

Comparative LCA of treatment options for US scrap tires: material recycling and tire-derived fuel combustion

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Abstract

Purpose This life cycle assessment (LCA) study compares two prevalent end-of-life (EOL) treatment methods for scrap tires: material recycling and energy recovery. The primary intended use of the study results is to inform stakeholders of the relative environmental burdens and trade-offs associated with these two EOL vehicle tire treatment methods. The study supports prioritization of the waste treatment hierarchy for this material stream in the US.

Methods This LCA compares (1) *material recycling* through ambient-temperature mechanical processing and (2) *energy recovery* through co-incineration of both whole and pre-processed scrap tires at a cement kiln. The avoided burden recycling methodology reflects the substitution of virgin synthetic rubber used in asphalt modification with the ground tire rubber from material recycling and the substitution of conventional kiln fuels with the tire-derived fuel (TDF). Both attributional (ALCA) and consequential (CLCA) methodologies are used: the ALCA assesses the environmental profiles of the treatment methods and the CLCA examines the potential effects of shifting more scrap tires to material recycling. The attributional portion of the LCA study was conducted in accordance with ISO standards 14044 series.

Results The results in both methodological approaches indicate that the material recycling scenario provides greater impact reductions than the energy recovery scenario in terms of

the examined environmental impact potentials: energy demand, iron ore consumption, global warming potential, acidification, eutrophication, smog formation, and respiratory effects. The additional impact reductions from material recycling are significant, and the establishment of new infrastructure required for a shift to material recycling incurs relatively insignificant burdens. Sensitivity analyses indicate that this conclusion does not change for (1) a range of TDF heating values, (2) a decrease in the mixed scrap tire rubber-to-steel composition ratio, (3) two alternative electricity grid fuel mixes with higher and lower carbon dioxide emission rankings than that of the baseline scenario, or (4) a comparison of material recycling to energy recovery when TDF is used in pulp and paper mills instead of cement kilns.

Conclusions These results provide a basis for more informed decision-making when prioritizing scrap tire waste treatment hierarchy.

Keywords Asphalt modification · End-of-life management · Life cycle assessment · Recycling · Energy recovery · Scrap tires · Waste management hierarchy

1 Introduction

The results of this life cycle assessment (LCA) contribute information on the relative environmental impacts of scrap tire management methods to regulatory and market decision-makers in the USA. The volume of scrap tires requiring management in the USA, over 135,000 mt in 2008, is correlated with dependence on cars and trucks as a primary mode of transportation and annual vehicle miles traveled (VMT) (Rubber Manufacturers Association (RMA) 2009a). Though the rate of growth in VMT has slowed in recent years, the fact remains that there is strong dependence on vehicles and the overall annual VMT are still increasing in the US (US DOT 2012). These factors ensure a sustained volume of scrap tire

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generation that must be managed for the foreseeable future. Over the last decade, various states have implemented landfill bans on scrap tires as well as scrap tire stockpile abatement programs. These efforts have proved very successful. Each year, market segments are emerging and maturing to manage and utilize this waste stream, and more tires are being consumed in end-of-life (EOL) markets. Overall, US scrap tire EOL market consumption has increased from 11 % of annual generation in 1990 to almost 90 % in 2007 (RMA 1999–2007).

Combustion of tire-derived fuel (TDF) currently consumes over half of scrap tires generated in the USA (RMA 2009a). Though facilities dedicated solely to scrap tires are rare, co-incineration of TDF is fairly widespread in numerous cement kilns, pulp and paper mills, and some utility boilers in order to replace some amount of conventional fossil fuels. The dramatic increase in the consumption of TDF can be largely explained by three factors. First, elevated fuel prices have caused industries with high thermal energy consumption to seek alternative fuels (TDF has a heating value similar to coal). Second, statewide stockpile abatement programs and landfill bans have increased the availability of scrap tires to EOL markets. Third, as the infrastructure for collecting and processing scrap tires matures, the quality/reliability of tire granulates for combustion improves.

The next largest market segments for EOL tires in the USA are ground rubber material applications and civil engineering projects, which consumed 17.2 and 12.2 %, respectively, of the volume generated in 2007 (RMA 1999–2007). Using scrap tires in these applications replaces the need for materials otherwise used in civil engineering projects, such as virgin and synthetic rubber and, in some cases, sand.

In addition to avoiding the use of conventional fossil fuels and/or primary materials, both the energy recovery and material recycling routes divert EOL tires from taking up valuable space in US landfills. However, EOL tire treatment methods could impose environmental burdens as well as displace them (e.g., possible heavy metals and/or polyaromatic hydrocarbon releases). To contribute to the decision-making context, there is a need for the examination and comparison of the environmental trade-offs and impact reductions of each EOL method.

A previous study performed by Ecobilan examined nine recovery methods for EOL tires in France using conventional attributional LCA (ALCA) methodology (Clauzade et al. 2010). This study grouped the nine EOL methods for scrap tire treatment into nondestructive methods of EOL scrap tire treatment (i.e., material recycling). The study concluded that, in France, using scrap tire material as a substitute for polyurethane in molded objects had greater potential to provide environmental impact reductions than destructive EOL scrap tire treatment methods (i.e., energy recovery at cement works).

The LCA discussed in this article used two methodological approaches to compare the environmental profile of each EOL treatment method in the USA. The ALCA approach was used to

compare the environmental profiles of the two EOL methods used to treat the greatest volume of scrap tires in the USA, while the consequential LCA (CLCA) approach examined the potential environmental impacts resulting from shifting all US scrap tire generation to the material recycling treatment route. The primary intended use of the study results is to inform stakeholders of the relative environmental burdens and trade-offs associated with these two EOL vehicle tire treatment methods. The results provide a basis for more informed decision-making when prioritizing scrap tire waste treatment hierarchy.

2 Methods

2.1 Functional unit and scrap tire composition

This analysis compared the treatment of pneumatic car and truck scrap tires generated in the USA, either by energy recovery through incineration at a cement kiln or by material recycling through ambient-temperature mechanical granulation. The functional unit for this analysis is *treatment of 1 mt of mixed US scrap tires*.

Pneumatic tires include reinforcing material between layers of compounded rubber. These layers, called plies, contain fiber or steel cords that give the tire structure and carry tension, while the sandwiching rubber acts as a sealant. Specific tire material ratios and compounded rubber compositions depend on the intended application and desired performance of the tire. Primary data availability is low because tire manufacturers are highly competitive and formulations are proprietary. Generally, the rubber fraction is a blend of natural rubber and styrene butadiene rubber (SBR) compounded with filler, vulcanizing chemicals, and softening oils. Applications such as large utility vehicles, which require a higher tensile strength, use more natural rubber than synthetic rubber. Synthetic rubber, however, is superior in protecting against chemical degradation. Thus, in passenger vehicles, SBR is used in larger proportions than natural rubber. Reinforcing agents, or fillers, such as carbon black and silica, increase the mechanical strength and stiffness of the rubber. Sulfur or an equivalent curative is added to natural rubber or synthetic polymers to form cross-links between individual polymer chains. This chemical process, also known as vulcanization, makes the product more durable. Most tire rubber is sulfur-vulcanized, which requires catalysts. The most common accelerating agents used for tire rubber are zinc oxide, stearic acid, and anti-degradants. Extender oils are also used to plasticize the rubber and reduce the compounding viscosity.

Table 1 defines the material composition of the mixed US scrap tires used for the functional unit in this analysis. The RMA provides percentages for the general material composition and total weight of EOL passenger and truck tires generated in the USA (RMA 2009b). The RMA also supplies data

Table 1 Material composition calculated for mixed US scrap tires, reflecting material loss due to tread wear and weighting composition of each tire type for its respective market share

Material composition	New tires		Scrap tires		
	Passenger (light duty) Weight %	Truck (commercial) Weight %	Passenger (light duty) Weight %	Truck (commercial) Weight %	Market mix Weight %
Compounded rubber fraction	80	83	77	80	78
Synthetic rubber	27	14	26	13	24
Natural rubber	14	27	14	26	15
Carbon black	28	28	27	27	27
Sulfur	0.48	0.25	0.46	0.24	0.43
ZnO (vulcanizing agent)	0.83	0.43	0.80	0.41	0.74
Other oils and chemicals	10	13	9	13	10
Steel (average)	15	15	16	17	16
Textile (average)	6	3	6	3	6
Typical mass (kg per tire)	10.2	54.4	9.07	45.4	14.5
Annual EOL market share	n/a	n/a	85	15	100

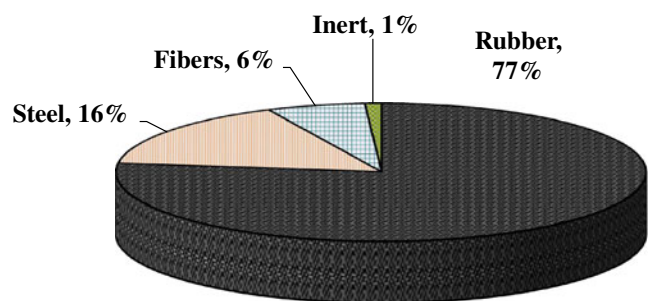
on the industry total replacement tire shipments listed for passenger vehicles and light duty and commercial trucks (RMA 2009c). The authors used these data to calculate the relative market share of each of the tire classes. Passenger tires tend to dominate scrap tire generation at about 85 %; the remainder is truck and/or larger commercial vehicle tire types. To estimate the average composition of mixed *new* tires in the USA, the authors considered the RMA data for weight, composition, and relative market share of passenger and truck tires (RMA 2009b); an average rubber compounding formulation from a US Department of Energy (DOE) report (Dodds et al. 1983); and data on the average fiber weight in tires as indicated in state waste management case studies (CA IWMB 2003; TX NRCC 1999). In order to estimate the composition of mixed US *scrap* tires, the authors considered that a fraction of the compounded rubber tire mass will be lost during the tires use phase due to tread wear. Per values used in a previous case study and those indicated by personal communications with the RMA, the authors estimated a 10 to 20 % loss of tire tread mass (Schmidt et al. 2009). Figure 1 presents the overall average material composition used to determine mass balance in the investigated EOL treatment methods.

In the energy recovery route, this material composition was used to determine the mass balance for tire-derived steel inputs. Proximate, ultimate, and metal analysis of 90+% wire-free TDF as reported by the US Environmental Protection Agency (EPA) was used to define and model mass balance for the combustible portion of scrap tires (EPA 1997; Gray 2004). The average heating value indicated in the literature for TDF, 32.5 MJ/kg, was used in the baseline assessment; the range of values from the literature was considered in a sensitivity analysis (Blumenthal 1992a, b; Boateng 2008; CA IWMB 2003; EPA 1997; Kaelin and Blumenthal 2001; Nakajima and Matsuyuki 1981; RMA

1999–2007; Sharma et al. 2000; Singh et al. 2009). The authors used data on the chemical characteristics of the recovered fiber fraction from material recycling in Europe to model mass and energy balance for the co-incineration of this material at the cement kiln (Schmidt et al. 2009).

2.2 Life cycle inventory

For both LCA approaches, each EOL treatment system was examined for its short-term (2009–2014) and long-term (2020) environmental impacts in the USA. For electricity consumption in the ALCA long-term scenario, the authors considered average percent changes in each grid mix fuel source projected for 2020 by the US DOE's Energy Information Administration (EIA) in their 2009 Annual Energy Outlook (EIA 2009b). System expansion (i.e., the avoided burden method) was employed to reflect the substitution of materials and/or processes realized by the material produced or energy recovered from the EOL treatment methods. In the material recycling route, virgin synthetic rubber used in asphalt modification is substituted with the ground tire rubber produced at the granulation facility. In the energy

**Fig. 1** Average material compositions of mixed US scrap tires

recovery route, conventional kiln fuels are substituted with the TDF fed to the kiln. Figure 2 gives an overview of the system boundaries for this analysis.

2.2.1 Material recycling

For this analysis, material recycling was modeled using primary data from Genan, the largest recycler of scrap tires in the world. Genan uses ambient-temperature mechanical processing technology to produce fine rubber granulates used as feedstock for value-added rubber products. The inventory was modeled after a Genan facility in Germany operating with a capacity to treat 65,000 mt of tires annually. Process requirements at this facility were modified to reflect differences in European versus US mixed scrap tire material composition. The main processes involved at the recycling facility are shredding, cleaning with water, steel removal, and iterative granulation of the compounded rubber and fiber portion using industrial-sized steel rotary knives powered with electricity. The process can be adjusted to produce the desired size of rubber granulate; finer granulates require more electricity consumption. During the process, steel and fiber fractions are removed. Periodically, the shredding and granulation knives must be sharpened. Knife sharpening occurs on-site and consumes electricity as well as

steel. However, the knife line produces steel scrap that is recycled back to the knives. Rainwater for the washing step is collected from the facility roof, cleaned, and recirculated within the plant. Relative to the initial cleaning step in the granulation processes, the cleaning of the steel fraction requires insignificant water inputs. Running at capacity, the net annual water demand for the facility is about 3,000,000 L. The only air emissions from the facility are dust particles from the air outlet of the granulation filter systems. Depending on the level of the finer granulate produced, dust emissions occur on the order of 41–62 mg of dust/mt of tires treated. From operations in Europe, Genan has determined that, after processing the scrap tires, about 1 % of the resulting output is sand and gravel and an average of 58 % of the weight of outgoing fiber fraction is residual rubber granulate. This analysis considered full granulation of all the rubber content to produce a finely ground tire rubber (<1.4 mm), or GTR 14. Table 2 defines the unit process requirements for the treatment of 1,000 mixed US scrap tires to produce GTR 14.

GTR 14 is the primary product from recycling scrap tires; it is further processed with a plasticizer to produce the proprietary asphalt modifier Road+. Used in asphalt modification, Road+ has the potential to displace the virgin synthetic rubber currently used in US asphalt modification, styrene butadiene styrene

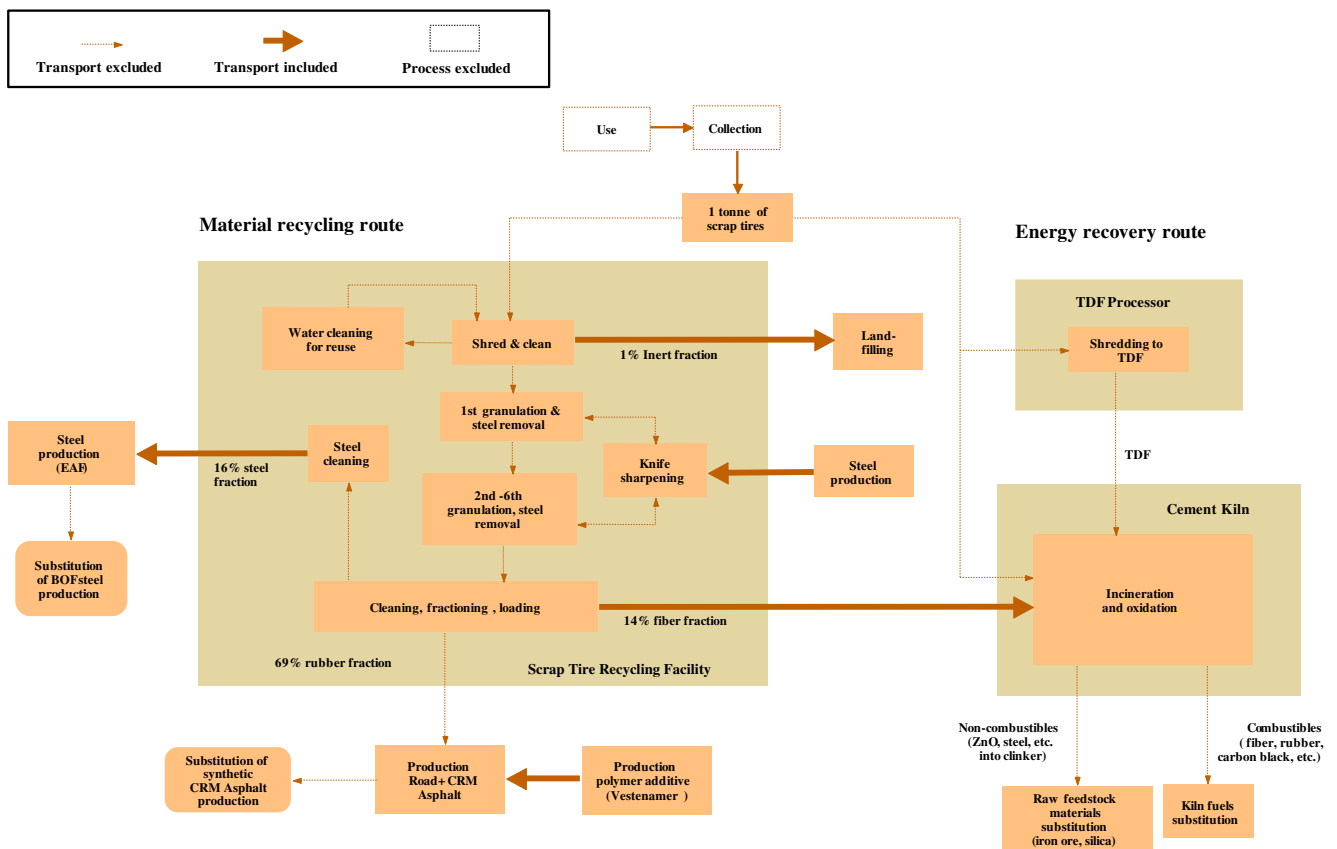


Fig. 2 Overview of the study boundaries for the comparative LCA of EOL treatment methods for mixed US tires

Table 2 Unit process requirements for ambient-temperature mechanical recycling of 1 mt of scrap tires for the production of finely ground tire rubber (GTR 14)

	Value	Unit
Process inputs		
Electricity	354	kWh
Mixed US scrap tires	1,000	kg
Steel knives	0.60	kg
Harvested rain water	46.2	L
Process outputs		
Rubber granules (<1.4 mm)	690	kg
Steel scrap	160	kg
Fiber/rubber residual fraction	140	kg
Inert materials	10.0	kg
Used knives (to knife sharpening)	0.60	kg
Recovered rinse water	46.2	L
Particulate matter to air	0.062	kg

rubber (SBS). The removed steel by-product is cleaned, baled, and sold. This scrap is modeled to be remelted in an electric arc furnace (EAF) to produce secondary steel and displace demand for blast oxygen furnace (BOF) steel. The separated fiber/rubber fraction is used as secondary fuel in pyroprocessing. The inert sand and gravel fraction is sent to a landfill.

The preparation and use of Road+ is in compliance with the American Society for Testing and Materials' definition 6114 for asphalt rubber binder (Caltrans 2006). As described in a previous case study, the Road+ formulation contains 4.5 % of the plasticizing additive by product weight (Schmidt et al. 2009). Road+ is added to hot asphalt and agitated in a low shear mixer at 180 °C for 120 min, requiring 32 kWh/h for mechanical agitation and 7.9 kWh/h for heating and circulating oil on the outside of the mixing tank (Schmidt et al. 2009). Volatile organic compounds (VOCs) are released during the application of the modified asphalt. Compared to the use of SBS, in asphalt modification, the use of Road+ requires 75 % less energy at the mixing step and emits 30 % less VOCs upon application (FABES 2006; Lindner 2007; McGraw and Lott 2005).

As is prevalent in the USA, all scenarios in this study considered only wet processing for asphalt modification. Weight factors for raw material inputs for the production of SBS bitumen modifiers were adapted from product data sheets made publicly available by Kraton, a leading global producer of SBS polymers (Kraton 2011). Data for the polymerization of SBS from styrene and butadiene were not available. Process data for polymerization of SBR from styrene and butadiene were used as a surrogate. VOC emissions from mixing were estimated using EPA AP-42 emission factors for stationary drum and batch mix hot mix asphalt plants (EPA 2004). Asphalt modified with either

Road+ or SBS was assumed to be recyclable to the same application.

The Road+ product can also improve the overall performance of the rubber-modified asphalt and reduce common failures such as fatigue cracking, corrugations or “shoving,” and the “rutting” that causes channels in the asphalt surface. Though the USA has not yet commercially adopted the Road+ product for asphalt modification, equivalence tests in Germany indicate that asphalt modified with 10 % Road+ has the same properties as asphalt modified with 4 % SBS and that this performance ratio is not expected to vary with geography (HeidenLabor 2005). The authors considered this performance ratio to model the displacement of synthetic rubber in US conditions. Per the ratio, the asphalt modified with Road+ offers 60 % more material mass than an equivalent unit of asphalt modified with SBS and the authors assumed a 95 % bitumen material mass displacement. For each metric ton of mixed scrap tires, 690 kg of GTR 14 are produced and processed to 722 kg of Road+ for asphalt modification. This amount of Road+ displaces 700 kg of SBS-modified asphalt (412 kg of bitumen and 288 kg of SBS).

According to the Association of Modified Asphalt Producers, the global market for butadiene is 14,000,000 mt/year, of which 6 % is for the production of virgin rubber polymer for asphalt modification (Berkley and Romagosa 2008). Considering the average butadiene content of SBS, 68 to 69 %, used to model SBS production, this translates to more than a million metric tons of virgin SBS production for the global asphalt modification market. With each US material recycling facility producing 44,850 mt of GTR annually, 18,720 mt of SBS could be substituted with GTR. At this annual per facility potential for substitution, the market can easily absorb GTR produced from up to about 66 scrap tire material recycling facilities. This estimate assumes that, while the facilities recycle scrap tires generated in the USA, some of the resulting Road+ product may be exported.

The steel used to manufacture tires is coated with copper, zinc, bronze, or brass to protect the bead and belt wires from corrosion. Copper and/or zinc coatings can preclude the scrap from being accepted to a BOF (CA IWMB 2003). A BOF has stricter quality standards for scrap acceptance than an EAF. Also, EAF locations in the USA are numerous and varied, while BOF locations are few and concentrated in the Northeastern states. The mixed quality of the tire-derived steel scrap would not justify its transport beyond 200 to 400 mi (CA IWMB 2003). Steel from scrap tire bead has a medium to high carbon content and conforms to the 1070 steel classification standard as defined by the American Iron and Steel Institute (CA IWMB 2003). Thus, steel scrap from processed scrap tires was modeled to go to a local EAF in the short-term and long-term scenarios.

2.2.2 Energy recovery

The pyroprocessing step of cement production is where wastes may be treated/energy recovered by co-incinerating them with conventional fuels. Cement kilns are large, burn at higher temperatures, and have longer gas residence times than most solid waste incineration facilities. The fact that the alkaline clinker can absorb sulfur and halogen compounds and noncombustibles adds to the attraction of using kilns to treat waste. An individual cement kiln may use up to 20 to 30 % TDF as a combustion fuel substitute (RMA 2009a). However, of the total energy consumption at the pyroprocessing step for US cement production, TDF has remained at 5 % or less over the last decade, while coal and petroleum coke contribute nearly 90 % (USGS 1999–2009). Preliminary screening shows that, given their small contribution to overall kiln energy requirements, including the small fractions of natural gas and other waste fuels in the substituted fuel mix has minimal effect on the overall comparison. In this analysis, coal and petroleum coke were the conventional kiln fuels modeled to be displaced by TDF. Because these fuels are consumed in different ratios depending on the kiln type, the average values for these ratios were weighted with statistics on US kiln technologies to calculate the overall petroleum coke-to-coal ratio for US cement kilns: 0.206 for the short-term scenario (PCA 2006). The US Portland Cement Association states that, because of the lower thermal energy requirements, newly installed cement capacity uses dry processing technology (PCA 2006). The phaseout of wet kiln processing is simulated to obtain the fuel mix ratio used to model displacement of kiln fuels in the long-term scenario. The simulated phaseout results in a higher petroleum coke-to-coal ratio, 0.209. Nearly all coal used in cement kilns is of the bituminous variety mined in the Eastern and Midwestern USA (PCA 2006; USGS 1999–2009).

The environmental effects of alternative fuel combustion depend on the elemental composition of the fuel type, as well as the kiln conditions in which the fuels are used (e.g., emission control technology). The authors used a multi-input allocation method and average US kiln conditions to calculate fossil fuel savings and changes in atmospheric emissions due to conventional fuel substitution. This approach is similar to that used in previous LCA studies (Seyler et al. 2005; Boesch et al. 2009). The energy and mass balance considered the average US kiln fuel mix ratio, heating values of each fuel, basic combustion stoichiometry, and emission factors for cement kilns. The elementary composition and heating value of the fuels were the main input parameters required. Input mass was organized into macro-elements and mineral fractions. Output mass was organized

into combustibles going to the flue gas and inert fractions that are incorporated into the clinker.

In this analysis, the authors considered the average higher heating value of US bituminous coal and petroleum coke to be 24.9 and 32.5 MJ/kg, respectively, as applied in Franklin Associates' Private LCI Database. The lower heating value (LHV) of each fuel was used to calculate the energy balance and amount of fuel substituted. Using a heat balance approach, similar to that used in a previous LCA for waste solvent fuel substitution in cement kilns (Seyler et al. 2005), the following two relationships formed the basis of the assumptions for the energy and material balance for co-incineration of TDF at the cement kiln (Eqs. 1 and 2):

$$\frac{\text{Mass}_{\text{coal}}}{\text{Mass}_{\text{pet coke}}} = \frac{\text{Fuel Mix } \%_{\text{coal}}}{\text{Fuel Mix } \%_{\text{pet coke}}} \quad (1)$$

$$\begin{aligned} \text{Mass}_{\text{TDF}} \times \text{LHV}_{\text{TDF}} &= (\text{Displaced Mass}_{\text{coal}} \times \text{LHV}_{\text{coal}}) \\ &+ (\text{Displaced Mass}_{\text{pet coke}} \times \text{LHV}_{\text{pet coke}}) \end{aligned} \quad (2)$$

Given the LHVs and the average conventional fuel mix ratio determined for US cement kilns, the mass of fuel displaced by a particular mass of TDF was determined as follows (Eqs. 3 and 4):

$$\begin{aligned} \text{Displaced Mass}_{\text{coal}} &= \frac{(\text{Mass}_{\text{TDF}} \times \text{LHV}_{\text{TDF}})}{\text{LHV}_{\text{coal}} + \left(\frac{\text{Fuel Mix } \%_{\text{pet coke}}}{\text{Fuel Mix } \%_{\text{coal}}} \right) \times \text{LHV}_{\text{pet coke}}} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Displaced Mass}_{\text{pet coke}} &= \text{Displaced Mass}_{\text{coal}} \\ &\times \frac{\text{Fuel Mix } \%_{\text{pet coke}}}{\text{Fuel Mix } \%_{\text{coal}}} \end{aligned} \quad (4)$$

The amount and composition of air emissions do not necessarily correlate linearly to fuel inputs, so some assumptions must be defined. All carbon content is assumed to be oxidized and released as carbon dioxide (CO₂) gas to air. The 100 % conversion assumption captures the maximum possible change in CO₂ emissions due to fuel substitution. The change in CO₂ emissions per unit of conventional fuel substitution may be calculated by a simple stoichiometric balance. Per the calculated composition of mixed US scrap tires, 15 % of the rubber in TDF is *natural* rubber, which is approximately 88 % carbon. Therefore, 13 % of the carbon content of TDF is considered to produce biogenic CO₂ upon oxidation; the remainder is assumed to be the fossil CO₂ resulting from combustion of the plastics and synthetic rubber.

For some pollutants, assumptions about combustion reactions are not as straightforward. Nitrogen oxides (NO_x), particulate matter (PM), hydrogen chloride (HCl), and dioxin/furan (PCDD/F) emissions are not only fuel-related but

also process-related. Changes in these emissions are estimated based on fuel-specific flue gas production rates in dry standard cubic meters (dscm) and national emission factors (EF) as follows (Eq. 5):

$$\frac{\Delta \text{kg}_{\text{pollutant}}}{\text{treated kg}_{\text{TDF}}} = \text{EF}_{\text{pollutant}} \times \left[\frac{\text{dscm}_{\text{flue gas}}}{\text{kg}_{\text{TDF}}} - \left(\frac{\text{displaced kg}_{\text{coal}}}{\text{kg}_{\text{TDF}}} \times \frac{\text{dscm}_{\text{flue gas}}}{\text{kg}_{\text{coal}}} \right) - \left(\frac{\text{displaced kg}_{\text{pet coke}}}{\text{kg}_{\text{TDF}}} \times \frac{\text{dscm}_{\text{flue gas}}}{\text{kg}_{\text{pet coke}}} \right) \right] \quad (5)$$

The calculations used to estimate changes in these emissions reflect standard emission control technology. The authors used national emission factors from the US Code of Federal Regulations and/or standards used in EPA's Municipal Solid Waste Management Decision Support Tool (MSW DST) Waste-to-Energy LCI model (EPA 2000, 2006). A Boie-based equation (Eq. 6) was used to estimate

volume of flue gas per unit fuel energy input at standard pressure and temperature. This calculation is based on the dry fuel's hydrogen to carbon ratio (H/C) and the percent oxygen in the flue gas (%O) (Annamalai and Puri 2007). The authors assumed 7 % oxygen in the flue gas, as this is the common base correction factor used in US environmental regulations for incineration of wastes:

$$\left(\frac{\text{m}^3}{\text{GJ}} \right)_{\text{STP}} = \left[3.55 + 0.131 \times \% \text{O}_2 + (0.018 \times \% \text{O}_2)^2 \right] \times \left(\frac{\text{H}}{\text{C}} \right)^2 - \left[27.664 + 1.019 \times \% \text{O}_2 + (0.140 \times \% \text{O}_2)^2 \right] \times \left(\frac{\text{H}}{\text{C}} \right) + \left[279.12 + 10.285 \times \% \text{O}_2 + (1.416 \times \% \text{O}_2)^2 \right] \quad (6)$$

Sulfur dioxide and metal atmospheric emissions were estimated using transfer coefficients specific to the element's behavior in cement kilns. The amount of trace metals that may be emitted as particulate or vapor depends on the metal content of the fuel and raw feedstock. Generally, metals may be classified as volatile, semivolatile, or non-volatile. The nonvolatile metals tend to concentrate in the cement clinker, so the likelihood of these metals being transferred from combusted fuels to air is very low. The portion of fuel constituent not transferred as an air emission

was assumed to be incorporated into the cement clinker. The semivolatile and volatile metals are the compounds of concern when considering the changes in air emissions due to fuel substitution. The authors used maximum air emission transfer coefficients from published case studies on incineration tests to calculate the atmospheric metal emission due to fuel substitution (Boesch et al. 2009; IFEU 1998; MUNLV 2001, 2007; Seyler et al. 2005). The approach used to model changes in sulfur dioxide and metal emissions to air due to fuel substitution is as follows (Eq. 7):

$$\frac{\Delta \text{kg}_{\text{metal}}}{\text{treated kg}_{\text{TDF}}} = \text{TC}_{\text{metal}} \times \left[\frac{\text{kg}_{\text{metal}}}{\text{kg}_{\text{TDF}}} - \left(\frac{\text{displaced kg}_{\text{coal}}}{\text{kg}_{\text{TDF}}} \times \frac{\text{kg}_{\text{metal}}}{\text{kg}_{\text{coal}}} \right) - \left(\frac{\text{displaced kg}_{\text{pet coke}}}{\text{kg}_{\text{TDF}}} \times \frac{\text{kg}_{\text{metal}}}{\text{kg}_{\text{pet coke}}} \right) \right] \quad (7)$$

The elemental analysis for 90 % or more *de-wired* tire-derived crumb was used to reflect TDF composition in this analysis (Gray 2004; Jones et al. 1990). However, scrap tires may be fed to cement kilns *whole* or after preprocessing into fuel chips and/or crumb and removing steel. The form of TDF used to displace conventional fuels at cement kilns largely depends on the kiln type. Because national statistics were not available and the state of Texas has a relatively large cement processing capacity, the authors used statistics for Texas facilities to calculate the ratio of scrap tires burned

whole to those preprocessed: 40 and 60 %, respectively (TCEQ/TxDOT 2004). Per a previous case study, an average of 100 kWh of electricity is required for the preprocessing of 1 mt of TDF (Viridis 2003). For the fraction of TDF that is preprocessed, the removed steel was modeled to go to an EAF as it does in the material recycling route. When tires are fed whole to the cement kiln, the steel content is incorporated directly into the clinker. The incorporation of steel into the solid matrix displaces the need for an equivalent iron ore source. The authors estimated that over 97 % of the

ferrous feed used at a cement kiln is from iron ore or mill scale iron (USGS 1999–2009). The iron content in steel is nearly 99 %; the iron content in iron ore is only around 60 % (AISI 2009). The displacement of iron ore from tire-derived steel was calculated as follows (Eq. 8):

$$\begin{aligned} \frac{\text{kg}_{\text{Fe ore displaced}}}{\text{kg treated TDF}} &= \frac{0.99 \text{ kg}_{\text{Fe}}}{1 \text{ kg}_{\text{steel}}} \times \frac{0.16 \text{ kg}_{\text{steel}}}{\text{kg treated TDF}} \\ &\times \frac{1 \text{ kg}_{\text{Fe ore}}}{0.6 \text{ kg}_{\text{Fe}}} \times 0.4 \\ &\times 0.34 \text{ kg}_{\text{Fe ore displaced}} \quad (8) \\ &= 0.036 \end{aligned}$$

Details on the emission standards, transfer coefficients, and fuel characteristics used to model the LCI at energy recovery are available in the supporting documentation.

2.2.3 Consequential LCA modeling

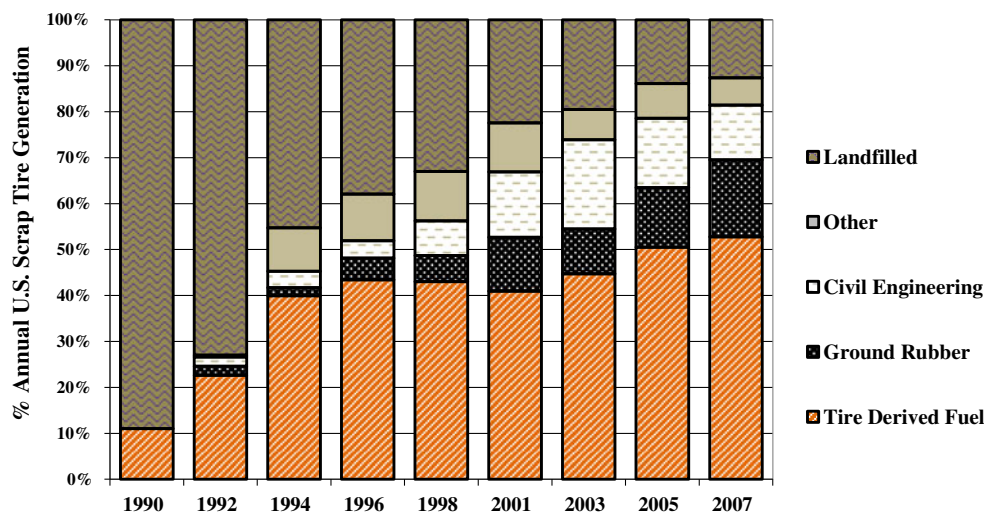
The ALCA results indicate that material recycling offers greater environmental benefits and, thus, should be prioritized above energy recovery as a scrap tire management method. However, it is also important to consider the possible consequences of prioritizing material recycling of scrap tires over energy recovery methods (i.e., assess the consequences of increased material recycling). The authors used values reported in the RMA market reports to estimate the utilization trends of US scrap tires in EOL markets (RMA 1999–2007). Figure 3 presents the fates of US scrap tires by percent of total annual generation. Of annual scrap tire generation in the USA, TDF markets currently consume over three times the volume that ground rubber markets consume. Shifting scrap tire generation from TDF markets to material recycling would require an increase in infrastructural capacity, which requires energy and materials. In addition, modeling the same level of substitution benefits from material

recycling at this increased volume assumes that there are markets to absorb the additional GTR and tire-derived steel produced. The authors used a consequential LCA modeling approach to assess the impact of shifting all scrap tire generation to the material recycling. This approach includes modeling the building materials and additional electricity required per marginal metric ton of treated scrap tires. Construction requirements were assumed to take place over the long term. The CLCA also examined the absorption potential for markets utilizing GTR from the additional material recycling facilities.

In this approach, the volume currently used in ground rubber markets, or projected to be used based on current trends, is the *normal* portion; the amount currently used or, projected to be utilized in TDF markets based on current trends, constitutes the *marginal* portion (i.e., the portion that would be shifted to material recycling). Given the current market trend, it is estimated that 24 % of scrap tires are recycled normally, while 76 % will be shifted from TDF markets or processed marginally. The authors used total annual scrap tire generation in millions of tires from RMA scrap tire market reports to calculate the average biannual growth rate of scrap generation: 4 % (RMA 1999–2007). This growth rate was then extrapolated to project scrap tire volume generated for each market in the long-term scenario. From this calculation, shifting all scrap tire generation to the material recycling would require about 3.7 new facility installations of the aforementioned capacity per year over the assessment period.

Marginal power supply mix is estimated according to theoretical arguments proposed by LCA and electricity system experts. Namely, plants with the highest variable operating costs will respond to short-term changes in electricity demand, while long-term changes in demand eventually affect installed capacities (Curran et al. 2002). At 19.5 GWh of annual electricity consumption per facility of the aforementioned capacity, the newly installed tire recycling facilities would collectively consume 72 GWh/year of marginally supplied electricity. This

Fig. 3 Trends for the fate of US scrap tires over time as percent of annual generation (generated with data from the RMA Scrap Tire Market Reports, 1999–2007; RMA 1999–2007)



increase in electricity demand is approximately 0.002 % of the total US electricity production for the year 2008 and 0.001 % of the demand projected for 2030 (EIA 2009a, b). In the short term, the increased electricity demand is predicted to be supplied by natural gas as they have the highest variable costs and are usually brought onto operation to meet peak demand. In the long term, the increase in demand requires power supply from newly installed capacity. The EIA predicts the majority of new capacity to be fueled by natural gas (EIA 2009b). Relative to coal, nuclear, and renewable technologies, natural gas plants have a low construction cost and can be built quickly. Projections of other energy source additions depend on possible changes in plant costs. In the case of frozen plant costs, EIA projects a US mix for newly installed capacity of 58.8 % natural gas, 22 % renewables, 18 % coal, and 1.2 % nuclear (EIA 2009b). No projections for the fuel mix of newly installed grid capacity were available for specific regions. Thus, this average mix projected for the USA is used to model marginal power to recycling facilities in the long-term consequential approach for all regions.

Though capital requirements are not assessed in the ALCA, the CLCA examines whether building materials required for the new material recycling infrastructure have a significant effect on the environmental comparison of the treatment methods assessment time. Per Genan, each facility of the aforementioned capacity requires about 4.8 million kilograms of steel and 11,400 m³ of concrete, and the facility is estimated to last at least 20 years. Given the projected growth in scrap tire generation, approximately 7.69×10^{-7} facilities are required per metric ton of mixed scrap tires per year of the assessment period. In other words, each marginal metric ton of mixed scrap tires sent to material recycling incurs additional average material burdens of 3.7 kg steel and 0.009 m³ concrete.

In the CLCA, steel scrap is still modeled to be processed into secondary steel at an EAF. The rates of steel demand and production are currently increasing; thus, EAF production is constrained primarily by the availability of scrap. The steel market is of such magnitude that rendering all of the steel in US scrap tires available as secondary steel does not affect the overall supply of secondary steel in the USA. Because shifting all US scrap tires to material recycling cannot significantly affect the demand and/or price of steel scrap, no change in EAF processing is modeled for the consequential analysis.

Shifting US scrap tire generation to material recycling removes the availability of TDF from energy recovery markets. This analysis assumes that cement kilns would replace previously used volumes of TDF with energetically equivalent volumes of conventional kiln fuels. The return to conventional kiln fuels is modeled using the same approach as is used for fuel substitution in the ALCA. The fiber fractions from material recycling are still modeled to be sent to cement kilns for co-incineration, as in the ALCA.

2.2.4 Assumptions and limitations

To feasibly model the complex systems investigated in this analysis, the authors needed to make some assumptions. The main inventory assumptions were as follows:

- Except for the examination of additional infrastructure requirements in the CLCA, capital goods are not included in the system boundaries of this analysis. Other aspects excluded from the analysis are: space conditioning requirements for facilities; energy and wastes associated with support personnel, and miscellaneous materials and/or additives which individually account for <0.25 % by weight of the net process inputs.
- The authors used region-specific (Texas) values to model for the ratio of scrap tires fed whole versus those preprocessed to TDF at cement kilns, as well as values for transport distances between cement kilns and EAFs, as national averages were not publicly available.
- For modeling emissions at the cement kiln, the authors converted the default NO_x emission standard for combustion facilities (per EPA's MSW DST waste-to-energy model) from the reported units, parts per million of nitrogen oxides by volume of flue gas, to mass, assuming the molecular weight of NO₂; the standards do not specify a particular species of nitrogen oxide (i.e., nitrogen monoxide or NO₂).
- Transfer coefficients for metal emissions to air, specific for cement kilns, are from European case studies, as publicly available US factors are general for waste incineration.
- There is a large range of uncertainty in transfer coefficients to air for metal and sulfur oxide emissions from cement kilns. To be conservative, the authors used the highest transfer coefficient of each metal of those found in the literature review to model the baseline change in atmospheric emissions due to fuel substitution at the cement kiln. This assumption was made to capture the largest potential changes occurring due to kiln fuels substitution.

3 Life cycle impact assessment results

Table 3 shows the net quantitative results of the baseline scenario using both methodological approaches for both the short-term and long-term time scenarios. Cumulative energy demand, as assessed with Franklin Associates' own method, includes energy of material resources or embedded energy. Global warming potential (GWP) was characterized using factors reported by the Intergovernmental Panel on Climate Change in 2007. Figure 4 displays the GWP results graphically in order to show the trends for the process contribution results indicated in this and the other impact categories. The mass of iron

Table 3 LCIA results for the baseline scenario of EOL treatment of 1 mt of mixed US scrap tires

Impact category	Characterization factor	Attributional approach						Consequential approach	
		Short term			Long term			Short term	Long term
		MR	ER	Delta	MR	ER	Delta	Shift to MR	Shift to MR
Global warming	kg CO ₂ eq	-1,487	-501	-985	-1,480	-503	-978	-999	-1,004
Energy use	GJ	-56.6	-34.2	-22.5	-58.8	-35.5	-23.3	-22.3	-23.5
Iron ore	kg iron ore	-178	-143	-35.2	-178	-143	-35.2	-35.2	-35.2
Acidification	H ⁺ moles eq	-825	-277	-548	-822	-267	-555	-557	-568
Eutrophication	kg N eq	-0.20	-0.067	-0.13	-0.20	-0.056	-0.14	-0.14	-0.14
Smog	kg NO _x eq	-6.39	-1.52	-4.87	-6.4	-1.28	-5.11	-5.07	-5.22
Respiratory effects	kg PM ₁₀ eq	-1.71	-1.04	-0.68	-1.7	-1.02	-0.67	-0.67	-0.71

Negative values indicate potential environmental impact reductions. The short-term results are estimated for the years 2009 through 2014, while the long-term results are estimated for the year 2020

MR material recycling, ER energy recovery

ore consumed in each system was used to reflect mineral resource depletion because it is the individual parameter most relevant to the studied systems. The remaining impact categories examined in this study were characterized using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) methodology developed by EPA especially for US conditions (Bare et al. 2003). Stratospheric ozone depletion is not presented in the results because the contributing substances (freons and halons) are not present in significant quantities in the LCI material flux of either treatment method. Only midpoint indicators are assessed as there is a higher level of scientific consensus in the

associated environmental mechanisms (e.g., human and ecosystem health endpoint methods are not employed). Water consumption and land-use impacts are not included in the life cycle impact assessment (LCIA).

The authors normalized LCIA values for each impact category by a US-specific reference value so they could be presented in the same units—person equivalents. This unit represents the per capita impacts for treatment of 1 mt of scrap tires relative to the average impact caused per US citizen over a year for each impact category. It is important to note that the long-term results were not normalized using projected impact and population values, but rather for the current situation in

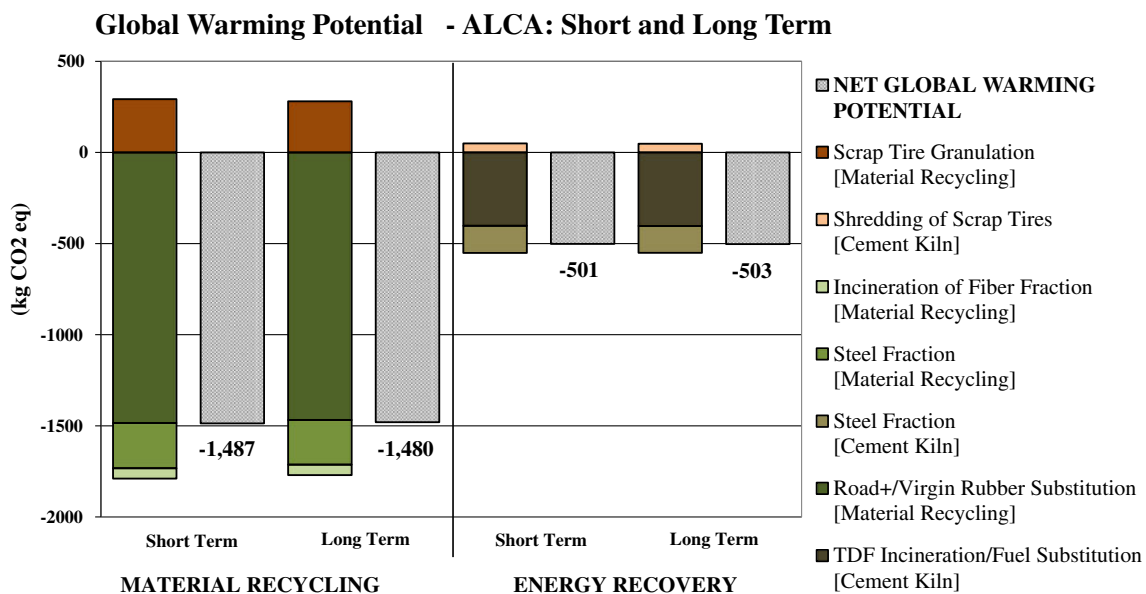


Fig. 4 GWP of the baseline ALCA scenario by process contribution. Processes contributing <1 % of net impacts are not shown in the graph bars or legend

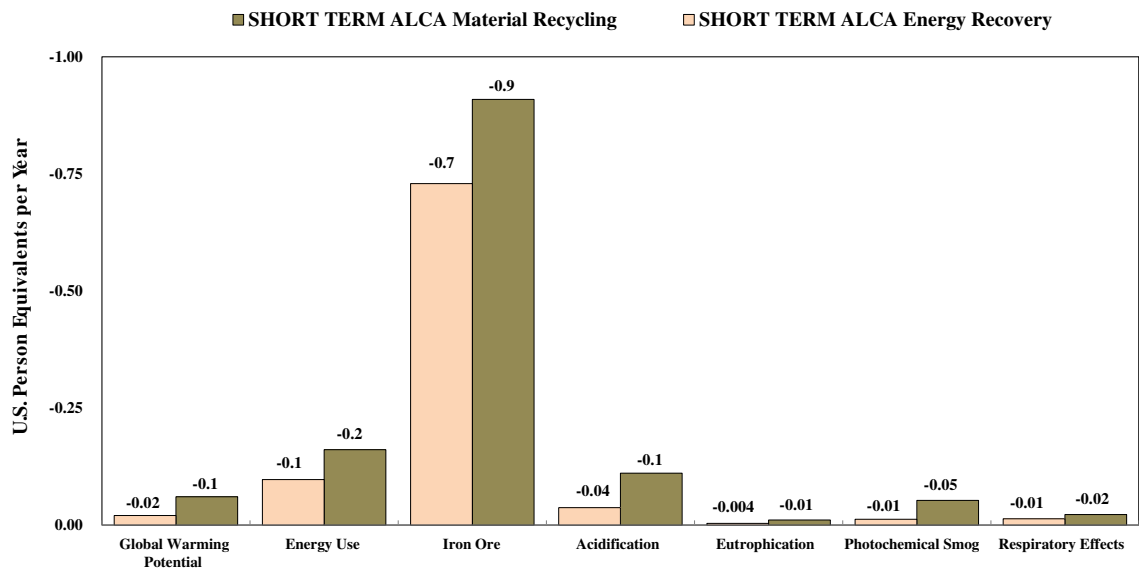


Fig. 5 Attributional LCIA results for the short-term baseline scenario of EOL tire treatment methods. The results for the short-term scenario do not vary significantly from those for the long-term scenario; only

the short-term ALCA results are presented in this article. Results are normalized to US person equivalents per year

the USA. Because the ALCA results are generally consistent for the short-term and long-term time period assessed, only the short-term ALCA results are presented in Fig. 5. The impact burdens and reductions in the consequential results are generally smaller than those seen in the attributional approach. This difference is expected because the consequential approach only models burdens resulting from changes to the system rather than burdens of the entire system. The long-term results are shown for the CLCA in Fig. 6.

4 Discussion

In the baseline attributional approach, results for all seven impact categories indicate greater environmental impact reductions for the material recycling route relative to energy recovery in a cement kiln. In terms of the normalized results, all impact reductions are less than one US person equivalent. The decrease in consumption of mineral resources appears to be significant for both the material recycling and energy recovery route due to the recovery of steel scrap. However,

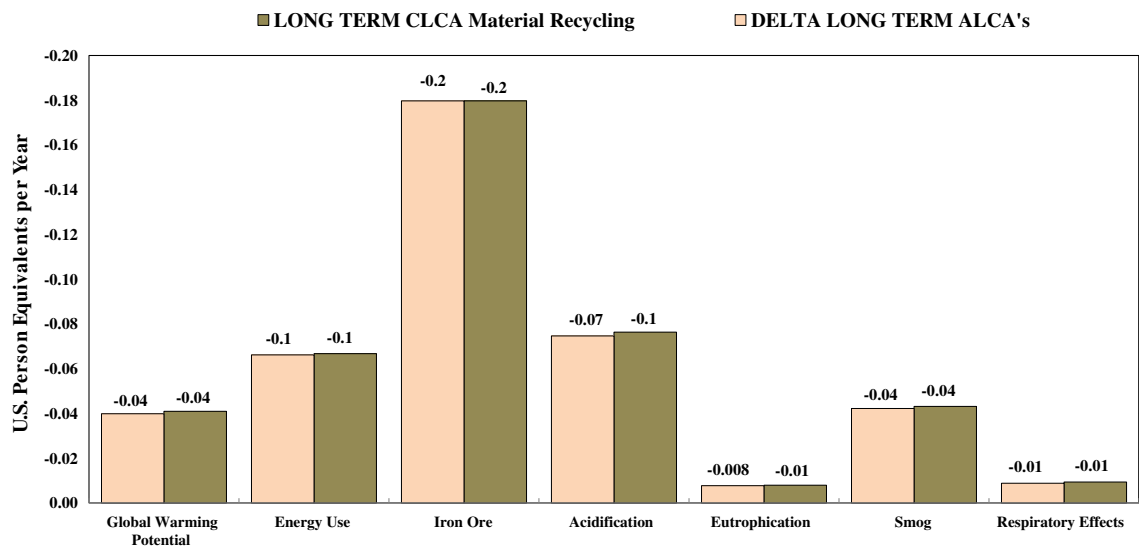


Fig. 6 Consequential LCIA result for the baseline scenario of EOL tire treatment methods. The results for the long-term scenario do not vary significantly from those for the short-term scenario; only the long-term

CLCA results are presented in this article. Results are normalized to US person equivalents per year

treatment of scrap tires through energy recovery in a cement kiln downcycles more of the steel by incorporating the steel from tires fed to kilns whole into the clinker; material recycling allows more closed loop recycling. The greater impact reductions for material recycling in other impact categories can primarily be attributed to the burdens avoided through substitution of the synthetic rubber-modified asphalt. Impact reductions occurring in the baseline energy recovery route are largely due to substituted fossil-based cement kiln fuels.

The results of the CLCA indicate that shifting scrap tires currently managed using energy recovery methods to material recycling management methods offers significant potential environmental benefits and a more favorable option in terms of waste management hierarchy (EPA 2012). Shifting scrap tire generation from TDF markets to material recycling would require an increase in infrastructural capacity, which requires energy and materials. However, the added infrastructure and electricity requirements would incur insignificant burdens in comparison to the potential impact reductions of substituting recycled tire rubber for synthetic rubber used in modified asphalt. These benefits also outweigh those currently assessed for substitution of conventional cement kiln fuels.

The authors conducted sensitivity analyses to evaluate the influence of variation in several key parameters in the inventory. The sensitivity analysis indicates that the study conclusion does not change for: (1) the range of TDF heating values reported in relevant US literature, (2) variation in the mixed scrap tire rubber to steel composition ratio, (3) alternative electricity grid fuel mixes with higher and lower carbon dioxide emission rankings than that of the baseline scenario, or (4) a comparison of material recycling to energy recovery in pulp in paper mills instead of in cement kilns.

The authors also conducted an uncertainty analysis on the metal transfer coefficients used to model changes in air emissions at the cement kiln due to fuel substitution. The uncertainty analysis captures the range of possible outcomes and indicates that results for the energy recovery route may vary for respiratory effects ($\leq 40\%$), acidification ($\leq 37\%$), and smog formation ($\leq 8\%$), relative to their baseline values. The results for the material recycling route do not vary significantly due to uncertainty in kiln emissions because only the incineration of the fiber fraction depends on these values. Given that differences in impact reductions between material recycling and energy recovery are greater than the magnitude of uncertainty for these categories, the uncertainty does not affect the overall conclusion of the study.

5 Conclusions

Combustion of TDF currently consumes over half of scrap tires generated annually in the USA; ground rubber markets are the second largest market segment but currently

consume only a fifth of the total generated. As stockpiles decrease and more scrap tires are made available to EOL markets in the USA, further guidance will be needed to rank the benefits of EOL management strategies for scrap tires. The results of this LCA indicate that material recycling management methods offer greater potential impact reductions and a more favorable option in terms of waste management hierarchy (EPA 2012). The added infrastructure and electricity consumption required for a shift of scrap tire volumes from energy recovery to material recycling markets incur insignificant burdens in comparison to the potential impact reductions from substituting recycled tire rubber for synthetic rubber used in modified asphalt. These benefits also outweigh those currently assessed for substitution of conventional cement kiln fuels. Sensitivity analyses indicate that this conclusion does not change for a range of examined scenarios including a comparison of material recycling to energy recovery in pulp in paper mills in place of cement kilns. These results lend important environmental impact information to the body of knowledge available to decision-makers prioritizing scrap tire waste treatment hierarchy.

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