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Cost-benefit analysis of a circular economy project: a study on a recycling system for end-of-life tyres

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Abstract

End-of-life vehicles (ELV) represent a relevant waste source in Europe, even if ELV recycling is a priority of the European Union waste legislation and Environment Action Programmes (EAPs). End-of-Life Tyres (ELTs) constitute a relevant portion of ELV waste. Textile fibre, which is a relevant portion of the ELT material, is considered as a special waste (European Waste Catalogue – EWC code 19.12.08). The main problem related to textile fibre is its contamination with rubber which does not allow to obtain a pure product economically and qualitatively usable.

The aim of this paper is to illustrate an innovative technology for ELT fibre's recycling, which allows to transform textile fibre into a useful secondary raw material for different applications.

In particular, the use of ELT fibre as additive for bituminous conglomerates has been investigated. The different processes have been analysed from an environmental point of view, applying the Life Cycle Assessment methodology. It came up there is an impact reduction in case the ELT fibre is reused as additive for bituminous conglomerates, instead of disposing it (through incineration).

Moreover, the financial and economic sustainability of the related technological process has been evaluated to check whether the process is sustainable in the long term. Starting from the results of the Life Cycle Assessment, economic performance indicators have been calculated, by applying the European Commission methodology for cost-benefit analysis. According to the present cost-benefit analysis, in the medium and long term the system is financially viable, and the high economic profitability makes the process economically sustainable. Furthermore, a sensitivity analysis as well as a risk assessment have been carried out in order to identify critical variables, evaluate risks and define risk mitigation measures. According to the sensitivity analysis performed, the project is not highly risky since even in the worst scenario the possible loss is moderate.

Based on the results of this analysis, it can be concluded that this ELT fibre's recycling system can be replicated across Europe, conveniently fostered by national policies (such as subsidies, value added tax etc.).

Keywords: circular economy, end-of-life tyres, cost-benefit analysis, second applications.

1. Introduction

Nowadays, end-of-life vehicles (ELVs) constitute a massive waste source in Europe, even if ELV recycling is a priority of Union waste legislation, as underlined in the ELV Directive 2000/53/EC (European Commission, 2000).

End-of-life tyres (ELTs) constitute a major portion of the ELV waste: every year, about 3.4 million tonnes of old tyres are disposed of in Europe, most being dumped or sent to landfill, in direct contravention of the EU rules banning landfilling of both whole and shredded tyres (EASME, 2015; ETRMA, 2015; European Directive 2000).

The Italian law defines the legal framework and assigns the responsibility to the producers (tyre manufacturers and importers) to organise the management chain of ELTs (DL 2006; DM 2011; DM 2012). The crucial steps are collection, sorting, transformation and recovery in authorized treatment companies. The treatment and the recovery process of ELTs is primarily aimed at recovering triturated rubber in various sizes and types, which represents the main portion of the ELT material (Ramarad et al., 2015; Schnubel, 2014; WBCSD, 2010). During the treatment of tyres, two other sub-products are generated in significant quantities, namely steel and textile fibre (Pacheco-Torgal et al.; 2012; Ecopneus, 2013).

Regarding the textile fibre's recycling, the main problem is the presence of rubber within the ELT fibre (40-60%), which makes it impossible to obtain a pure product economically and qualitatively usable. The cleaning practice is not commonly adopted due to the absence of a market that justifies the required efforts and resources. The main consequence is that both ELT treatment companies and end-users are discouraged to invest in fibre's recycling; thus, the dirty fibre goes to landfill or to waste incineration plants and cement production furnaces (ETRMA, 2015; Ecopneus, 2013).

Besides these problems, the use of fibre as recovery material presents mechanical and technological limitations. After the process, the textile fibre takes the form of "soft bundles", which poses numerous problems such as: 1) the fibre bundle materials cannot be mixed and dispersed uniformly within any material (such as plastic compounds or bitumen conglomerates); 2) due to the accumulation of electrostatic charge within the bundles, an electrostatic effect is generated (called "bridge effect"), which, together with the fibre morphology, tends to obstruct the loading and extruding phases; 3) the low specific weight of fibre bundles (140 kg/m³) makes their transportation too expensive, hence strongly limiting the possibility of selling them in the market. For these reasons, as mentioned, ELTs are usually disposed.

The present paper focuses on the use of the ELT fibre as reinforcement in asphalt. The value of roads and infrastructures realized with the reinforced asphalt mix is expected to be higher due to a longer lifetime (a lifetime of 40-50 years is expected, while the lifetime of "normal" asphalts is 6-7 years) (Gonzalez et al. 2012, Liang et al., 2015). Moreover, the new conglomerates can be used in different climatic conditions ensuring wider market opportunities as well as replication across the EU. Furthermore, due to its mechanical properties, the new asphalt will consistently reduce the public procurement costs related to the rehabilitation and maintenance of roads and infrastructures (Blessen, 2016).

Besides presenting this new technological process, the aim of this paper is to assess its environmental and economic sustainability, by conducting a Life Cycle Assessment (LCA) analysis as well as a cost-benefit analysis (CBA).

This research draws primarily on the European Commission’s “Guide to Cost-Benefit Analysis of Investment Projects” and on the European Investment Bank’s “Economic Appraisal of Investment Projects at the (EIB)”. The former illustrates principles and rules to apply the CBA approach in different sectors, while the latter presents the economic appraisal methods that the EIB adopts in order to assess the economic viability of projects.

The present paper is organized as follows: Section 2 illustrates the project background, the cost-benefit methodology and Life Cycle Assessment methodology. In Section 3 results of the two analyses are presented, while in section 4 the financial sustainability and the economic performance of the process are discussed, together with the results of the risk assessment. Lastly, in Section 5 conclusions and recommendations are drawn.

2. Methodology

2.1. Background of case study

Three phases compose the usual ELT disposal process. The first phase is the production of ground particles accompanied by the removal of the metallic fraction. For this phase, a double shaft grinder (which includes single knife elements), as well as electricity, water and oil are employed. The second phase consists in grinding the ground particles to reduce their dimensions. The equipment used in this phase is a fixed external cylinder (equipped with blades) which contains a rotating cylinder with blades that fit the ones on the external cylinder, thus crunching the inlet material. To remove the dust, a suction system equipped with fabric filters is also employed. Magnetic belts are used for iron scrap separation. The last phase is the pulverization and separation of the tyre material. A machinery composed of a fixed and a rotating disk, equipped with blades, is used. A fan is utilised to separate the granule from the rubber powder.

Figure 1 shows the current process of the ELT disposal (Business-As-Usual process).

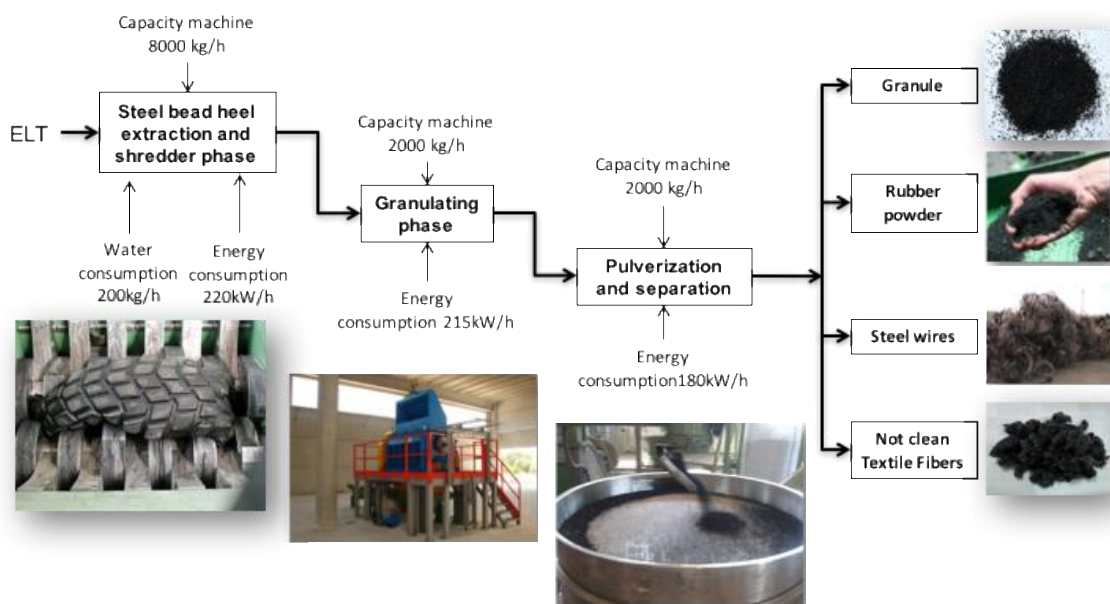


Figure 1 - ELT disposal process in Business-As-Usual scenario

In the REFIBRE project, ELTs cleaning and compacting process are integrated into the ELT disposal process. Through the cleaning of the textile material, in addition of recovering rubber

dust, it is possible to reduce the fibrous material produced. The cleaning operation itself is beneficial from both an economic and environmental point of view. Starting from this activity, the REFIBRE project aims to completely eliminate the ELT disposal, implementing the circular economy concept: once the ELT fibre has been cleaned, it can be used as a reinforcing material in different applications (such as bituminous conglomerates and plastic compounds). For both second life applications, a fibre compaction is required to simplify the subsequent dosing and mixing phases. Figure 2 shows the disposal process within the REFIBRE project. The compacted fibre can be used as a second life raw material.

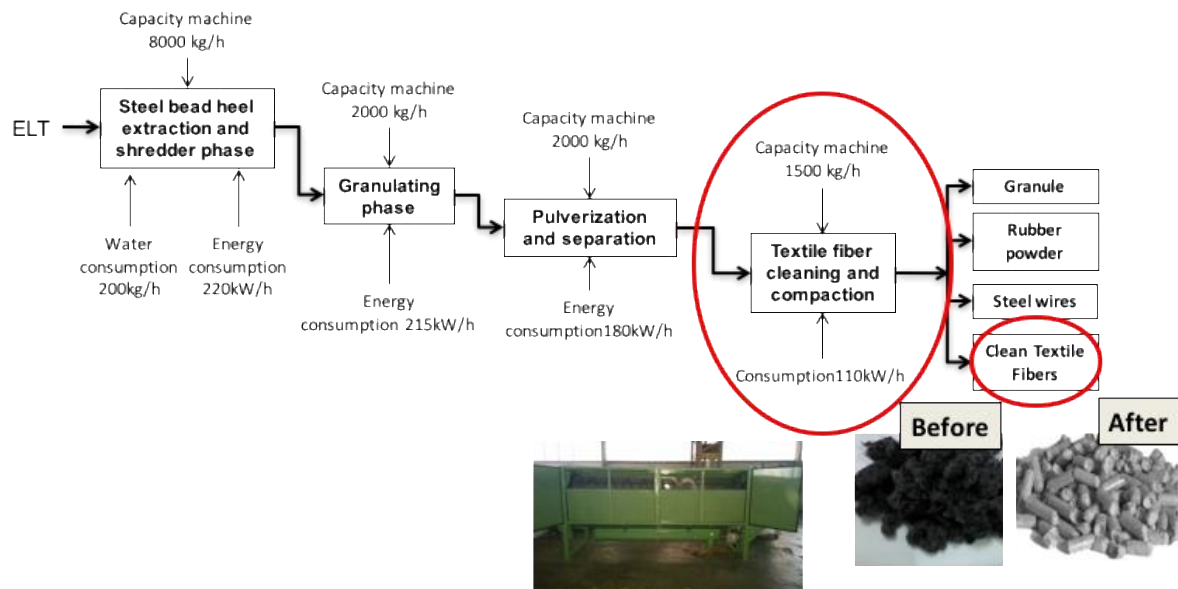


Figure 2 – ELT treatment process in With-the-Project (WP) scenario

2.2. Cost-benefit analysis: framework

The CBA aims at identifying and valuing the impacts of a project in terms of their effects on social well-being, comparing the positive effects (benefits) with the negative effects (costs).

The essential theoretical foundations of CBA are:

- costs and benefits are expressed in monetary terms to allow comparison;
- the present value of benefits must exceed the present value of costs;
- the incremental approach is adopted (comparing a scenario with-the-project with a counterfactual baseline scenario without-the-project).

According to the European Commission guidelines, the CBA should be conducted following seven steps:

1. Description of the context
2. Definition of objectives
3. Identification of the project
4. Technical feasibility & Environmental sustainability
5. Financial analysis
6. Economic analysis
7. Risk assessment.

For further details on the procedure, it is possible to refer to the above-mentioned guidelines.

Regarding the description of the context and definition of objectives, information on this matter has been provided in the introduction and in the previous paragraph. The other sections of the present paper will focus on the financial and economic analysis, along with the risk assessment.

Inflows and outflows considered in the financial analysis are the following ones:

Table 1- Financial inflows and outflows

INFLOWS	OUTFLOWS
Revenues	Initial investment
Sources of financing	Replacement costs
Residual value of the fixed investments	Operating costs
	Reimbursement of loans and interest payments
	Taxes on capital/income and other direct taxes

The difference between inflows and outflows constitutes the deficit or surplus accumulated each year. A project is financially sustainable if the cumulated cash flow is positive for the entire period considered.

In order to move from the financial analysis to the economic one, it is necessary to perform the following adjustments:

1. fiscal corrections
2. conversion from market to shadow prices
3. evaluation of non-market impacts and correction for externalities.

After performing the financial and the economic analysis, a crucial operation is the discount of costs and benefits, using the Social Discount Rate (SDR). Once costs and benefits have been discounted, the project economic performance is measured by the Economic Net Present Value (ENPV), Economic Rate of Return (ERR) and Benefit/Cost ratio (B/C ratio).

The ENPV is the difference between the discounted total social benefits and costs:

$$ENPV = PV(B) - PV(C) \quad (1)$$

where PV(B) refers to the present value of economic benefits, PV(C) refers to the present value of economic costs, with present values calculated at the social discount rate (Pearce D. et al, 2006).

The Economic Rate of Return is calculated as follows:

$$B_0 - C_0 + \frac{B_1 - C_1}{(1+i)} + \frac{B_2 - C_2}{(1+i)^2} + \dots + \frac{B_T - C_T}{(1+i)^T} = 0 \quad (2)$$

Where i is the ERR, namely the discount rate that solves the equation.

The B/C ratio is the ratio between discounted economic benefits and costs:

$$B/C = \frac{PV(B)}{PV(C)} \quad (3)$$

2.3. Cost-benefit analysis: methodology choices

In order to perform a cost-benefit analysis, preliminary methodology choices were made:

1. The reference period considered in the analysis is 30 years, so as to evaluate the environmental and economic effects during the system implementation as well as its outcomes after the implementation. Moreover, a period of 30 years is in line with the recommendations made by the European Commission as regards to the CBA.
2. In accordance with the case study on waste management presented by the European Commission in its “Guide to Cost-Benefit Analysis of Investment Projects” the residual value is set at zero since it is assumed that at the end of the reference period the plant and machines will have provided nearly all their potential, hence the market value will be negligible (European Commission, 2014).
3. The choice of a correct social discount rate is crucial. Percoco estimated a social discount rate for Italy finding that a 3.7–3.8 rate would be appropriate (Percoco M., 2007). According to Better regulation guidelines, “the recommended [real] social discount rate is 4%” (European Commission, 2015). According to Annex III to the Implementing Regulation on application form and CBA methodology, for the programming period 2014-2020, the European Commission recommends that “for the social discount rate 5 % is used for major projects in Cohesion countries and 3 % for the other Member States” (European Commission, 2014). Due to this controversy about the precise value of an appropriate rate, two alternative discount rates, 4 % and 3%, have been used to discount costs and benefits.
It is noteworthy to mention that different experts have raised the problem of the so-called “tyranny” of discounting.

As illustrated in the OECD “Cost-Benefit Analysis and the Environment”, keeping a constant discount rate such as 4%, environmental damage 100 years from now would be valued at just one fiftieth of the value that would be assigned to it if it occurred today. Therefore, it is suggested to adopt a time declining discount rate, even if “time-consistency problems remain and some experts would regard any time declining discount rate as being unacceptable because of such problems” (Pearce D. et al, 2006).

In the present paper, it has been decided to not adopt a time declining discount rate for two reasons:

- the European Commission (EC) guidelines do not recommend the use of this type of discount rate;
- regarding the monetization of costs and benefits, it has been observed that: (i) emissions have been expressed in monetary terms taking into account an increase in value per year (this will be explained in the following section); (ii) the value of SO₂ emissions considered

in this study is fixed, however the total value of SO₂ emissions has a limited impact on the total value of benefits; (iii) costs considered in the analysis do not refer to environmental damages.

2.4. Life cycle assessment

As mentioned, the CBA is based on the results of the LCA, which evaluates and quantifies the environmental impact of a product throughout its lifetime (from the production of raw materials to the end-of-life stage, including all the intermediate steps). In this case, the environmental impact has been evaluated using the methodology defined in the standard ISO 14040 (ISO, EN ISO 14040,2006), ISO 14044 (ISO, EN ISO 14044, 2006). Companies can rely on LCA to identify, assess, consolidate, interpret and disseminate data on the environmental impacts generated by their activities.

The LCA consists of four independent stages: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and life cycle interpretation phase.. During the first stage, the functional unit and the system boundaries are determined. In the second stage, the full life cycle is decomposed into elementary steps and for each step the energy balancing and the material balancing are carried out. All the environmental impacts are evaluated in the third stage: for each flow identified during the LCI, a specific characterization factor determines its impact in the studied impact category. For the LCI, a large amount of data is required. Primary data is necessary for the assessment of foreground processes (i.e., core processes, directly related to the product system at stake) and background processes (i.e., not specifically related to the product system). These processes comprise input and output flows. Input flows include consumed products (e.g., materials, services, consumables, etc.), input of wastes (in the case of waste management services) and resources from nature (i.e., from ground, water, air, biosphere, land, etc.). Output flows comprise waste (e.g., solid, liquid and gaseous waste for waste management), emissions to air, water and soil as well as the final goods and services being produced. Each of these flows includes several variables (e.g., productivity, distance travelled, types of transport used, quantities of materials and energy used, etc.) that might be taken into consideration during the data collection (European Commission, 2010b). Background processes' data related to basic commodities are common secondary data sources for LCA practitioners. The LCIA phase enables to evaluate the environmental impacts of the street sweeping services investigated in the case study, with the relative contribution of each single stage included in the system boundaries. For each scenario, data regarding energy and material consumption, emissions and waste are converted into environmental impacts over numerous categories. A specific score is finally obtained for each impact category analysed and, starting from these results, an interpretation of the environmental performances of the product/system is provided. In this last phase, the principal indicators are defined considering the analysis' objectives. Furthermore, the main causes of the impacts analysed are identified.

2.5. LCA: goal and scope definition

The goal of this case study is to determine whether and in what extent the different end-of-life treatments of the ELT fibrous material affect the environmental impact. According to Directive 2008/98/EC, a Life Cycle approach should be adopted to assess and compare the overall environmental impact of different waste treatment scenarios in order to identify the best environmental solution. A previous study (Landi et al., 2015, Landi et al., 2018, Marconi et al., 2018) provided a comparison between different second life applications of the fibrous material in terms of environmental benefits and waste disposal reduction.

In this paper, the aim of the LCA analysis is to assess the environmental impact of the textile fibre deriving from different end-of-life tyres. Two different scenarios are considered:

- Business-As-Usual scenario (BAU): the textile fibre, after the cleaning process, is transported to the incineration plant in Switzerland.
- With-the-Project scenario (WP): the textile fibre is treated so as to obtain pellets which are stored in big bags. Afterwards, these pellets are transported to Toto S.p.A Costruzioni plant, where are triturated and then introduced to the processing of bituminous conglomerate.

The functional unit that has been chosen is the amount of fibre that Steca S.p.A is able to clean in a year, which is equal to 787,5 tonnes (3.150 kg/day multiplied by 250 working days). The textile fibre derives from the annual production of 15.000 tonnes of ELTs, considering a plant capacity of 60 tonnes/day and a 16-hour daily production of ELTs. The current study is a “gate to gate” one; thus, the considered system boundaries include all the activities related to a specific life cycle phase of the textile fibre. More specifically, it includes all the different processes, from the cleaning of the textile fibre to its incineration or its reuse for the production of bituminous conglomerates. Therefore, all the transport phases are considered in the study. On the contrary, other phases are excluded: (i) secondary processing (for instance, the movements within the different plants), (ii) manufacturing of the transportation vehicles, (iii) possible losses caused by the inefficiency of transports, (iv) manufacturing of the plant for the fibre’s treatment. The latter assumption is justified by the fact that the entire lifetime of the plant is much longer than the period considered for the chosen functional unit (i.e. one year).. Therefore, the construction of the process plant and equipment have not been included in the LCA study.

System boundaries are illustrated in the following figures:

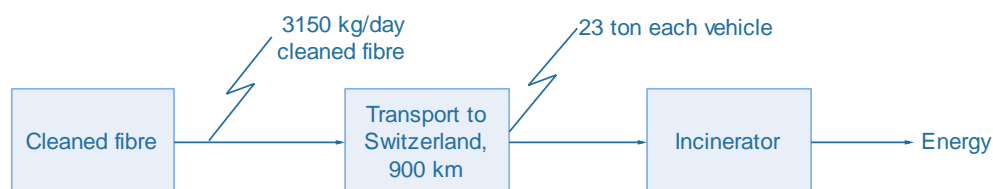


Figure 3 - Scenario Business-As-Usual, system boundaries

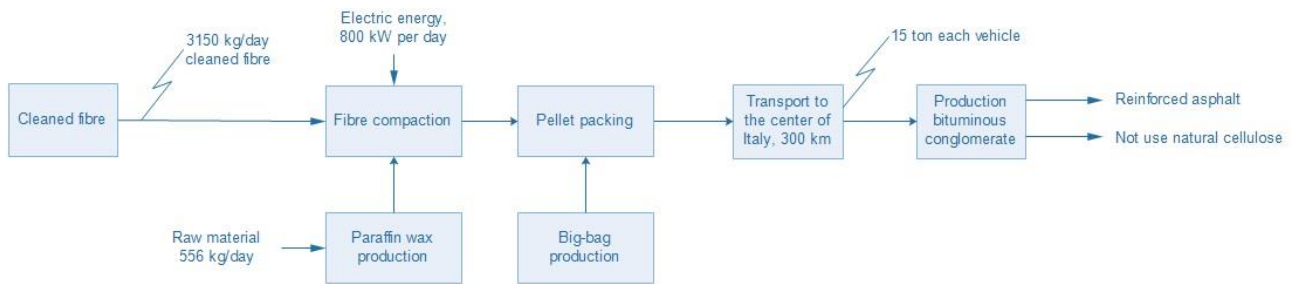


Figure 4 –Scenario With-the-Project, system boundaries

For the purposes of the current LCA, a cut-off has been applied to all the energy intensive processes with an impact on the total energy consumption lower than 1%. The following assumptions have been made during the Life Cycle Inventory phases:

- for all the transport phases, Euro 5 Diesel articulated vehicles have been chosen, considering an Italian average (Myrsini et al, 2007);
- for the transport of the ELT fibre to the Swiss plant (the distance is about 900 km), it has been considered a Euro 5 Diesel articulated vehicle with a load capacity of 23 tonnes (12,4 tonnes net) which is fully loaded before the departure;
- it has been considered the 2012 Italian energetic mix, included in the software database used (according to a recent academic paper, this energy mix can be considered valid (Cucchiella et al, 2017));
- it has been assumed that the volume reduction of pellets (compared to the fibre in its natural state) is equal to 10 times;
- concerning the calculation of the energy consumption related to pellets production, it has been considered an annual activity of the machine equals to 2.000 hours;
- as regards to the energy consumption related to pellets shredding, it has been supposed a consumption of 50 kg of pellets for a cycle of bituminous conglomerate (10 seconds).

Regarding the cut-off, all processes with an impact on the total energy consumption that is lower than 1 % have been neglected.

2.7. LCA: life cycle inventory analysis

Life cycle inventory (LCI) data fall into two main categories: primary data and secondary data. Primary data, which includes all the relevant inputs and outputs directly related to the processes, has been collected by interviewing the key managers of the companies included in the scenarios under investigation. Data related to the fibre realization and transport has been provided by Steca S.p.A, while data related to the consumption of the machinery for the treatment of fibre to be introduced in the bitumen manufacturing process has been provided by Tires S.p.A. Interviews with Toto S.p.A's employees have been conducted as regards the laying of the bituminous conglomerate (Table 2; Table 3).

Table 2 - Inventory Data Business-As-Usual scenario

Description	Value
Clean fibre	787.5 tonnes

Fibre mass fraction within the tyre	10%
Manual compact time	1,5 h
Lorry's load capacity	25 tonnes
Distance (Steca S.p.A – Forsthaus)	900 km
Fibre disposal cost	100 €/tonnes

Table 3 - Inventory Data With-the-Project scenario

Description	Value
Clean fibre	787.5 tonnes
Paraffin wax cost	1.000 €/tonnes
Pellet machine cost	300.000 €
Compression ratio	1/10
Pellet shredder cost	2.000 €
Mass fraction of additive pellets (wax paraffin 10%)	78.75 tonnes
Hourly consumption pellet processing machine	20,000kWh
Distance (between companies)	300 km
Quantity transported (volume limit)	14 tonnes
Percentage of fibre in each tonne of bituminous conglomerate	0,03%
Hopper energy consumption	10 kWh
Shredder energy consumption	42kWh
Cycle time shredder	10 s
Mass chopped pellets per cycle	50 kg
Avoided cellulose consumption	787.5 tonnes
PP for “big bag” production	340 kg

Regarding the energy model developed for the electricity supply and generation, an electricity production mix has been elaborated using the data given by the Energy Market Regulatory Authorities (EMRA, 2013), and considering the general electricity transportation efficiency presented by the Ecoinvent database equipped with the GABI Software Version 8.1.

The environmental impact caused by the incinerator has been assessed according to the principles included in Boesch's study (Boesch M. et al, 2014). This model includes combustion with a grate

incinerator, several flue gas treatment technologies, electricity and steam production from waste heat recovery, metal recovery from slag and fly ash, and landfilling of residues. It is noteworthy to underline that Boesch's model can be tailored according to specific plants and sites.

Other secondary data, such as emissions due to the extraction and processing of equipment, has been collected from the PE International (PE International, Germany), the Ecoinvent 3.1 databases using the Gabi 7 platform, and academic papers (Huang et al., 2011; Wu, 2014).

2.8. LCA: Life cycle impact assessment

The Life Cycle Impact Assessment (LCIA) characterizes the environmental impact based on the LCI results using certain characterization models (ISO, 2006a, ISO, 2006b).

The LCIA method used for the calculation of the environmental impacts is ReCiPe mid-point - Hierarchist (H) version - Europe (Goedkoop et al. 2009, Huijbregts et al. 2017).

Since the object of this study is an industrial process, energy and natural resources are of primary importance. In order to consider these aspects, this study uses Human Health (HH) and Resources (RA) mid-point impact categories as well as Human Health (HH) Ecosystem quality (ED) and Resources (RA) end-point damage categories from the internationally accepted method ReCiPe (H) (Goedkoop et al. 2009, Huijbregts et al. 2017). The climate change impact category within the ReCiPe mid-point (H) method includes all greenhouse gases specified in the Kyoto Protocol using global warming potentials from the IPCC Fourth Assessment Report, with a 100-year time horizon (IPCC 2007).

The default ReCiPe mid-point method perspective used is the Hierarchist (H) version which refers to the normalisation values of Europe. Perspective H is based on the most common policy principles with regards to 100 [year] timeframe (as referenced in the ISO 14044:2006 standards on LCA).

The average results of the LCA analysis are reported in Figure 5 and Table A.1. The latter shows the process impact of the two scenarios described.

The results of the characterisation process illustrate the contribution of each scenario to the selected impact categories.

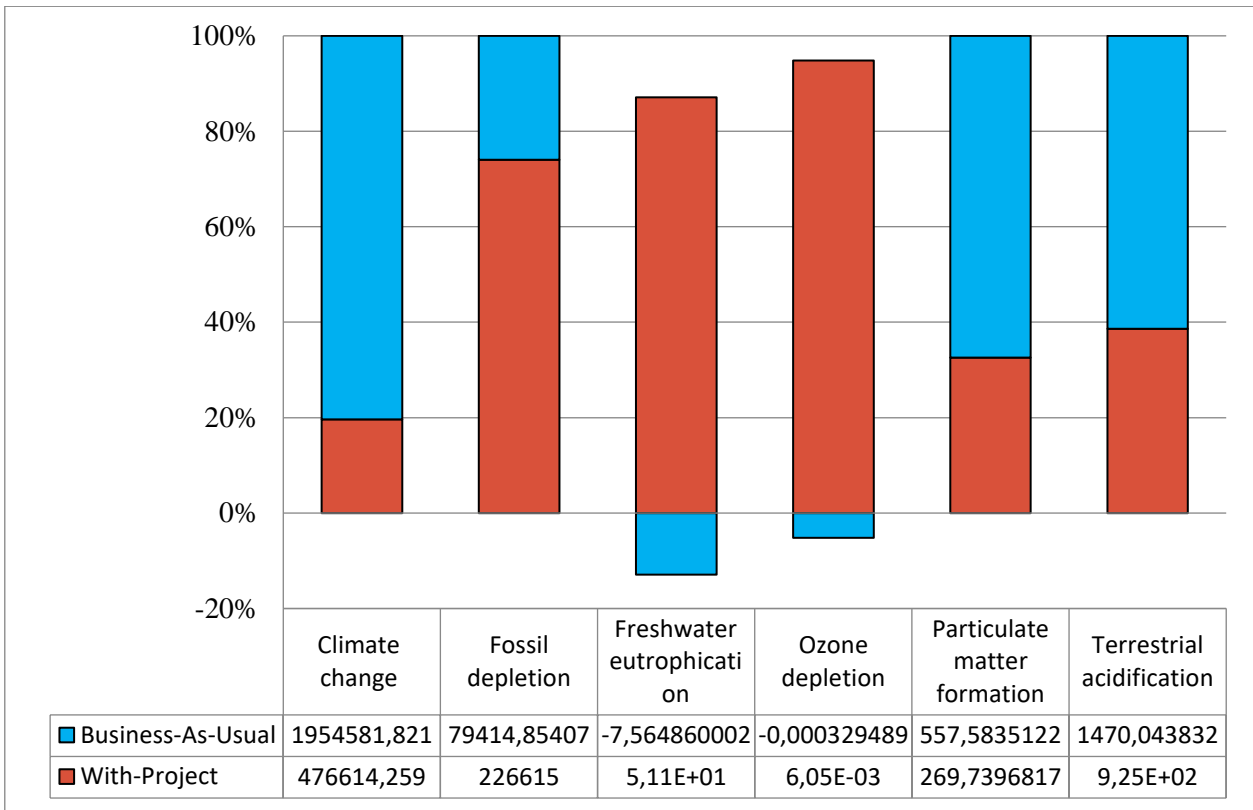


Figure 5 – Characterized LCA result

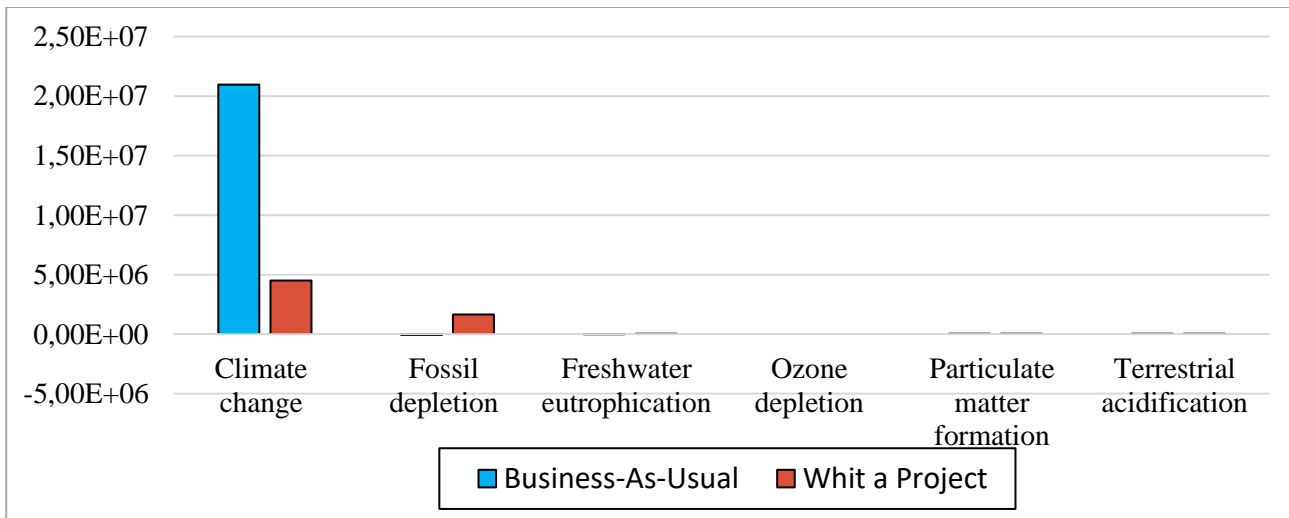


Figure 6 – Comparison between two scenarios

3. Results

3.1. LCA: life cycle interpretation

In Figure 5 and Table 4, the average contribution of both scenarios for each impact category is reported. At first sight, neither scenario presents a clear environmental benefit.

Solely specific impact categories have been considered in this analysis, as some categories have not gained a world-wide recognition in the scientific community, differently from "toxicity" category (Renou et al., 2008). Other categories related to terrestrial transformation and terrestrial occupation have not been taken into account since they are not considered in the Midpoint Health and Human Resources category (Goedkoop et al., 2013).

A particular attention is given to climate change indicator as well as to indicators related to the loss of material and resources, eutrophication, acidification and particulates. As shown in Figure 3, according to three indicators, from an environmental point of view, it is convenient to reuse the fibre, while for the remaining three indicators it is more convenient to dispose the fibre. As explained above, the fibre to be included into the asphalt production process must be extruded to obtain pellets, in order to facilitate the storage, transport and dosing phases. Particular attention is to be paid to the fibre compaction process because of the high consumption of electricity and the use of the paraffin wax required to reduce the temperature reached during the extrusion phase. In the WP scenario, the main environmental benefit is the non-production of virgin cellulose used for the production of reinforced asphalt. On the other hand, in the BAU scenario, the incineration phase presents a significant environmental impact; however, through this phase, it is possible to obtain both energy and heat. Due to all these factors, different indicators provide different results.

3.2. CBA: financial analysis

As mentioned in Section 2, the incremental approach is adopted, comparing the (Business As Usual) BAU and the With the Project (WP) scenarios.

The main differences between the BAU and the WP scenarios are the following ones:

- in the BAU scenario, Steca S.p.A. disposes the ELT fibre, hence costs related to the disposal are included in the analysis;
- in the BAU scenario, the energy produced by the incineration is sold;
- in the WP scenario, the incineration is not part of the process anymore, therefore revenues originated from the sales of thermal and electrical energy are not included; however, it has been assumed that the consumption of the incinerator is approximately equal to the reduction of the revenues originated from the sales of the energy;
- in the WP scenario, costs for the disposal of the ELT fibre are nihil, moreover the purchase costs of the cellulosic fibre are reduced, as explained below.

Costs and revenues associated to the different activities are described in detail in this section.

As mentioned in

Figure 2, the fibre cleaning is the preliminary activity performed by the recycling company. More specifically, Table 5 shows the costs for the cleaning process. In particular, fixed costs, initial

investments and variable costs are reported. The item “transport and disposal of the fibre”, indicates the cost for the fibrous material disposal (incurred by Steca S.p.A). The cleaning process of the fibre allows the recovery of rubber powder that can be sold on the market. The following table shows cost and revenue items related to this activity:

Table 4 – Costs and revenues associated to fibre cleaning

Activity: fibre cleaning		
Machinery (initial investment)	200.000 €	Cost
Building	Negligible ¹	Cost
Energy	Machine consumption: 160kW/h (18cent/kWh)	Cost
Personnel	0,1 person per hour (14 €/h)	Cost
Maintenance (average)	1.000 €/year	Cost
Transport and disposal of the fibre	80 €/tonne	Cost
Savings (due to non-disposal of the fibre)	787,5 tonnes/year (80 €/tonne)	Benefit
Sale of rubber powder	337,5 tonnes/year (350 €/tonne)	Benefit
Direct tax rate	44,5%	Cost

As the ELT fibre is no more incinerated, the cost for disposal becomes nil, while 337,5 tonnes of fibre (more specifically rubber powder) is sold. In particular, savings are equal to $787,5 \text{ t} * 80 \text{ €} = 63.000 \text{ €}$, while revenues are $337,5 \text{ t} * 350\text{€} = 118.125 \text{ €}$.

On this matter, it is important to underline that it has been assumed that the consumption of the incinerator is approximately equal to the reduction of the revenues originated from the sales of thermal and electrical energy (Boescha et al, 2014).

The following table illustrates cost and revenue items of the subsequent activities in the process: compaction and packing of fibre, and transport of the ELT fibre to the bitumen producer plant.

Table 5 - Costs and revenues associated to the compaction and packing of textile fibre, as well as to transport

Activity: compaction and packing of textile fibre

¹ The building, which was already owned by Steca S.p.A, covers a total area of 2.200 m², the machinery for cleaning occupies around 5m², that means 0,23 % of the total. The opportunity cost of the building is set to zero.

Machinery (initial investment)	600.000 €	Cost
Building	Negligible ²	Cost
Energy	Machine consumption: 100kW/h (18cent/kWh), 2.000 hours/year	Cost
Personnel	0,1 person per hour (14 €/h)	Cost
Maintenance (average)	31.500 €/year	Cost
Paraffin wax	500 €/tonne (quantity: 15% of the fibre)	Cost
Pellets	906 tonnes/year	
Big Bag	8€ each (capacity: 1m ³ , a big bag contains 1,5 tonnes of pellets)	Cost

Activity: transport

Load capacity (articulated lorry)	25 tonnes	
Number of journeys	37	
Cost of a journey	1.300 €	Cost
Savings (due to non-disposal of the fibre)	787 tonnes/year (80€/tonne)	Benefit

It is well known that adding 0,3% of cellulosic fibre to bituminous conglomerates increases the lifetime of asphalts by around 50%. The idea of REFIBRE project is to produce bituminous conglomerate using the ELT fibre instead of cellulosic fibre. Following lab tests, it came up that the ELT fibre can guarantee the same performance of the cellulosic fibre. Nevertheless, it is necessary to introduce in the process a shredder to simplify the blending of the pellets within the bituminous dough. It is necessary to add 3 kilos of fibre for each tonne of bitumen and, as mentioned above, each year 906 tonnes of pellets are produced, therefore each year an amount of 250.732 tonnes of bitumen is realized, allowing to asphalt around 300 km of a motorway.

² The building, which was already owned by Steca S.p.A covers a total area of 2.200 m², the machinery for cleaning occupies around 16m², that means 0,72 % of the total. The opportunity cost of the building is set to zero.

Table 6- Costs and savings related to the production of bituminous conglomerate

Activity: production of bituminous conglomerate			
Machineries (initial investment)	(initial	2.000 €	Cost
Building		Negligible	Cost
Energy		5.000 kW/year (18cent/kWh)	Cost
Personnel		3 hours per day (14 €/h)	Cost
Maintenance		Negligible	Cost
Extra bitumen ³		0,30 €/tonne	Cost
Savings (due to the reduced price for the acquisition of the fibre)		300 €/tonne	Benefit

According to the EC Guidelines “operating cost savings generated by the operation shall be treated as net revenue”. Since the ELT fibre is less costly than the cellulous fibre (600€ rather than 900€), such price difference has been considered as an operating cost saving.

It is noteworthy to mention that, after the performance of these activities, bitumen is sold as usual (in the same quantity it was sold before the REFIBRE project), therefore this revenue is not considered in the cost-benefit analysis.

Regarding the replacement costs, both in the financial and economic analysis, it has been considered the following replacements:

- Cleaning machinery (lifetime: 10 years): replacements will occur in the 10th and the 20th year.
- Machines for the production of pellets and for the production of conglomerates (lifetime: 15 years): replacement occurs in the 15th year, the residual value is estimated close to zero.

Replacements costs are equal to the value of the initial investments; however it is assumed that the new machines will consume 10% less than the former ones. Since one of the Europe 2020 targets is to achieve 20% increase in energy efficiency, and the first replacement of a machine will occur in 2028, it is considered that energy consumption will decrease by 10%, due to an increased efficiency (prudentially it has been considered 10%). Regarding the energy costs, it has been taken into account the same value for all the years avoiding any estimate on possible modifications as “the financial analysis should usually be carried out in constant (real) prices, i.e. with prices fixed at a base-year. The use of current (nominal) prices [i.e. prices adjusted by the Consumer Price Index (CPI)] would involve a forecast of CPI that does not seem always necessary” (European Commission, 2014).

³ Tapkin et al., 2014

3.3. CBA: Economic analysis

The financial costs of the project are used as a basis to estimate its economic costs.

As the CBA methodology includes monetization of intangible items, it is intrinsically subject to assumptions and discretion. Nevertheless, it is essential to include these items to take into account the benefits which derive from the project (Senaratne et al. 2015).

The following economic and environmental benefits have been monetized in the economic analysis:

Table 7 – Monetization of project benefits

A) Resource cost savings	
<u>A1) Economic value of recovered material</u>	118.125,0 €
The economic value of the recovered material (rubber powder) is based on the financial price paid on the local market (given that the trade market for rubber powder is efficient in the country). Calculation of avoided financial cost of powder production is as follows: Amount of rubber powder recovered annually (337,5 t) x average market price (350€/t) = 118.125 €	
	63.000,0 €
<u>A2) Avoided cost for the fibre's disposal</u>	
It is possible to “save” from the incineration 787,5 tonnes of fibre per year, which corresponds to the following avoided costs: Amount of fibre which is not disposed each year (787,5 t) x cost of transport and disposal per tonne (80€) = 63.000 €	
<u>A3) Avoided cost for the acquisition of fibre</u>	268.970,0 €
Since it is possible to use ELT fibre instead of cellulosic fibre, the following avoided costs have been calculated: Quantity of pellets each year (906 t) x cost saving per tonne (300€) = 268.970,6 €	
B) Avoided environmental externalities	
<u>B1) Avoided CO₂e emissions through non-production of cellulous</u>	See appendix A
According to the LCA analysis, the avoided production of cellulous fibre enables to avoid 300 tonnes of CO ₂ e emissions per year. The value of an emission per tonne of CO ₂ e emissions is based on the calculations illustrated by the European Investment Bank: “it consists of a central estimate for the damage associated with an emission in 2010 of EUR25 per tonne of carbon dioxide equivalent. [...] Reflecting a common finding that the marginal damage of emissions increases in function of the atmospheric concentrations of carbon, annual “adders” are applied after 2010 – i.e. an absolute	

increase in value per year (measured in constant 2006 prices)” (European Investment Bank, 2013).

	Value 2010 (Euro/t- CO ₂ e)	Annual adders 2011 to 2030
High	40	2
Central	25	1
Low	10	0,5

In the appendix A, all the calculations are presented. An example of calculation:

Amount of CO₂e emissions avoided each year (300 t) x cost of CO₂e emission per tonne in 2019 (34€) = 10.200 €

B2) Avoided CO₂e emissions through fibre's reuse

See
appendix A

According to the LCA analysis, the reuse of ELTs (instead of its incineration) enables to avoid 1.523,68 tonnes of CO₂e emissions per year.

An example of calculation of avoided CO₂e emissions is as follows:

Amount of CO₂e emissions avoided each year (1.523,68 t) x cost of CO₂e emission per tonne in 2019 (34€) = 51.805,12€

B3) Avoided SO₂ emissions through fibre's reuse

7.408,8 €

According to LCA analysis, the reuse of ELT fibre allows to avoid 0,759 tonne of SO₂ emissions per year. According to the CAFÉ CBA report, a SO₂ damage per tonne emission in 2010 is equal to 9.800 euro (taking a crude average across the EU15, namely excluding all the countries that acquired the EU membership after 1995 plus Luxembourg) (Holland et al., 2005). Since it is generally considered that emissions in future years will have a greater impact than emissions today (European Commission, 2014), the cost of SO₂ emissions might be underestimated (as the above-mentioned value refers to 2010). However, this is the most recent estimate presented in an official EC study.

Calculation of avoided SO₂ emissions is as follows:

Amount of SO₂ emissions avoided each year (0,759 t) x cost of SO₂ emission per tonne (9.800 €) = 7.408,80 €.

It is noteworthy to mention that LCA analysis has shown that avoided SO₂ emissions through non-production of cellulous are negligible.

Moreover, LCA analysis has provided data on other relevant aspects such as abiotic depletion and human toxicity, however these effects are not included in the present cost-benefit analysis. Researchers ideally should be able to measure all nonmarket environmental impacts in monetary terms. Nonetheless, all the different evaluation methods (e.g. revealed preference methods and stated preference methods) present limits in terms of their applicability and/or in terms of objectivity.

Furthermore, ethical objections have been raised, in particular when it is required to put a price on human lives.

For these reasons, in the present paper solely the environmental aspects that have been economically evaluated by the European Commission and the European Investment Bank have been included,

bearing in mind that other relevant aspects must be considered when assessing the impacts of a project or a policy. Indeed, appraisal methods can be used alongside each other to provide a wider picture of the effects of policy or project options.

4. Discussion

4.1. Financial sustainability

Financial sustainability is a key feasibility condition for any typology of project. More specifically, “a project is financially sustainable when the risk of running out of cash in the future, both during the investment and the operational stages, is expected to be nil” (European Commission, 2014). To assess the financial sustainability, inflows are measured against outflows.

In the present analysis, in the first year the net cash flow is negative, due to relevant disbursements occurred in this period. Starting from the second year, net cash flows become positive, excluding the 15th year when it is foreseen the replacements of different machines. Nevertheless, the cumulated generated cash flow becomes positive in the 5th year. Theoretically, this value should be positive or, at least, zero throughout all the reference period. This is not the case, however the medium and long term sustainability is ensured.

Moreover, the total sources of financing (in this case, the EU funds and the private equity) cover the initial investment costs, in accordance with the EC guidelines.

The CBA suggests that the most impactful costs are the initial costs for the installation of machines, as well as purchase costs of bitumen and wax, and disposal costs.

It has been decided to not estimate the financial net present value and the financial rate of return on investment (financial profitability's indicators) as it has been preferred to calculate the economic net present value as well as the economic rate of return, which measure the project economic performance, as shown in the next paragraph.

4.2. Economic performance

Regarding the economic perspective, it appears that in the first year costs are greater than the benefits, but since the second year net benefits are positive.

In terms of annual benefits, the two most relevant items are the economic valorisation of the rubber powder (118.125 €) and the avoided cost for the acquisition of cellulous fibre (268.970 €). Valorisation of the avoided CO_{2e} emissions through fibre's reuse is a relevant benefit as well (equals to 51.805 € in 2019, and then increasing every year).

As explained above, two different discounting rates have been taken into account. Considering a 4% discount rate, the performance indicators are the following:

ENPV= 3.330.902,02€

B/C ratio = 1,52.

The economic net present value “expresses” benefits and costs in a unique value. The rule of thumb is to adopt any project with a positive ENPV. Therefore, according to this principle, this project should be approved and implemented.

The B/C ratio is equal to 1,52, meaning that 1 euro of costs correspond to 1,52 euro of benefits.

As mentioned above, two different discount rates have been considered. From the theory, a zero-social rate of time preference derives from the assumption that today’s and future consumptions are indifferent to the utility point of view. A positive discount rate, on the other hand, indicates a preference for current over future consumption. The lower the discount rate, the more future consumption matters.

This is the reason why if a 3% discount rate (rather than a 4% one) is considered, the economic indicators do increase as follows:

$$\text{ENPV} = 3.892.842,92$$

$$\text{B/C ratio} = 1,55.$$

Regarding the economic indicator, the Economic Rate of Return, in the present analysis is equal to 30,21%. Normally, the ERR is compared to the social discount rate. Whether the ERR is lower than the social discount rate, the project is considered not economically justified, and therefore should not be implemented, since it would represent a misallocation of economic resources. If the ERR is equal or greater than the social discount rate, the project should be financed (European Investment Bank, 2013).

In the present analysis, 30,21% is significantly greater than the two discount rates above considered (3% and 4%), another proof that the project is economically viable.

However, the use of the Economic Rate of Return is controversial as this indicator presents different limitations. For instance, it is “a true indication of a project’s annual return on investment only when the project generates interim cash flows that can be invested at the actual ERR” (Kelleher J., Mac Cormack J., 2004). Therefore, it should be interpreted with some caution when assessing project’s profitability.

4.3. Risk assessment

According to the EC guidelines, the steps for assessing the project risks are the following ones:

- sensitivity analysis
- qualitative risk analysis
- probabilistic risk analysis (not mandatory)
- risk prevention and mitigation.

Sensitivity analysis

The sensitivity analysis “enables the identification of the ‘critical’ variables of the project. Such variables are those whose variations have the largest impact on the project’s financial and/or economic performance.” (European Commission, 2014).

In order to identify these critical variables, a sensitivity analysis has been carried out by varying one variable at a time keeping the value of the other variables constant (taking into account the figures considered in the project), and determining the effect of that change on the ENPV. As a rule-of-thumb, it is considered as “critical” those variables for which a variation of $\pm 1\%$ of the value considered in the project leads to a variation of more than 1% in the value of the ENPV. (Tab A.5).

Another significant component of the sensitivity analysis is the calculation of the switching values, namely the values that the different variables must take to make the ENPV become zero.

Spider diagrams to illustrate the elasticities and switching values for the above-mentioned variables are shown below.

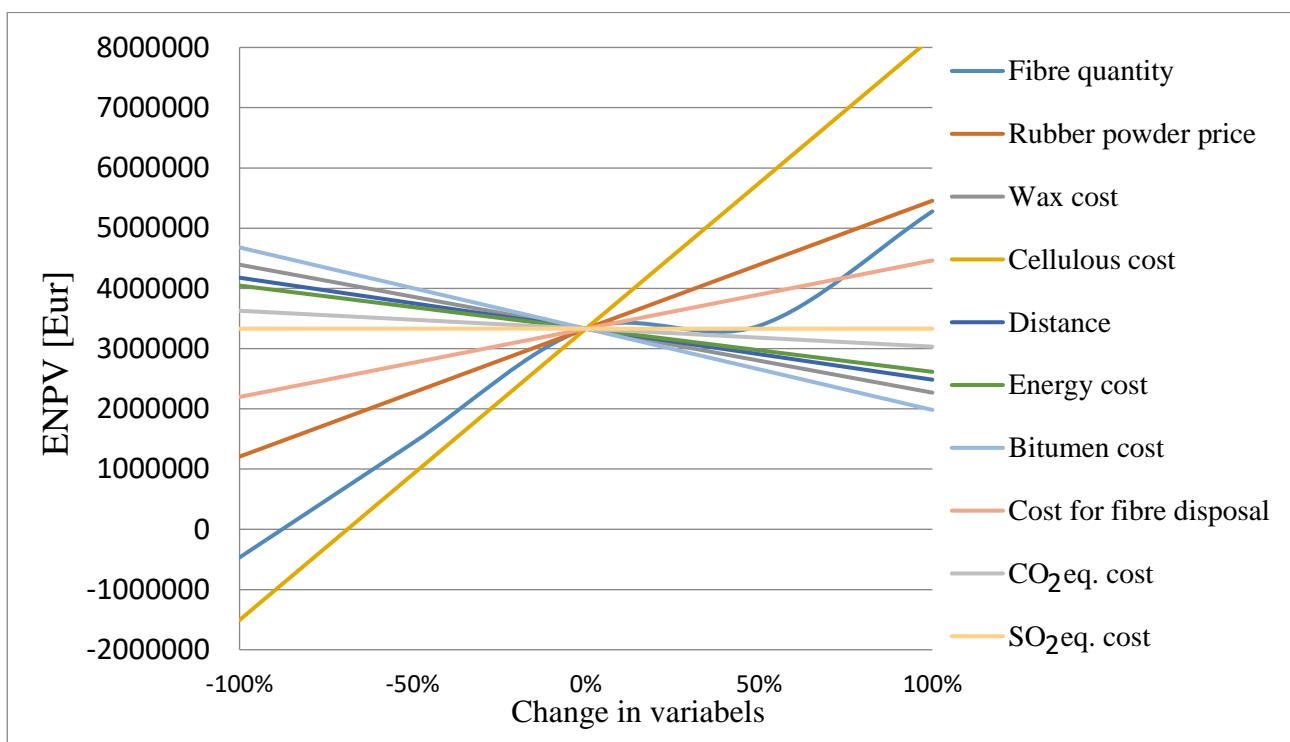


Figure 7 - Sensitivity analysis – spider diagram (4% discount rate)

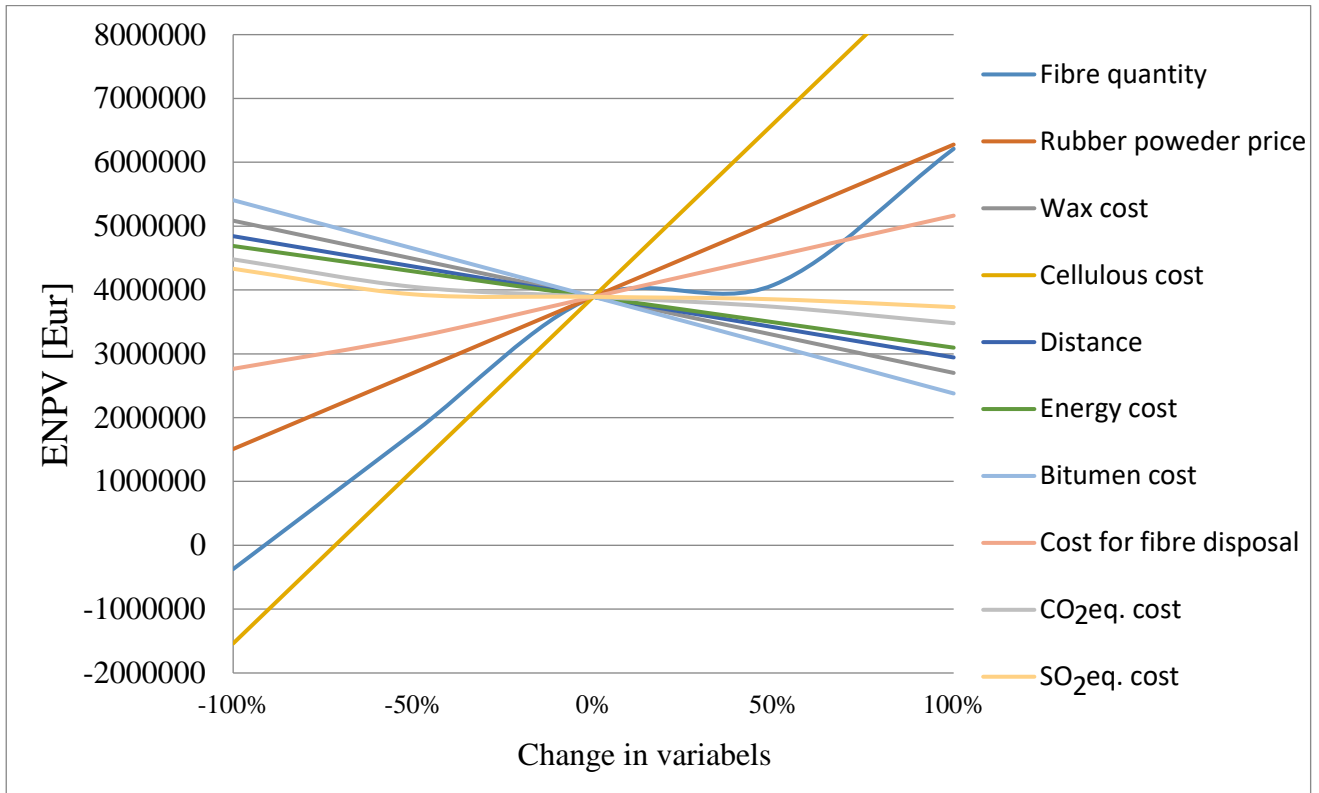


Figure 8 - Sensitivity analysis – spider diagram (3% discount rate)

The sensitivity analysis shows that only the fibre quantity and the cellulose cost constitute critical variables. In particular, the cellulose cost appears as the most critical variable as a change of this cost has a relevant impact on the ENPV. As a matter of fact, in the spider diagrams above, it is possible to note that the straight line of the cellulose cost is the steepest one.

It is noteworthy to highlight that the project should not be considered highly risky as the above-mentioned variables must change considerably to make ENPV become negative. For instance, a nearly 90% fibre quantity decrease must be observed to make the ENPV become zero.

Finally, the sensitivity analysis must be completed with a “scenario analysis”, which assesses the impact of combination of values taken by the critical variables. In order to define the optimistic and pessimistic scenarios it is necessary to choose for each variable the extreme (lower and upper) values (within a range defined as realistic).

Table A.6 show variables and range of values have been taken into consideration:

As the results are similar, calculations have been done considering only the 4% discount rate. The table A.7 shows the pessimistic and optimistic scenarios:

In case all the conditions related to the pessimistic scenario occur, a maximum loss of 467.631 € is foreseen; on the other side, in the optimistic scenario the profit would be around 18.000.000 € (considering the timeframe of 30 years). Therefore, the scenario analysis confirms that the project is not very risky as even in the worst scenario the possible loss is moderate.

Risk analysis

Based on the results of the sensitivity analysis, a risk matrix has been prepared so as to identify possible risk prevention and mitigation measures.

The probability classification, risk severity classification and risk levels are drawn from the EC guidelines. In order to assess all the project's risks, historical trends and forecasts have been considered, as well as the opinion of companies' experts.

It is noteworthy to mention that the probabilistic risk analysis has not been performed as it is required only in the case the residual risk exposure is still significant.

As shown in the risk analysis, (table A.8) the residual risks for the project are either low or moderate, as a consequence of the measures foreseen or already implemented with the aim of preventing the occurrence of the identified risks and mitigating their adverse impact in case these should materialize.

5. Conclusions

End-of-life tyres are one of the main source of waste in ELV sector. One aspect of fundamental importance for ELT recycling and valorisation of recovered materials is the proper implementation of European legislation regulated at the Italian national level by the DM Environment April 11, 2011, n. 82. The Directive 2000/53/EC is aimed primarily at preventing the production of waste resulting from vehicles, including tyres (classified as CER160103), and to encourage the reuse, recycling and other forms of recovery of components while reducing disposal and incineration.

The textile fibre represents a limit for the application of a recovery methodology since suitable technologies for fibre purification and densification have not been identified yet, as well as useful applications for its reuse.

The REFIBRE project aims to overcome such limitations by proposing a crucial technological add-on to existing installations, as well as studying a series of solutions designed and tested to prepare the material for subsequent processing.

In this context, a LCA analysis has been performed to assess the environmental impact related to two different scenarios. In particular, after having demonstrated the technical feasibility of the second life application of the ELT fibre, the different processes have been analysed from an environmental point of view. It came up there is an impact reduction in case the ELT fibre is reused as additive for bituminous conglomerates (instead of disposing the ELT fibre through incineration). A cost-benefit analysis has also been carried out to evaluate the impacts of the recycling system in terms of effects on social well-being, comparing the positive effects (benefits) with the negative effects (costs). The CBA relies primarily on the results of the LCA process.

From the presented CBA, it can be concluded that:

- in the medium and long term the project is financially viable;
- the high economic profitability (ENPV: 3.330.902,02€, B/C Ratio: 1,5) makes the project economically sustainable;
- the greatest economic and environmental benefits are the economic valorisation of the rubber powder and the savings due to non-use of cellulosic fibre.

As the project technology can be transferable to other similar plants allowing its replication in Italy and across Europe, a sensitivity analysis has been carried out to identify the most critical variables and it came up that: 1) the quantity of fibre and the cellulosic cost are the most impactful variables; 2) the project is not highly risky as the variables must change consistently to make the ENPV become negative. Moreover, a risk assessment has been performed in order to identify the main risks and the possible mitigation measures. As shown in the risk matrix, the residual risks are low or moderate, and therefore manageable.

In conclusion, the present analysis proves that the REFIBRE project can be considered as a successful application of the circular economy principles. Thereby extending such practices on a wider base would be efficient and beneficial in a global perspective bringing considerable results in the reduction of ELV waste, bearing in mind that single projects must be assessed case by case as one size does not fit all.

In this context, different national policies can be introduced to boost the rate of recycling of ELTs, such as government subsidies or a value added tax.

Regarding further advances in ELT recycling, the next step would be to investigate and evaluate diverse second life applications (for instance, plastic compound and concrete blocks), and identify the optimal end-life-scenario for the ELT fibre, ensuring the lower environmental impact and the best economic performance.

Acknowledgements

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Appendix A

Table A.1 Characterized results obtained with the Recipe 1.08 method

Scenario	Process	GWP [kg CO ₂ eq.]	Fossil depletion [kg oil eq]	Freshwater eutrophication [kg P eq]	Ozone depletion [kg CFC eq]	Particulate matter formation [kg PM10 eq]	Terrestrial acidification [kg SO ₂ eq]
Scenario 1 Whit project	Cellulose production	-4,19E+04	-3,69E+04	4,88E+01	6,04E-03	-1,73E+01	-5,67E+01
	Transport	1,34E+05	3,20E+04	4,67E-01	6,70E-08	4,44E+01	1,09E+02
	Polypropylene fibres	6,90E+03	3,98E+03	8,36E-03	4,26E-08	3,33E+00	8,64E+00
	Wax Paraffin	1,11E+06	9,30E+05	2,22E+00	2,64E-06	6,80E+02	2,12E+03
	Electricity consumption	3,31E+06	7,20E+05	1,17E+01	7,68E-05	1,14E+03	3,35E+03
	Total	4,51E+06	1,65E+06	6,32E+01	6,12E-03	1,85E+03	5,54E+03
Scenario 0 Business As Usual	Electricity generated	-1,71E+06	-2,79E+05	-5,77E+00	-2,62E-03	-6,25E+02	-1,72E+03
	Heat generated	-3,75E+05	-6,32E+04	-7,95E+01	-1,25E-05	-4,20E+03	-1,01E+04
	Transport	4,51E+05	1,08E+05	1,57E+00	2,26E-07	1,48E+02	3,65E+02
	Incineration	2,26E+07	1,77E+05	7,15E-01	2,56E-06	8,62E+03	1,98E+04
	Total	2,10E+07	-5,77E+04	-8,30E+01	-2,63E-03	3,94E+03	8,32E+03

Financial analysis

Table A.2 - Financial analysis - first part

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	
Loans	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
Private equity	560.000,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
Revenue																															
>Sale of rubber powder	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	118.125,00	
Operating cost: savings																															
>Savings 1	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	63.000,00	
>Savings 2	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	268.970,63	
TOT CASH INFLOW	1.810.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	450.895,63	
Investments																															
>Machine (for fiber's cleaning)	200.000,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
>Machine (spinet production)	400.000,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
>Installation costs*	200.000,00	100.000,00	50.000,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
>Machines (opper and shredder)	2.000,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	
TOT	1.812.895,63	180.895,63	50.895,63	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	

(continue in the following page)

Fibre quantity (tonnes)	1,14%	-87,7%	1,09%	-91,2%
Rubber powder price (€/tonne)	0,63%	(*)	0,61%	(*)
Wax cost (€/tonne)	0,32%	+314,6%	0,31%	+328,1%
Cellulous cost (€/tonne)	1,45%	-68,8%	1,39%	-71,7%
Distance (km) (**)	0,25%	+393,6%	0,24%	409,6%
Energy cost (€/kwh)	0,21%	+465,1%	0,20%	+488,8%
Bitument cost (€/tonne)	0,40%	+246,6%	0,38%	+256,6%
Cost for fibre disposal (€/tonne)	0,34%	(*)	0,32%	(*)
CO ₂ cost (€/tonne)	0,37%	(*)	0,36%	(*)
SO ₂ cost (€/tonne)	0,04%	(*)	0,038%	(*)

(*) No switching values were calculated in these cases as the ENPV would not become 0 even if the variable were 0.

(**) The “distance” variable indicates the distance between a recycling company and bituminous conglomerate producer’s facilities.

Table A.6 - Range of values considered in the analysis

	MIN VALUE	MAX VALUE	Value considered in the project	Explanation
Fibre quantity (tonnes)	0	4.000,00	787,50	Every year, in Italy about 371.000 ton of ELTs are disposed, that means that 23.000 ton of fibre has to be treated yearly. On average, 50% of the ELTs is produced in the North of Italy, 30% in the Centre, 20% in the South of Italy. Considering the presence of 2 plants in the Centre of Italy, it is possible to reach a production of fibre equals to 4.000 ton per year (Ecopneus, 2013).
Rubber powder price (€/tonne)	250,00	450,00	350,00	This range has been defined after a consultation with the companies’ managers.
Wax cost (€/tonne)	450,00	550,00	500,00	In this case, prices fixed by the different companies’ suppliers have been considered.

Cellulose cost (€/tonne)	850,00	950,00	900,00	This range has been defined after a consultation with the companies' managers.
Distance (km)	100,00	1.000,00	300,00	As minimum value, the distance between Steca S.p.A. and the nearest producer of bituminous conglomerates has been considered. As maximum value, the distance between Steca S.p.A. and the incineration plant in Switzerland has been taken into account.
Energy cost (€/kwh)	0,10	0,50	0,18	Energy price statistics have been considered (Eurostat 2016).
Bitumen cost (€/tonne)	0,20	0,40	0,30	Data have been drawn from the Global Natural Bitumen Industry Market Research 2017.
Cost for fibre disposal (€/tonne)	60	100	80	Data have been drawn from the WRAP Gate Fees Report 2015 (Waste and Resources Action Programme, 2015).
CO₂ cost (€/tonne)	Not applicable	Not applicable	Variable	Not applicable.
SO₂ cost (€/tonne)	Not applicable	Not applicable	9.800	Not applicable.

Table A.7 – Scenario analysis

	Optimistic scenario	Pessimistic scenario
Fibre quantity (tonnes)	4.000,00	0
Rubber powder price (€/tonne)	450,00	250,00
Wax cost (€/tonne)	450,00	550,00
Cellulose cost (€/tonne)	850,00	950,00
Distance (km)	100,00	1.000,00
Energy cost (€/kwh)	0,10	0,50
Bitumen cost (€/tonne)	0,20	0,40
Cost for fibre disposal (€/tonne)	60	100
ENPV(€)	18.071.793,58	-467.631,22

Table A.8 Risk matrix

Risk description	Probability	Severity	Risk level	Risk prevention/mitigation measures	Residual risk
<u>Regulatory risks</u>					
Changes of environmental requirements and regulatory instruments (e.g. change of regulations regarding ELT treatment)	A (0–10 %)	IV	Low	Advocacy activities are foreseen as well as a continuous dialogue with public authorities and associations (e.g. Ecopneus, ETMRA) in charge of elaborating directives and regulations (e.g. regarding the disposal of rubber) aiming to control the impacts of the ELT treatment.	Low
Changes of economic instruments (e.g. introduction of a tax on ELT treatment)	B (10-33%)	II	Low	It is possible to define the input variables as a specific distribution (representing the probability of each value to occur). Hence it is possible to carry out a stochastic analysis so as to identify a variation range of the economic instruments. Moreover, it has been considered that a part of profit would be able to cover possible higher taxes.	Low
<u>Demand side risks</u>					
Waste generation lower than predicted	A (0–10 %)	III	Low	It is foreseen to analyse the trends of different sectors (automotive, transports and tyres production) in order to define a realistic amount of waste generation over the years.	Low
Quantity of ELT to be treated lower than predicted	C (33–66 %)	IV	High	The Italian trade association provides companies with a certain amount of ELTs to be disposed. The association selects the companies according to their energetic and environmental performances, and the amount of waste generated during the process.	Moderate

Since two-year contracts are concluded, it is crucial to maintain state-of-the art facilities (in order to be selected by the association).

Administrative risks

The permission for road paving with the new asphalt is denied	A (0–10 %)	IV	Low	In order to prevent stop or delay of planned activities the verification of required authorization will be performed in advance and subsequent requests will be sent. Moreover, it is foreseen to produce a typology of asphalt with improved mechanical and technological characteristics.	Low
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Construction risks

Investment costs overrun	C (33–66 %)	III	Moderate	Investment cost estimates are compared with costs experienced with similar projects implemented in the EU in the last few years. Consultations with plant and equipment manufacturers have been carried out to cross-check estimates with current market conditions.	Low
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Operational risks

Operating costs overrun (e.g. energy costs, paraffin wax costs, bitumen cost, transport cost, maintenance and repair costs)	C (33–66 %)	III	Moderate	Operating cost estimates are compared with costs experienced with similar projects implemented in the EU in the last few years. Consultations with plant and equipment manufacturers have been carried out to cross-check estimates with current market conditions. Waste disposal costs have been defined after consultation with disposal companies active in the region.	Low
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Product workability	A (0–10 %)	III	Low	The change of fibre composition may produce a temperature increase during the fibre compaction phase. In order to reduce this risk, it is possible to increase the cycle time.	Low
Technical characteristics of the modified asphalts do not meet the expectations	B (10-33%)	IV	Moderate	This risk is related to a poor performance of the finished products in terms of fatigue strengths, stress resistance, vertical deformation, lifetime and other relevant parameters of the conglomerate. To mitigate problems during the asphalt laying, a continuous improvement process is foreseen, while carrying out in-house tests to optimize the formulation of the compound. In case of residual problems, Toto S.p.A will continue to work on the conglomerate formulation: new mixtures, additives etc. which can enhance the compatibility of the ELT fibre with the new asphalt.	Low
<u>Others</u>					
Environmental impact reduction lower than predicted	A (0–10 %)	II	Low	The over mentioned operating risks may lead to a greater environmental impact than the estimated one. It is possible to reduce this risk by optimizing the production process, reducing the waste, monitoring energy flows, taking into account the Industry 4.0 paradigm. Moreover, it would be beneficial to use a reliable database (LCI) and, consequently, significant information, as well as a robust model for the calculation of the indicators.	Low
Problems with public opposition to the plant construction	B (10-33%)	III	Moderate	Publicity measures aimed at informing the public about the process, its objectives, its environmental and societal impacts are foreseen.	Low

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