of lack of inventory data.

Clauzade et al. [12] have provided LCA impact assessment for nine recovery treatments and concluded that the most beneficial scenarios are the production of synthetic ELT-based turf, the manufacturing of moulded objects from ELT and energy recovery in cement works. However, authors did not provide the input/output data employed for the analyses (the Life Cycle Inventory, LCI), and, as a consequence, the study is not easily replicable and updatable. Artificial turf and energy recovery in cement plant has been identified as the most environmental friendly solutions also by Fiksel et al. [13], who provided a complete analysis considering nine scrap tyre applications.

Different scenarios were considered by Li et al. [14], who assessed the treatments of ambient grinding, dynamic devulcanization, pyrolysis and illegal tyre oil extraction, concluding that the most environmental friendly scenario is the pyrolysis one. Even though pyrolysis of ELT is rarely performed [15], characteristics of this process have been recently analysed also by Hiba et al. [16] and its environmental performance has been compared with other scenarios by Efstathios Pasakopoulos [17].

According to the Waste Framework Directive (2008), reuse and recycle of waste should be prioritized compared to energy recovery. In line with this directive, the study of Feraldi et al. [18] demonstrated that higher environmental impact reductions can be obtained for the material recycling route relative to energy recovery in a cement kiln.

Among the most investigated recycling routes there is the use of crumb rubber (CR) for asphalt mixtures. Farina et al. [19] compared environmental impacts of asphalt with and without crumb rubber, resulting that this latter presents environmental benefits. Ortiz-Rodriguez [20] compared with a detailed LCA study the reuse for asphalts with other three different scenarios (production of floor, production of wire and landfill). As well, Bressi et al. and Puccini et al. [21,22] compared the use of CR with the use of reclaimed asphalt pavements (RAP). A literature review on environmental impacts of rubberized

asphalt has been provided by Wang et al. [23]. Emissions caused by CR used in asphalts has been the focus of the studies of Yang et al. and Zanetti et al. [24,25].

Few studies, such as the LCA analysis of La Rosa et al. [26], are available on the reuse of CR to produce new tyres. A very specific application of ELT was studied by Ayoob and Fadhil [27], who developed a process to employ this waste for the production of catalyst for biodiesel.

In this literature context, this paper aims to investigate the environmental impacts of two different scenarios of ELT treatments. Specifically, it is analysed the recycling of CR deriving from the tyre shredding for the composition of bituminous mixtures for the wearing course of roads and this scenario is compared with the energy recovery route in a dedicated incinerator. To this aim the standardised methodology of Life Cycle Assessment (LCA) (ISO 14040-44) is employed.

Results of this analysis will provide specific LCA-based information able to help decision-making in understanding which one of the analysed ELTs treatment offers the highest environmental benefit.

This work is therefore expected to support the scientific community and the tyres waste sector in the identification of the most suitable final treatment, where actions should be preferentially addressed to improve the environmental profile.

## 2. Materials and Methods

### 2.1. Analysed Processes

Recycling and incineration of ELTs are widespread and consolidated techniques. The first steps of both the value chains are finalised to the ELTs shredding. Specifically, the main steps are the following ones:

- i Collection of ELTs through collection points located throughout the Italian territory;
- ii Transportation to crusher plants;
- iii First shredding, where the ELT is reduced in pieces from 5 to 40 cm, named “tyre shreds”.

After these processes the tyre shreds can be sent to energy recovery in an incineration plant, or can be submitted to a second step of shredding. With this latter process the rubber is separated from steel and textiles and is subsequently treated to obtain granulates and crumb rubber (CR), which can be employed for new products.

In this paper, for the recycling scenario, the use of CR for the construction of an asphalt pavement is considered. Data for the road construction are mostly primary data collected during a previous study of our research group [19].

Figure 1 summarises the flows for the two analysed End of Life scenarios.

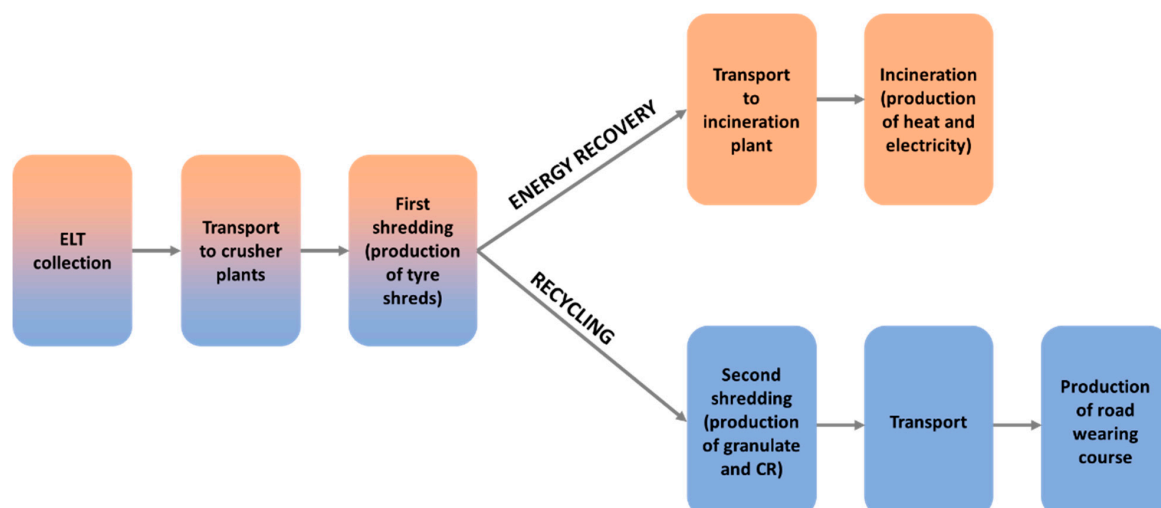


Figure 1. Flow chart of the two analysed scenarios for the ELTs.

### 2.2. Goal and Scope

As it emerges from literature, different studies have provided data on the environmental profile of different CR recycling routes. However, often the reproducibility of the studies is hindered by the lack of a detailed LCI, or refers to very specific applications or are referred to different geographies. In this context, this paper provides inventory data and life cycle impact assessments (LCIA) on the two common end-of-life (EOL) treatment methods for scrap tyres, with reference to the Italian context: the recycling for asphalt production and the energy recovery through the incineration.

The functional unit of the developed LCA is the treatment of 1 t of tyres.

Figures 2 and 3 show the system boundaries of the two analyzed scenarios. Specifically, the recycling scenario includes the impacts due to the tyres collection, the shredding into CR, the transports and the production of wearing course with CR and the benefits deriving from the avoided production of a standard wearing course with bituminous mixture. In this scenario it is therefore considered the difference in environmental impacts between the two alternative asphalts. The energy recovery scenario considers the tyres collection, the shredding into tyre shreds, the transports and the incineration process. This latter requires the use of materials and energy and produces electricity, heat, as well as emissions and wastes. To allow a fair comparison with the recycling scenario, the burdens avoided through the substitution of electricity and heat from the European mix are considered.

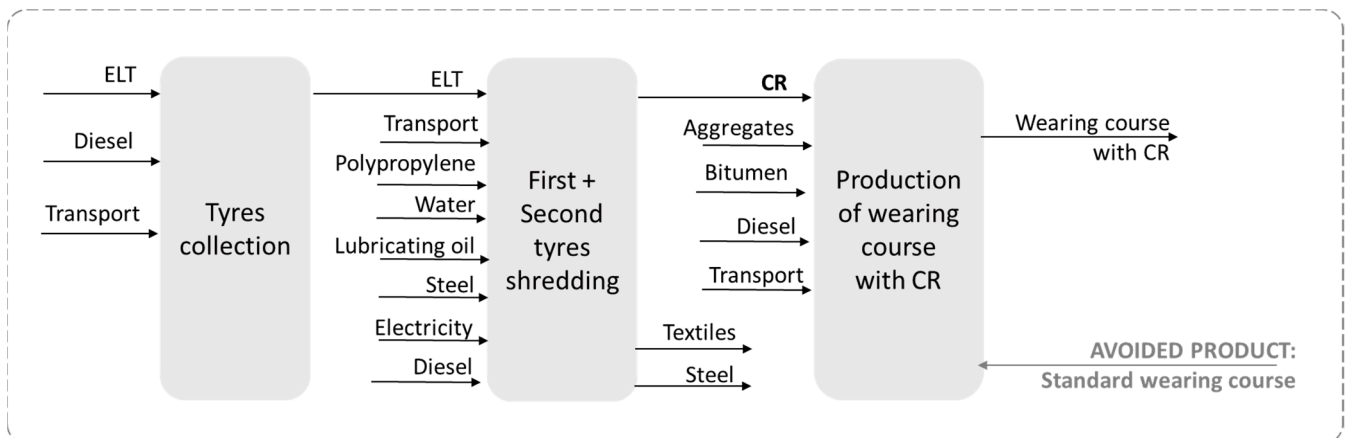


Figure 2. System boundaries of the recycling scenario.

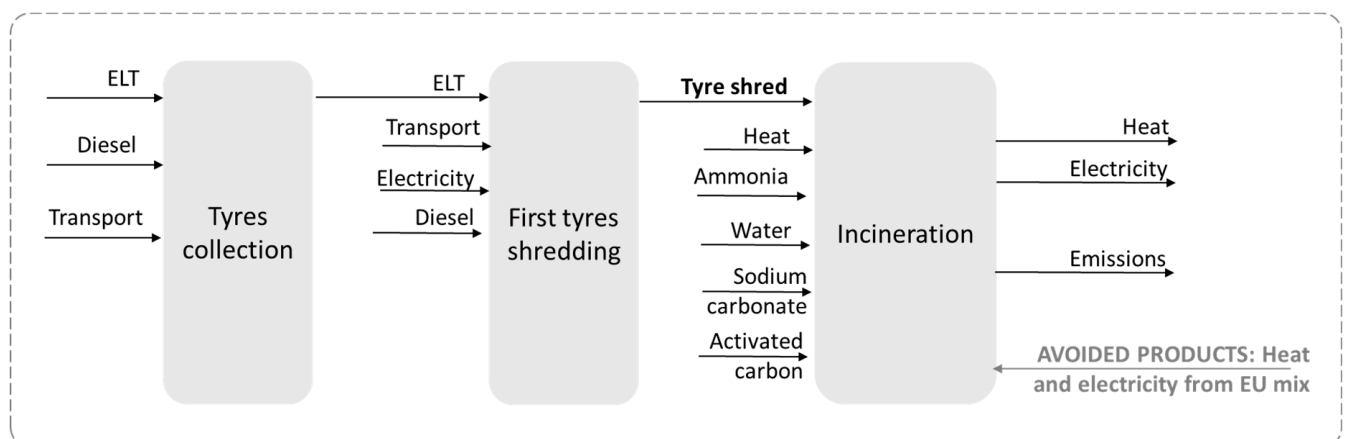


Figure 3. System boundaries of the energy recovery scenario.

When available primary data have been used. These have been integrated, when necessary, with secondary data from literature and Ecoinvent 3.4 database. For secondary data, particular attention has been paid to the geographical, technological and temporal representativeness, as specified in the next paragraphs. The LCA model has been developed with Simapro software.

The scenarios have then been analysed with the ILCD midpoint method for all the available impact categories, with particular attention to the categories of climate change (CC), particulate matter (PM), human toxicity-non cancer (HT-nc) and Mineral, fossil & renewable resource depletion (RD). These categories have been chosen because of their relevance for the analysed systems or for the interest in the international policies.

A contribution analysis has been developed as well to identify the processes that mostly contribute to the impacts or benefits of the analysed ELT scenarios.

### 2.3. Life Cycle Inventory

Inventory data used in the assessment are detailed in Table 1. The main source for the inventory of the CR recycle for asphalt rubber is a previous study of our working group (Farina et al., 2017). This latter provides recent primary data directly collected in quarries and hot mix plants of Piedmont (Italy). For this reason, data for this scenario are highly representative in geographical, temporal and technological terms. For the incineration data refers to the periodic measurements of TRM (Trattamento Rifiuti Metropolitan) [28]. This source ensures updated data, representative of the incineration in Piedmont (Italy).

**Table 1.** Inventory for the two analysed scenarios.

| O.                        | I | Dataset  | Quantity | Unit of Measure |
|---------------------------|---|--|----------|-----------------|
| <b>Recycling Scenario</b> |   |  |          |                 |
| X                         |   | Tyre collected   | 1        | t               |
|                           | X | Transport, freight, lorry 7.5–16 metric ton, EURO5 {RER}                         | 37.5     | tkm             |
|                           | X | Transport, freight, lorry 16–32 metric ton, EURO5 {RER}                          | 37.5     | tkm             |
|                           | X | Diesel, burned in building machine {GLO}   market for                            | 28.2     | MJ              |
| X                         |   | Tyres transported to shredding   | 1        | t               |
|                           | X | Tyre collected   | 1        | t               |
|                           | X | Transport, freight, lorry 7.5–16 metric ton, EURO5 {RER}                         | 9.4      | tkm             |
|                           | X | Transport, freight, lorry 16–32 metric ton, EURO5 {RER}                          | 69.8     | tkm             |
|                           | X | Transport, freight, lorry >32 metric ton, EURO5 {RER}                            | 70.6     | tkm             |
|                           | X | Transport, freight, inland waterways, barge tanker {RER}   processing            | 0.5      | tkm             |
| X                         |   | Granulate from tyres shredding   | 695      | kg              |
| X                         |   | Avoided product: Steel, unalloyed {RER}   steel production, converter, unalloyed | 199      | kg              |
| X                         |   | Avoided product: Viscose fibre {GLO}   viscose production                        | 106      | kg              |
|                           | X | Tyres transported to shredding   | 1        | t               |
|                           | X | Polypropylene, granulate {RER}   production                                      | 1.667    | kg              |
|                           | X | Packaging film, low density polyethylene {RER}   production                      | 0.185    | kg              |
|                           | X | Transport, freight, lorry 7.5–16 metric ton, EURO5 {RER}                         | 0.711    | kg              |
|                           | X | Tap water {Europe without Switzerland}   market for                              | 220      | kg              |
|                           | X | Lubricating oil {RER}   production   | 0.04     | kg              |
|                           | X | Polymer foaming {RER}   processing   | 0.185    | kg              |
|                           | X | Steel, unalloyed {RER}   steel production, converter, unalloyed                  | 0.29     | kg              |
|                           | X | Hot rolling, steel {RER}   processing  | 0.29     | kg              |
|                           | X | Sheet rolling, steel {RER}   processing  | 0.29     | kg              |
|                           | X | Electricity, medium voltage {IT}   market for                                    | 384      | kWh             |
|                           | X | Diesel, burned in building machine {GLO}   market for                            | 111      | MJ              |
| X                         |   | Wearing course with CR   | 1        | m <sup>2</sup>  |
|                           | X | Natural aggregate  | 79.65    | kg              |
|                           | X | Bitumen adhesive compound, hot {RER}   production                                | 2.41     | kg              |
|                           | X | Granulate from tyres shredding   | 0.43     | kg              |
|                           | X | Diesel, burned in building machine {GLO}   market for                            | 2.09     | MJ              |
|                           | X | Transport, freight, lorry 16–32 metric ton, EURO5 {GLO}   market for             | 4948     | kgkm            |

Table 1. Cont.

| O.                              | I | Dataset   | Quantity | Unit of Measure |
|---------------------------------|---|---|----------|-----------------|
| X                               |   | Avoided product: Standard wearing course  | 1        | m <sup>2</sup>  |
| X                               | X | Natural aggregate   | 104.1    | kg              |
| X                               | X | Bitumen adhesive compound, hot {RER}   production   | 2.54     | kg              |
| X                               | X | Diesel, burned in building machine {GLO}   market for   | 2.70     | MJ              |
| X                               | X | Transport, freight, lorry 16–32 metric ton, EURO5 {GLO}   market for                              | 6398     | kgkm            |
| <b>Energy Recovery Scenario</b> |   |   |          |                 |
| X                               |   | Tyre collected  | 1        | t               |
| X                               | X | Transport, freight, lorry 7.5–16 metric ton, EURO5 {RER}  | 37.5     | tkm             |
| X                               | X | Transport, freight, lorry 16–32 metric ton, EURO5 {RER}   | 37.5     | tkm             |
| X                               | X | Diesel, burned in building machine {GLO}   market for   | 28.2     | MJ              |
| X                               |   | Tyres transported to shredding  | 1        | t               |
| X                               | X | Tyre collected  | 1        | t               |
| X                               | X | Transport, freight, lorry 7.5–16 metric ton, EURO5 {RER}  | 9.4      | tkm             |
| X                               | X | Transport, freight, lorry 16–32 metric ton, EURO5 {RER}   | 69.8     | tkm             |
| X                               | X | Transport, freight, lorry >32 metric ton, EURO5 {RER}   | 70.6     | tkm             |
| X                               | X | Transport, freight, inland waterways, barge tanker {RER}   processing                             | 0.5      | tkm             |
| X                               |   | Tyres shred   | 1        | t               |
| X                               | X | Tyres transported to shredding  | 1        | t               |
| X                               | X | Electricity, medium voltage {IT}   market for   Cut-off, S  | 104      | kWh             |
| X                               | X | Diesel, burned in building machine {GLO}   market for   | 111      | MJ              |
| X                               |   | Electricity   | 9.6      | MJ              |
| X                               |   | Heat  | 16       | MJ              |
| X                               | X | Tap water {Europe without Switzerland}   market for   | 1.77     | kg              |
| X                               | X | Ammonia, liquid {RER}   market for  | 0.003    | kg              |
| X                               | X | Activated carbon, granular {RER}   activated carbon production, granular from hard coal           | 0.001    | kg              |
| X                               | X | Granulate from tyres shredding  | 1        | kg              |
| X                               | X | Heat, district or industrial, natural gas {RER}   market group for                                | 0.103    | MJ              |
| X                               |   | Emission in air: Carbon dioxide   | 0.9      | kg              |
| X                               |   | Emission in air: Ammonia  | 3.25     | mg              |
| X                               |   | Emission in air: Antimony   | 3.25     | mg              |
| X                               |   | Emission in air: Arsenic  | 3.25     | mg              |
| X                               |   | Emission in air: Cadmium  | 3.25     | mg              |
| X                               |   | Emission in air: Cobalt   | 3.25     | mg              |
| X                               |   | Emission in air: Chromium VI  | 3.25     | mg              |
| X                               |   | Emission in air: Dioxins (TEQ)  | 0.65     | ng              |
| X                               |   | Emission in air: Polycyclic organic matter, unspecified   | 0.65     | mg              |
| X                               |   | Emission in air: Manganese  | 3.25     | mg              |
| X                               |   | Emission in air: Mercury  | 0.325    | mg              |
| X                               |   | Emission in air: Carbon monoxide  | 325      | mg              |
| X                               |   | Emission in air: Nickel   | 3.25     | mg              |
| X                               |   | Emission in air: Nitrogen oxides  | 1.3      | g               |
| X                               |   | Emission in air: Sulfur oxides  | 325      | mg              |
| X                               |   | Emission in air: Particulates, unspecified  | 65       | mg              |
| X                               |   | Emission in air: Zinc   | 3.25     | mg              |
| X                               |   | Emission in air: Hydrogen chloride  | 65       | mg              |
| X                               |   | Emission in air: Hydrogen fluoride  | 6.5      | mg              |
| X                               | X | Fly ash and scrubber sludge {Europe without Switzerland}   market for fly ash and scrubber sludge | 0.04     | kg              |
| X                               |   | Hard coal ash {CH}   treatment of, municipal incineration   | 0.15     | kg              |

Starting from these data, a comparison has been developed to define whether it is environmentally more sustainable the recycle ELTs for the realisation of a wearing course or to incinerate the tyre shreds for the production of electricity and heat. To allow a clear LCIA comparison, the scenarios both refer to the end-of-life of 1 t of ELT, in particular:

- For the recycling into AR, it is considered the impact of the wearing course construction and the credits given by avoiding the construction of a traditional wearing course. This latter has been calculated according to the inventory provided by Farina et al. [19].

The different lifetime of the two ARs (20 years for the CR wearing course and 18 years for the traditional one) has been considered as well.

- For the incineration scenario are considered: (i) the impacts of the incineration process; (ii) the benefits due to the avoided production of electricity and heat through the standard processes.

### 3. Results

Impact results are provided in Table 2 with reference to the treatment of 1 t of ELTs, for the two analysed scenarios (recycling and incineration). As it can be noticed, both the options generally lead to environmental benefits. Therefore, the incineration scenario provides heat and electricity, avoiding the impacts of energy production through the “standard” processes (the average European grid mix is considered). Figure 4 shows impacts (red arrows) and benefits (green arrows) of the incineration scenario, with reference to the CC impact category.

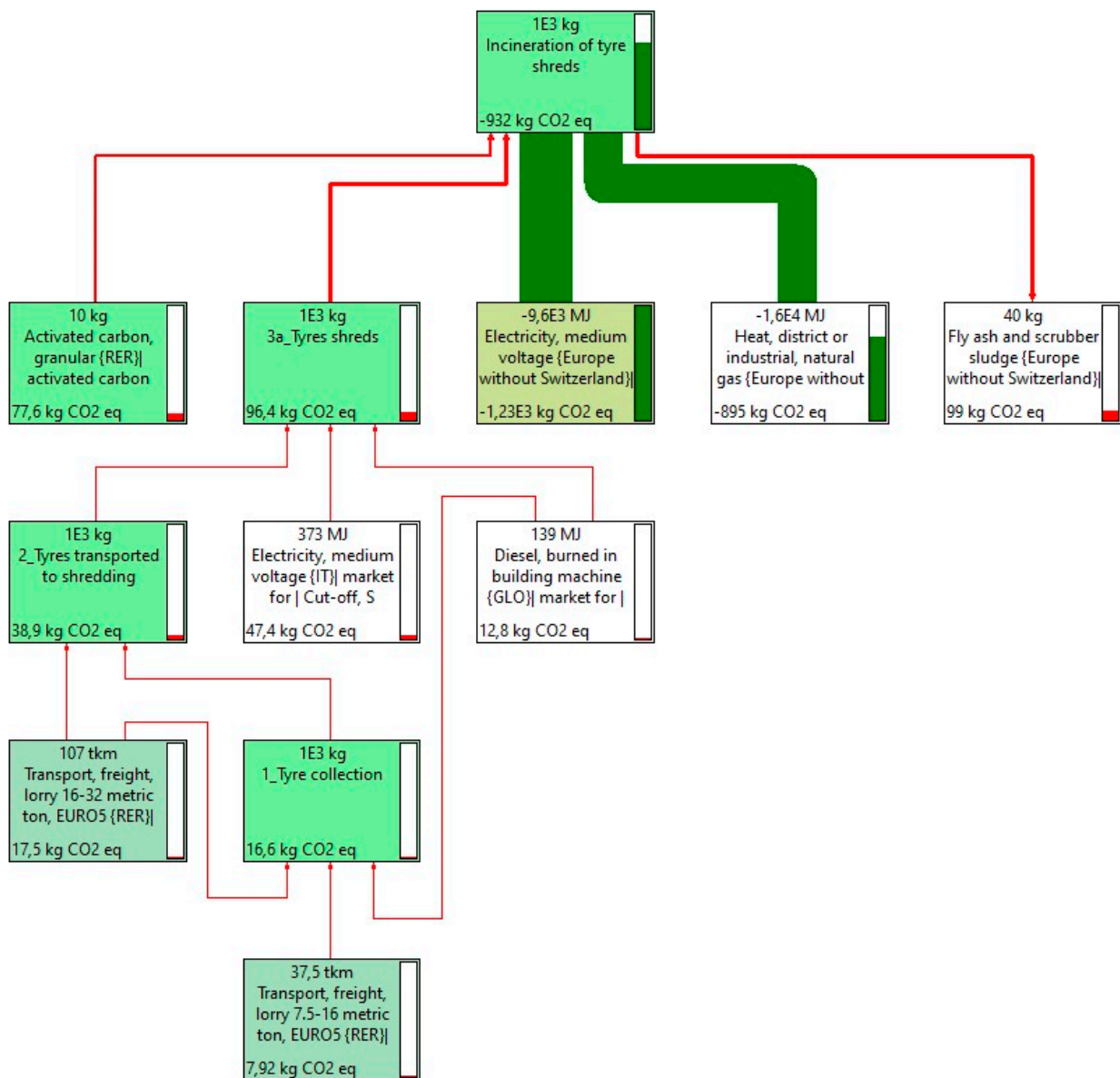


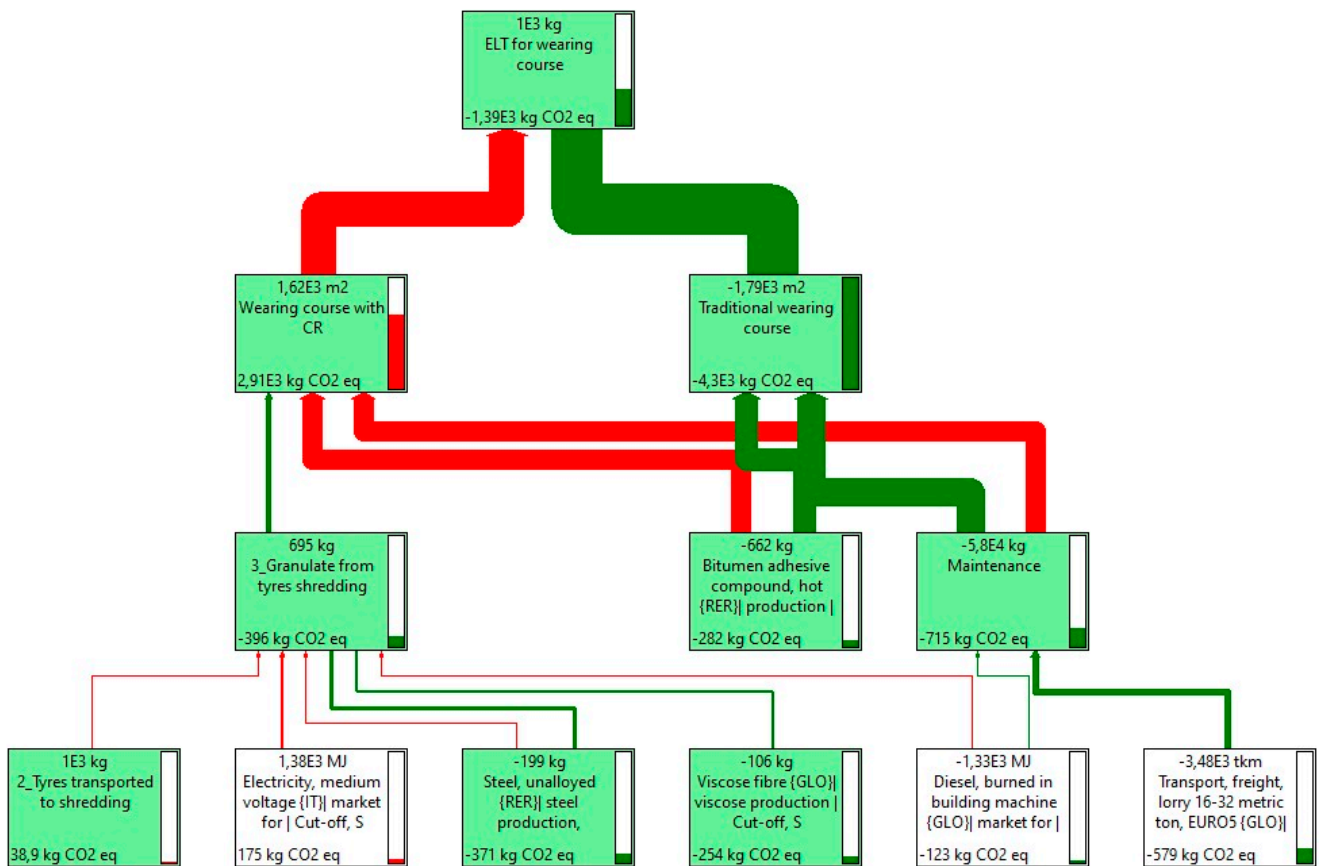
Figure 4. Flow chart with impacts and benefits of the incineration scenario.



**Table 2.** Impact results for the two analysed EoL scenarios for 1 t of ELT.

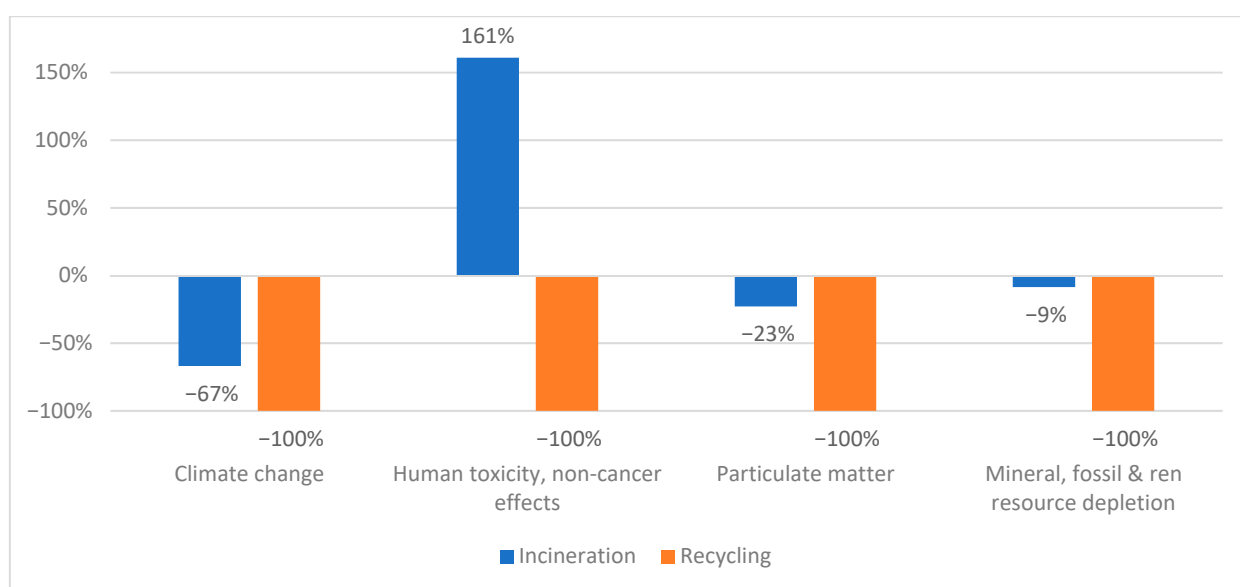
| Impact Category (Method: ILCD Midpoint)  | Unit                    | Incineration Scenario  | Recycling Scenario     |
|--|-------------------------|------------------------|------------------------|
| Climate change                           | kg CO <sub>2</sub> eq   | $-9.32 \times 10^2$    | $-1.39 \times 10^3$    |
| Ozone depletion                          | kg CFC-11 eq            | $-2.14 \times 10^{-4}$ | $-6.04 \times 10^{-4}$ |
| Human toxicity, non-cancer effects       | CTUh                    | $7.03 \times 10^{-4}$  | $-4.37 \times 10^{-4}$ |
| Human toxicity, cancer effects           | CTUh                    | $-5.70 \times 10^{-5}$ | $-1.32 \times 10^{-4}$ |
| Particulate matter                       | kg PM2.5 eq             | $-3.53 \times 10^{-1}$ | -1.54                  |
| Ionizing radiation HH                    | kBq U235 eq             | $-5.96 \times 10^2$    | $-2.10 \times 10^2$    |
| Ionizing radiation E (interim)           | CTUe                    | $-1.38 \times 10^{-3}$ | $-1.38 \times 10^{-3}$ |
| Photochemical ozone formation            | kg NMVOC eq             | -1.09                  | -8.92                  |
| Acidification                            | molc H <sup>+</sup> eq  | -5.72                  | $-1.06 \times 10^1$    |
| Terrestrial eutrophication               | molc N eq               | -6.98                  | $-2.14 \times 10^1$    |
| Freshwater eutrophication                | kg P eq                 | -1.11                  | $-3.83 \times 10^{-1}$ |
| Marine eutrophication                    | kg N eq                 | $-5.22 \times 10^{-1}$ | -2.18                  |
| Freshwater ecotoxicity                   | CTUe                    | $-4.73 \times 10^3$    | $-8.87 \times 10^3$    |
| Land use                                 | kg C deficit            | $-6.47 \times 10^2$    | $-9.13 \times 10^3$    |
| Water resource depletion                 | m <sup>3</sup> water eq | -7.77                  | $9.46 \times 10^{-1}$  |
| Mineral, fossil & ren resource depletion | kg Sb eq                | $-6.62 \times 10^{-3}$ | $-7.71 \times 10^{-2}$ |

On the other hand, through the recycling of ELT it is possible to recover rubber granulates, as well as steel and textile (these latter considered as avoided products, with a system expansion approach). In addition, the use of CR in asphalt wearing course allows to reduce the employment of primary raw materials and to extend the service life of the wearing course. Analogously to Figures 4 and 5 show impacts and benefits of the recycling scenario for the CC impact category.



**Figure 5.** Flow chart with impacts and benefits of the recycling scenario.

For most part of the impact categories, the recovery of material results providing higher environmental benefits than energy recovery. This result is in line with the Waste Framework Directive. Figure 6 shows the relative impacts/benefits of the two scenarios for the categories of CC, HT-nc, PM, RD. As it can be noticed, the employment of CR for roads construction results a better environmental choice for all these four categories. The highest benefits of recycling against incineration is reached for the category of human toxicity (non-cancer): while ELT incineration causes impacts (in absolute value  $7.03 \times 10^{-7}$  CTUh), the ELT recycling provides environmental credits (in absolute value  $-4.4 \times 10^{-7}$  CTUh). For the categories of CC, PM and RD, both the scenarios are responsible of environmental benefits, even though these latter are lower for incineration in comparison to recycling (67% for CC, 23% for PM, 9% for RD). The life cycle extension of the CR wearing course (20 years) against the traditional one (18 years) contributes to the 11% of the benefits of the recycling route. The only impact categories showing better results for incineration are the Ionising radiation HH, freshwater eutrophication and water resource depletion.



**Figure 6.** Percentage difference between impacts of recycling and incineration scenarios (the lowest value is fixed as  $-100\%$ ). A negative value means an environmental benefit, a positive value means an environmental impact.

#### 4. Discussion

The main aim of this study was to assess and compare the environmental consequences of two alternative end of life scenarios for ELTs: the recycling and the energy recovery. The recycling of ELTs has been largely studied by previous literature and several uses of CR have been identified. This study analysed its use for the realisation of an asphalt wearing course, whose composition was developed in the study of Farina et al. [19]. The incineration of ELT is a quite widespread technique, since ELTs have a high calorific value, of about 7500–8000 kCal/kg [29]. This latter scenario has been largely debated because from one hand it allows energy recovery, but from the other hand it is responsible of emissions into air released during the combustion.

The LCA analysis presented in this paper was developed with a system expansion approach, thus considering as well environmental credits coming from the products whose production has been avoided thanks to the incineration/recycling. Results show that for most impact categories both scenarios provide environmental benefits, even though the recycling one is generally preferable. Impacts and benefits of the incineration scenario are representative of an Italian incineration plant, but probably other incineration plants have similar input/output flows, since this technology is currently quite consolidated. On the contrary, the results of the recycling scenario are representative of a specific use of the

CR (the construction of wearing course) and, as a consequence, different impact results could be found from the analysis of other CR employments. Despite the analysis is in some aspects specific, the results are therefore in line with the waste management hierarchy.

As found in literature, the attention and the enhancements in ELT recycling and applications has grown in the last decades. However, the significant volumes of ELTs hinder a complete recycling of tyres and, as a consequence, the incineration could represent a valid alternative.

Finally, it has to be underlined that the ELT energy recovery analysed in this study is the incineration in a dedicated plant, but also other incineration scenarios are of common practice, such as the incineration in cement kilns. In this latter case, ELTs generally substitute the fuel (usually pet coke), that means, from a Life Cycle perspective, that the impacts related to the production and combustion of fuel are avoided.

## 5. Conclusions

This study has developed a comparative LCA between two common scenarios for ELTs: the recycling of CR for the construction of roads wearing course and the incineration of tyre shreds for energy recovery. For both the scenarios, the LCA has been modelled with a system expansion to consider both the impacts of the recycling/incineration and the credits derived from the respective avoided products (the steel and textile co-products of the ELT shredding, the construction of a traditional wearing course, for the recycling, and the production of electricity and heat, for the incineration). Results show that for most of the impact categories analysed through the ILCD midpoint method, the recovery of CR for its use in civil works has higher benefits than the energy recovery in incineration plants. These results confirm the indications given by the Waste Framework directive, suggesting that, when possible, the material recovery should have the priority on the energy recovery.

This study provides environmental data on two ELTs scenarios. Further end-of-life scenarios can be analysed to have a clearer overview. In addition, it is necessary to underline that LCA is able to analyse impacts on different categories, but it still remains difficult to use this methodology to analyse local environmental and sanitary issues. For example, LCA is hardly applicable to identify the impact on worker health. Further studies should therefore focus on the integration of LCA impact results with other aspects of sustainability.

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