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Research Paper

When solid recovered fuel (SRF) production and consumption maximize environmental benefits? A life cycle assessment

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A B S T R A C T

Solid recovered fuel (SRF) from non-recyclable waste obtained from source separation and mechanical treatments can replace carbon coke in cement plants, contributing to the carbon neutrality. A life cycle assessment (LCA) of the SRF production from non-recyclable and selected waste was conducted in an Italian mechanical treatment plant to estimate the potential environmental impacts per ton of SRF produced. The analysis would contribute to evaluate the benefits that can be obtained due to coke substitution in best- and worst-case scenarios. The avoided impacts achieved were assessed, together with an evaluation of the variables that can affect the environmental benefits: SRF biogenic carbon content (in percentage of paper and cardboard); transportation distances travelled from the treatment plant to the cement kiln; the renewable energy used in the mechanical facility. On average, about 35.6 $kgCO_2$-eq are generated by the SRF transportation and production phase. These impacts are greatly compensated by coke substitution, obtaining a net value of about −1.1 tCO_2-eq avoided per ton of SRF. On balance, the global warming potential due to SRF production and consumption ranges from about −542 $kgCO_2$-eq to about −1729 $kgCO_2$-eq. The research recommended the use of SRF to substitute coke in cement kilns also in low densely-populated areas to mitigate environmental impacts and achieve carbon neutrality at a global level.

1. Introduction

The European economy heavily relies on the trade of resources and natural materials from foreign continents (Giljum et al., 2008), while waste disposal is becoming increasingly challenging (Luttenberger, 2020). This business-as-usual consumption pattern is identified as the driver of global environmental issues (Dyllick and Muff, 2016), while the energy crisis and environmental emergency are affecting human development and health at a global level (Shivanna, 2022). The Circular Economy (CE) principles and the related European carbon neutral policies are therefore implemented to address these continental and international issues (Velenturf and Purnell, 2021; Perissi and Jones, 2022).

CE stands for reducing and optimizing natural resources exploitation, pushing the entire economic system toward a circular approach (Suárez-Eiroa et al., 2019; Leipold et al., 2023). CE is characterized by waste valorisation, the extension of product lifecycles, resource sharing, restoration of natural sites, and energy production from renewable sources (Kirchherr et al., 2017) Therefore, circularity is supported by a transition to the use of renewable energy and materials, decoupling economic activities from the consumption of the natural heritage (Ellen MacArthur Foundation, 2015) In addition, to reduce waste disposal, in a CE it is necessary to promote waste recycling and recovery (Singh and Ordoñez, 2016). In recent times, there has been a discussion about the most suitable systems for energy recovery from non-recyclable solid waste (SW) made of municipal and industrial activities (Grosso et al., 2016): either through dedicated waste-to-energy (WtE) facilities for heat and power generation or by incorporating solid recovered fuel (SRF) into existing industrial plants to replace fossil fuels (Ardolino et al., 2017).

In Europe, SRF are fuels prepared from non-recyclable and non-hazardous waste to be utilized for energy recovery in waste incineration or co-incineration plants (Iacovidou et al., 2018) and meeting the classification and specification requirements of the UNI EN 21640 from the European Committee for Standardization (European Commission,

Abbreviations: SRF, Solid recovered fuel; SW, Solid waste; SWM, Solid waste management; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCVSRF, Low calorific value of solid recovered fuel; LCVCOKE, Low calorific value of coke; MBT, Mechanical biological treatment; AU, Allocation unit; FU, Functional unit; GWP, Global warming potential.

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2019). This classification system (UNI EN ISO 21640:2021, 2020) is based on several indicators such as economic (net calorific value), operational (chlorine content) and environmental (mercury content) (Ramos Casado et al., 2016). Utilizing SRF as a replacement for coal or coke contributes to the reduction of carbon emissions and the preservation of Earth's natural systems (Kahawalage et al., 2023). Therefore, this recovered fuel can assist cement facilities in achieving their sustainability objectives by substituting over half of their fossil fuels (i.e., coal) (Aranda Usón et al., 2013). Indeed, SRF consumption can reduce the need for coal mining and allows mitigating non-biogenic sources of CO_2-eq if cellulosic and biogenic waste fractions are mixed with plastic fractions (Viczek et al., 2021b). On one hand, incorporating non-recyclable plastic waste into SRF is a strategy to enhance the lower calorific value (LCV) and to improve its chemical properties (Montané et al., 2013). However, the use of biogenic resources (e.g., paper and cardboard) in the SRF maximizes the positive effects in terms of carbon credits (Ferronato et al., 2022a), offering economic incentives to encourage reductions in pollutant emissions (Tripathi et al., 2016).

One significant challenge to produce high-quality SRF suitable for co-combustion in thermal power plants or cement plants is the commitment to sampling and analysis, leading to associated costs charged to waste generators and users (Bessi et al., 2016). However, it has been estimated that increasing the production of SRF leads to environmental and economic benefits, ultimately resulting in the avoidance of CO_2-eq emissions (Kara, 2012). Therefore, SRF production from selective collection residues obtained from high-quality standard sorting facilities is considered one important strategy to improve SRF production efficiencies and mitigate fossil fuels consumption in cement production (Nasrullah et al., 2015; Piaia et al., 2023). At the same time, the environmental impacts generated from sorting processes, transportation, and combustion should be carefully balanced with the avoided impacts that can be obtained thanks to coal mining avoidance and non-biogenic carbon emissions.

The current research would provide more insights about SRF production and consumption environmental patterns. The hypothesis, suggested by previous studies, is that the SRF production contributes to a minimal part to the environmental compared to the avoided fossil fuels (i.e., coal) (Kahawalage et al., 2023) but transportation and SRF composition can affect the environmental balance: the right mix of biogenic and non-biogenic sources of waste, and the location of cement kilns from waste generators, as well as coal mines from cement kilns can contribute to maximize or minimize the environmental benefits. Many studies about SRF production and environmental impacts mitigation were published in the literature in the last decade. Searching on the Scopus® databases, in the last 15 years, until June 2023, seventy-nine articles about SRF production and consumption were identified. Seventy-three studies aimed to compare, through a life cycle assessment (LCA), different types of SW management systems (Contreras et al., 2008; Cherubini et al., 2009; Koci and Trecakova, 2011), the carbon footprint of incinerators and landfills (Stafford et al., 2016; Karpan et al., 2022; Zhao et al., 2022)), or to estimate the environmental impacts of the mechanical and biological treatment (MBT) of mixed waste (Grzesik and Malinowski, 2017; Lima et al., 2018; Gadaleta et al., 2022). However, out of 79 articles, only six focused specifically on the environmental LCA of a SRF production process. Table 1 reports the scientific contributions specifically related to the LCA of SRF production systems.

Noone of these studies explicitly provided evidence about the environmental variability in terms of transportation distances between cement kilns and SRF production mechanical facilities and SRF composition (calorific value and biogenic carbon content variability). In addition, there is no specific quantification of the environmental impacts generated by an SRF mechanical treatment plant that contributes to the environmental product declaration of SRF production. Therefore, the research presented in this article introduced a real-world and primary data collection study regarding an attributional LCA of a SRF production facility located in Italy where municipal and industrial selected waste is sorted and treated.

Therefore, the research aims to fill this literature gap, effectively evaluating the balance between direct and avoided impacts by a scenario analysis that considers: (i) the transportation distance of waste to the sorting plant, as well as (ii) the transportation of SRF to the cement kiln; (iii) the biogenic carbon content of the SRF (expressed in percentage of paper and cardboard);; and the (iv) avoided coal transportation and extraction (in the function of SRF calorific value). The research questions that deserve an answer are: "*What is the impact of SRF production from selected waste in a mechanical treatment plant and how can be mitigated?*"; "*what is the potential optimal biogenic content (and calorific value) that a SRF should have to maximize the reduction of carbon footprint of the process?*". The LCA contributes to the international literature providing effective results to determine the potential right conditions to

Table 1
Literature review of LCA of solid recovered fuel production and consumption.

Authors	Country	Journal	Description of the analysis conducted	LCA software and impact assessment methods	FU
(Ardolino et al. 2017)	Italy	Waste Management (Elsevier)	LCA to evaluate the environmental impacts of different configurations of a material recovery facility (MRF) able to convert about 32 kt y^{-1} of unsorted mixed waste into SRF.	• SimaPro 8.2 and Ecoinvent 3.2 database. • IMPACT2002+.	100 t d^{-1} of mixed municipal waste
(Lombardelli et al. 2017)	Italy	Chemical Engineering Transactions (Italian Association of Chemical Engineering – AIDIC)	LCA assessment approach to evaluate the environmental impacts related to a process based on the separation of MSW into two different fractions: Refuse Derived Fuel (RDF) and Organic Fraction MSW (OFMSW).	• SimaPro 7.2.4 • CML2001 and Ecoindicator99 method.	1 ton of MSW
(Grzesik and Malinowski 2016)	Poland	Energy Sources, Part A: Recovery, Utilization and Environmental Effects (Taylor and Francis)	LCA to evaluate the potential environmental impacts caused by refuse-derived fuel (RDF) production from mechanical–biological treatment (MBT) plant.	• EASETECH model. • EDIP 2003 methodology.	1 Mg of mixed MSW
(Grosso et al. 2016)	Italy	Waste Management (Elsevier)	LCA assessment approach to evaluate a process for producing a solid recovered fuel (SRF) to be exploited via co-combustion in a cement kiln.	• SimaPro 8 and Ecoinvent v.2 database. • ILCD 2011 Midpoint.	1 t of residual waste
(Pressley et al. 2014)	USA and Denmark	Journal of Cleaner Production (Elsevier)	LCA to evaluate the conversion of USA MSW to liquid transportation fuels via gasification.	• Ecoinvent database. • ILCD.	1 Mg of MSW
(Reza et al. 2013)	Canada	Resources, Conservation and Recycling (Elsevier)	LCA approach to evaluate the environmental impacts related to RDF production from MSW generated in Vancouver, and co-incineration in two cement plants.	• Gabi LCA. • N.A.	1 t of RDF

Notes: MSW – Municipal Solid Waste; LCA – Life cycle assessment; RDF – Refuse Derived Fuel; FU – Functional unit; N.A. – Not Available; MBT – Mechanical biological treatment plant.

mitigate the carbon footprint and maximize environmental benefits of SRF production from pre-sorted waste used for cement production. Evidence is provided about the environmental benefits to import–export SRF from foreign countries and to substitute coal in cement kilns.

2. Methods

2.1. SRF production facility

The treatment plant generates about 35,220.7 t_{SRF} y^{-1}, handling about 43,487.11 t_{MSW} y^{-1}. The SRF characterization is reported in Fig. 1S. On average, about 23 % of the SRF is classified as biogenic fraction (wood, paper, and cardboard). The average lower calorific value (LCV) of SRF used within the study is estimated to 22.00 MJ kg^{-1}_{SRF}. This data refers to the average LCV provided by the local company. As a comparison, the LCV of coke employed in cement kilns has been defined equal to 29.60 MJ kg^{-1}_{COKE} (González-Arias et al., 2020). The technical operations that are carried out at the plant include the following: storage, material recovery, sorting, mixing, and SRF production.

The SRF production and consumption chain can be divided into seven main phases: Phase 1: SW transport and reception – the system begins with the transportation and reception of various waste fractions (Up-stream); Phase 2: Pre-treatments – it involves waste pretreatment processes. The treatment plant is divided in six main sites, from A to F. Reception and pre-treatment sites considered within the study are within site A, C and F, which deals with different waste fractions pre-treated; Phase 3: Internal handling and transport – it occurs by using different transportation trucks. The residues obtained from Phase 2 are sent to Phase 4; Phase 4: SRF production – it includes the mechanical processes required to produce SRF. Machineries are located in site D; Phase 5: Exhaust air treatment – Collection and treatment of exhaust air from site D; Phase 6: Waste transport, recycling, and disposal – Residues of the system are transported to recycling facilities or sanitary landfill; Phase 7: Transport and use at cement plants – External transport of SRF to cement kilns and combustion to the cement plant (down-stream).

In particular, Phase 6 and Phase 7 refer to the external management of residues and SRF consumption, which are out of the SRF treatment system. However, they were included within the system boundaries due to the importance in evaluating the avoided impacts that can be obtained thanks to coke substitution and recyclable waste valorisation, as well as the potential impacts due to SRF and waste transportation. Based on these assumptions, a system expansion approach has been included to consider these variables in the LCA (Cederberg and Stadig, 2003).

2.2. Goal and scope definition

An LCA was conducted for the environmental impacts assessment of SRF production. The research has been developed in the Varese province (Northern Italy), involving data collection from a typical European SRF production facility that generates secondary fuels employed by the cement industry. An attributional LCA was conducted to find: (i) the potential environmental impacts generated at the plant; (ii) the most relevant processes that contribute to these impacts; (iii) the parameters that influence the results (bin to gate approach). Outcomes were evaluated through a contribution analysis and results' normalization. The reference ISO 14040:14044 Standards were considered within the study to conduct the LCA (UNI EN ISO 14040:14044, 2021). After, a consequential analysis has been conducted. Scenarios based on assumptions made on renewable electricity use, SRF composition and substitution, and SRF transportation distances were included in the analysis.

Data collected were converted to the functional unit (FU), equal to 1 t of SRF. Unit of mass was employed instead of calorific value as FU since information about the composition of incoming waste was not available. For the inventory analysis, kilograms, tonnes, and Liters per FU were employed for the material balance, while kWh per FU were employed for the energy balance. Data were collected considering the yearly SRF

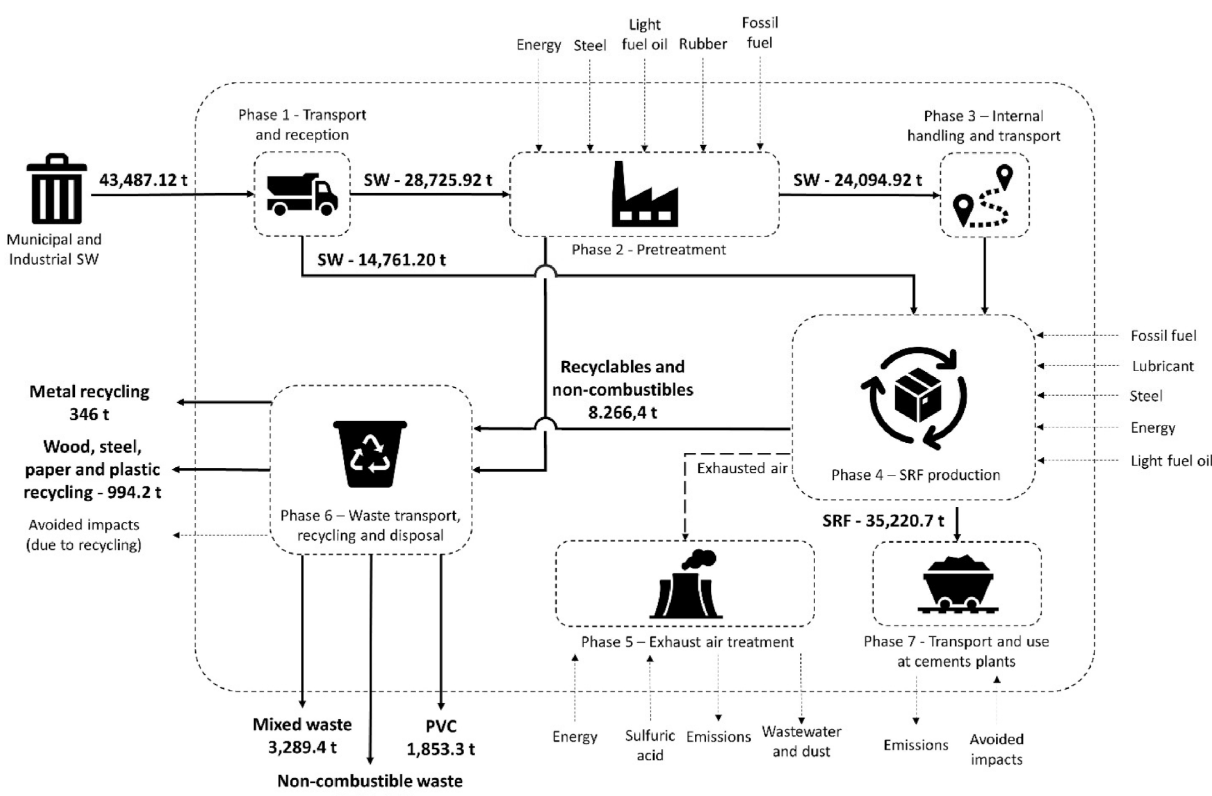


Fig. 1. Technical system boundaries related to the SRF life cycle. The use of SRF in the cement plant represents an expansion of the system. Dashed line refers to the system boundaries.. Dashed rows shows data input and output. Transport includes operational material and emissions.

production (SRF_{TOT}). Construction materials of machineries, covers, trucks, offices, among others, were not included within the inventory. Therefore, construction materials are outside the system boundaries.

Primary data collected at the plant refer to 2022. The LCA was performed using the SimaPro 9.4 Academic license software and the Ecoinvent 3.8 databases. The IMPACT 2002 + method was used to obtain the overall environmental profiles (mid-point and end-point categories). Globally, 15 mid-point categories were considered, as well as 4 end-point categories. For the analysis of the carbon footprint of specific scenarios, the IPCC2021 method was employed, splitting the contribution of biogenic and non-biogenic carbon to the global warming potential (GWP). The geographic and technical boundaries are related to the Northern Italy and European foreign countries. The schematic representation of material flows (preliminary obtained with the subSTance flow ANalysis software (Cencic and Rechberger, 2008)), and the system boundaries are reported in Fig. 1.

2.3. Life cycle inventory (LCI)

Primary data were used for conducting the research. Information about materials and energy consumption were provided from company reporting, while data concerning the energy and materials associated emissions linked to the transportation system were obtain from Ecoinvent 3.8 database. The inventory is reported in the following sections for each specific phase.

2.3.1. Phase 1 – SW transport and reception

Waste is transported to the plant using several types of trucks. Transport has an impact that depends on the tonnes carried and the distances travelled. There are not available data sheets specific per truck, but it has been verified on site that the vehicles are recent, and they can be considered modern and compliant to Euro6 trucks. Therefore, for modelling, it was considered a lorry 7.5–16 t Euro6 {Europe} for quantities exceeding 4000 t_{MSW} y^{-1}, while a lorry with a capacity of 3.5–7.5 t Euro6 {Europe} for quantities less than 4000 t_{MSW} y^{-1}.

The company provided information about cities from which the waste was obtained, and the quantities transported per year and per source. Therefore, average distances can be calculated per waste fraction. It is important to mention that to obtain 1 ton of SRF, larger quantities of MSW are required due to process residues. In this regard, a global allocation unit of 1.235 can be obtained. The allocation unit derived from the ratio between 43,487.12 t_{MSW} y^{-1} and 35,220.70 t_{SRF} y^{-1}. During the treatment phases, this leads to higher impacts associated to MSW transportation per FU. The amount of MSW transported per year and the average weighted distance of km travelled to reach the plant are reported in Table 1S.

2.3.2. Phase 2 – Pre-treatments

Depending on the waste type, different processes are involved to prepare waste to be converted into SRF. For site F, the treated waste includes Plasmix (European Waste Code - CER 191212 and 191204) and rubber scrap (CER 070299): pre-treatment is carried out to separate polyvinyl chloride (PVC) waste that should be disposed of to the sanitary landfill. In site C, industrial waste (rolls) (CER 150105) is pretreated using a mechanical shearer to reduce material size. In site A, the sorting operation for bulky waste (CER 200307) and industrial waste (CER 150,101 and 170904) is carried out to separate recyclable materials such as paper, cardboard, wood, and iron. Industrial waste (2,622.84 t_{MSW} y^{-1} - CER 150106) and mixed waste (12,138.36 t_{MSW} y^{-1} - CER 200301) are directly transferred to site D (SRF production) with direct unloading and no internal handling. The outputs of the pretreatment phase are sent to site D (SRF production). To obtain the material consumption per FU, ù data of material consumed per year was divided by the SRF_{TOT}.

To allocate the effective energy consumption per machine, a comparison was made between the company's actual energy consumption per year and the estimated yearly energy consumption per machinery. In particular, the following steps were carried out: (1) Determination of the company's real annual energy consumption for Phase 2 and Phase 4; (2) Estimation of electricity consumption per year per machine by multiplying the machinery's power by the average annual working hours (100 % of the power was considered); (3) Determination of the effective energy consumption ratio (company's real energy consumption and potential electricity consumption calculated). From this comparison, the effective energy consumption for Phase 2 amounts to 36 % of the nominal power and working hours, while for Phase 4 is 60 %. According to IEA (International Energy Agency) World Energy Statistics and Balances, in Italy, in 2018, the share of renewable energy in electricity was 40 %. This data has been used for the LCA (electricity mix – Ecoinvent Database).

Similarly, to allocate Diesel and light fuel oil consumption, the yearly energy and material consumption was calculated based on machine power (primary data collection). On the other hand, to estimate the potential annual steel consumption of machineries replaced periodically (e.g., shredder), the ratio between the machinery's weight and the machinery's warranty years was considered (assuming that the machinery is made entirely of steel). A similar procedure was employed to estimate the quantity of rubber used annually for transportation belts. In this case, to determine the weight of the transporting belt, the product of the average volume (0.09 m^3) and the density of the oil-resistant rubber 1,55 t m^{-3} was used. Then, values have been converted into FU (1 t SRF_{TOT}). Table 2S shows the inventory per FU, and data source.

2.3.3. Phase 3 – Internal handling and transport

Internal handling consists in transporting materials from Phase 2 (pre-treatments) to Phase 4 (SRF production). To estimate the average total distances travelled per day, the meters from one site to another were calculated together with the amount of waste transported per year for each transportation truck. As for Phase 1, vehicles are recent (about 2 years old trucks) and therefore it was assumed that they are modern and compliant Euro6 trucks. The vehicle type, the distances travelled, and the amounts of waste transported per site are reported in Table 3S. For modelling the impacts, the Ecoinvent 3.8 database was used. Distances and amounts are primary data provided by the company.

2.3.4. Phase 4 – SRF production

In this phase, it is possible to obtain the SRF that is subsequently sold to cement plants. Waste is handled by heavy machineries able to move the waste from the storing area to the mechanical treatment system. There, waste moves thanks to transporting belts. A first magnetic and non-magnetic separation take place, which is followed by a shredding system. A sieving system select the bigger fraction from the smallest one (<3 mm), and a sorting machine select the light fraction (combustible) from the heavy one (non-combustible). A shredder is located at the end of the line to uniformize the output.

Primary data are provided for the whole site D. Therefore, to allocate the values of operational materials consumed per machine, the nominal power was considered to allocate the energy and material use. For the maintenance of site D, lubricating oils, steel spare parts, and light fuel oil are used. About 888 kg y^{-1} of lubricating grease (machines and belts lubricant) are used globally. To allocate the respective quantities of lubricants to each belt and process, the installed power was considered. To convert lubricant oil consumption (Lc_{FU}) per FU, Eq. (1) and Eq. (2) were used, where: $AU_{LC}(i)$ is the allocation unit of the lubricant consumption per machine *i*; W_i the single power of the machine or belt; W_{TOT} the sum of powers of all the machines and belts; $Lc_{FU}(i)$ the lubricant consumed per FU for the *i-th* machine; l_c the total mass of lubricants consumed per year (lubricants – engine belts and machines).

$$AU_{LC}(i) = \frac{W_i}{W_{TOT}} \tag{1}$$

$$Lc_{FU}(i) = \frac{AU_{LC} \bullet lc}{SRF_{TOT}} \quad (2)$$

Regarding the maintenance of spare parts, 240 stainless steel knives (0.37 dm^3) are replaced each month. For the primary shredder, 36 stainless steel knives (0.15 dm^3) are replaced three times a year, and 9 stainless steel control arms (3.18 dm^3) are replaced six times a year. Stainless steel density corresponds to about 8 t m^{-3}. This data has been used to estimate the amount of steel consumed per year (in metric tonnes) and per FU. Like the approach employed for the lubricating oil, to convert the steel consumption per FU, the amount of steel used per year and per machinery was divided by SRF_{TOT}. The inventory analysis related to this Phase is reported in Table 4S.

2.3.5. Phase 5 – Exhaust air treatment

Air emissions generated in site D are collected and treated. Internal air suffers from persistent odour and the dust generated by the waste. Therefore, the air is collected with a vacuum system, making the hangar's internal pressure lower than the external one. This is guaranteed by a suction system made of electric pumps and fans. The exhaust air is then treated by a sleeve filter to reduce dust emissions and a humid scrubber. The first filter allows the decrease of the amount of PM2.5 and PM10 by a system of tubular membranes, while the scrubber foresees an acid shower that guarantees the balance of the pH and the removal of hydrocarbons or sulfuric compounds.

For the maintenance of the scrubber, 1 m^3 of 30 % sulfuric acid (SA) is annually used. This liquid substance has a density of about 1.16 g cm^{-3} at 20 °C. The total amount of sulfuric acid employed per year has been divided by SRF_{TOT} to allocate impacts to the FU. Table 5S reports the inventory analysis related to this Phase. Wastewater goes to off-site treatment (53 km), while the dust is transported to sanitary landfill (130 km). Particulate matter is the unique emission considered within the system. The plant complies with the limit of the Italian regulation (5.00 mg Nm^{-3}). According to the last sampling (2022), average dust emission is equal to0.27 mg Nm^{-3}. The amount of air treated per hour by the plant is 27,603 Nm^3 h^{-1}, for a total of about 18.6 kg_{PM10} produced per year. Like the approach employed for the sulfuric acid, the amount of exhaust air treated was converted per FU.

2.3.6. Phase 6 – Waste transport recycling and disposal

Data about the amount of waste and the average weighted distances travelled to reach different destination are reported in Table 6S. The waste produced by the system has different destinations: recycling for wood, paper, plastic, and metals; landfill for dusts, PVC (polyvinyl chloride), and general mixed waste; incinerator for industrial waste; and treatment plant for wastewater. For these four categories (polyethylene, polypropylene, paper, and wood recycling), electricity consumption in recycling facilities refers to the scientific literature. The energetic consumption related to paper recycling is estimated equal to 6 kWh per ton (Arena et al., 2004).

General mixed waste refers to inert and fine materials, mainly non-combustible. These wastes are discarded because they affect SRF quality (Viczek et al., 2021a). Following a characterization analysis, 50 % of this waste flow has a diameter smaller than 1 cm, and its composition is unknown. Therefore, it was classified as generic MSW. Additionally, plastic and textile fractions have been combined, as the textile fraction is not natural but plastic. Instead, general waste that is sent to incinerators are classified as combustible. Finally, transportation impacts were evaluated. As for Phase 1, a freight lorry with a capacity of 7.5–16 metric tons Euro6 was considered for quantities exceeding 4,000 t_{SRF} y^{-1}, while a freight lorry with a capacity of 3.5–7.5 metric tons Euro6 for quantities less than 4,000 t_{SRF} y^{-1}.

2.3.7. Phase 7 – Transport and use at cement plants

The SRF produced is sent to seven different cement plants. Avoided impacts can be obtain thanks to the replacement of conventional fuels (coke) (coal extraction and combustion). For the estimation, a replacement rate has been employed considering the different LCV of SRF and coke. The replacement rate is given by the rate between LCV_{SRF} and LCV_{COKE}. Eq. (3) gives the tons of coke potentially saved annually using SRF (m_{COKE}), equal to about 26,177.54 t per year.

$$m_{COKE} = m_{SRF} \bullet \frac{LCV_{SRF}}{LCV_{COKE}} \quad (3)$$

On balance, 1 ton of SRF produced at the plant and used at the cement kiln allows avoiding the extraction and combustion of about 743 kg of coke (average scenario). Coke substitution was modelled based on the Ecoinvent 3.8 database (Coke {GLO}| market for | APOS, S). A global source of data has been employed, which considers the transportation distances travelled to import coke from an average distance. Finally, impacts due to SRF transportation to cement plants is also added to the LCA. Table 7S reports the tons of SRF transported to reach the cement plants and the amount of coke substituted. Transportation impacts where modelled as for Phase 1 and Phase 6.

2.3.8. Final use and avoided impacts

Carbon dioxide avoided emissions were also considered within the LCA. In detail, the net value of fossil CO_2-eq emissions was calculated based on the potential amount of fossil CO_2-eq emitted from the SRF incineration (plastic combustion) and the avoided fossil CO_2-eq emissions due to coke replacement. To do that, the percentage of carbon content of coke and SRF was estimated. The literature gives an average carbon content of 87 % for coke (Grosso et al., 2016) and about 61.2 % for SRF with an LCV of about 22.16 MJ kg^{-1} and similar composition of the one under study (Edo-Alcón et al., 2016).

The carbon content of SRF depends on the composition, and it affects the LCV: since the SRF produced at the plant has an LCV equal to 22 MJ kg^{-1}, in proportion, it can be estimated a 60.77 % of carbon content to be employed for the CO_2 emission balance. Of this, 23 % is assumed biogenic, hypostasizing that the organic carbon content is proportional to the amount of paper, carboard, and wood available in the SRF. Based on that, it was estimated that the combustion of 1 ton of SRF produced about 512.95 kg of biogenic CO_2 and about 1717.27 $kgCO_2$-Fossil, while the avoided CO_2-Fossil emission due to coke substitution can be estimated to 2373.52 $kgCO_2$. Therefore, the combustion of 1 ton of SRF allows avoiding about −1.29 tCO_2-eq. Due to the variability of SRF characterization (LCV and carbon content), this parameter has been assessed in the interpretation phase.

2.3.9. Results interpretation

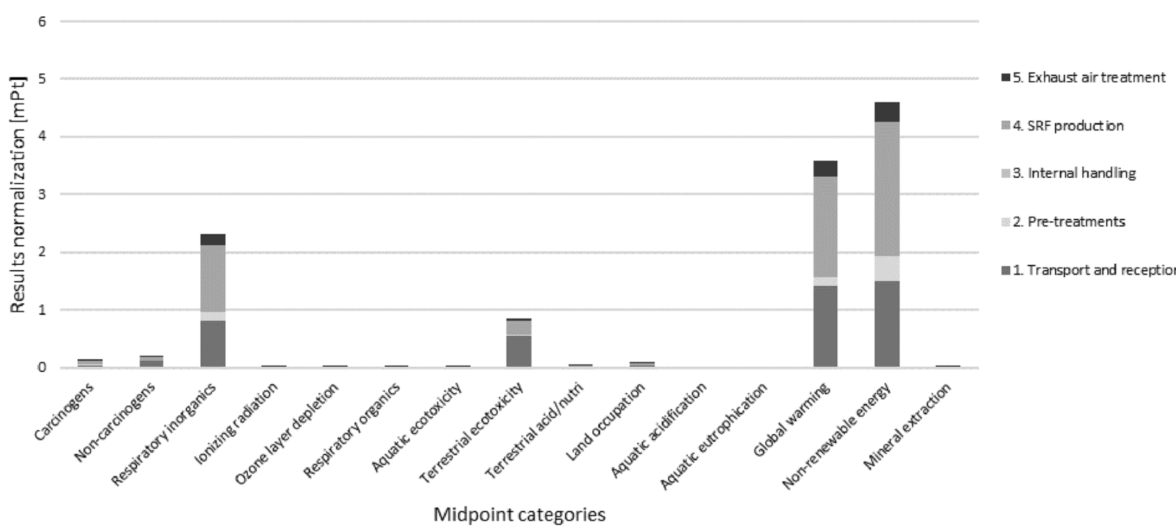
Normalized results are described in terms of milli-points (mPt) and presented in Mid-point and End-point (effects) categories to evaluate the most important environmental impact indicators (Jolliet et al., 2003). Then, a contribution analysis is conducted to define the most important process that influences the final impacts (upstream and core). Considerations about the avoided impacts obtained by coke replacement and combustion are introduced (system expansion approach) by including Phase 6 and 7 to the system boundaries and life cycle impact assessment. Finally, a scenarios analysis is introduced to identify the potential results' changes in terms of three different variables: (1) Renewable energy sources (i.e., solar panels) used at the SRF treatment plant (Phase 2, 4 and 5); (2) Potential variability in transportation distances travelled from the SRF treatment facility to the cement kilns (road transport); (3) Avoided impacts definition: SRF composition (percentage of paper and cardboard content) – biogenic source of carbon vs. LCV (variables related to the replacement rate).

The first scenario considers the potential impacts reduction due to the replacing of non-renewable energy with photovoltaic panels. This is identified as potential internal strategy to mitigate SRF production environmental impacts with the logic to improve the characteristics of the SRF environmental declaration. The potential changes in terms of GWP (kg CO_2-eq) are assessed. Three cases are considered for the analysis: Non-renewable energy source, with electricity produced by hard coal combustion; Baseline scenario, electricity taken from the national grid; Renewable energy sources, with electricity produced by a 570-kW open ground photovoltaic system. This analysis involved only the SRF treatment plant. Therefore, only processes from Phase 1 to Phase 5 are considered. The second scenario defines the maximum distance that can be travelled by trucks to still achieve environmental benefits. This can be a valuable assessment for non-densely populated areas. The assessment is made by changing the distances potentially travelled by the trucks considering the baseline conditions. The GWP changes due to the production and consumption of fossil fuels.

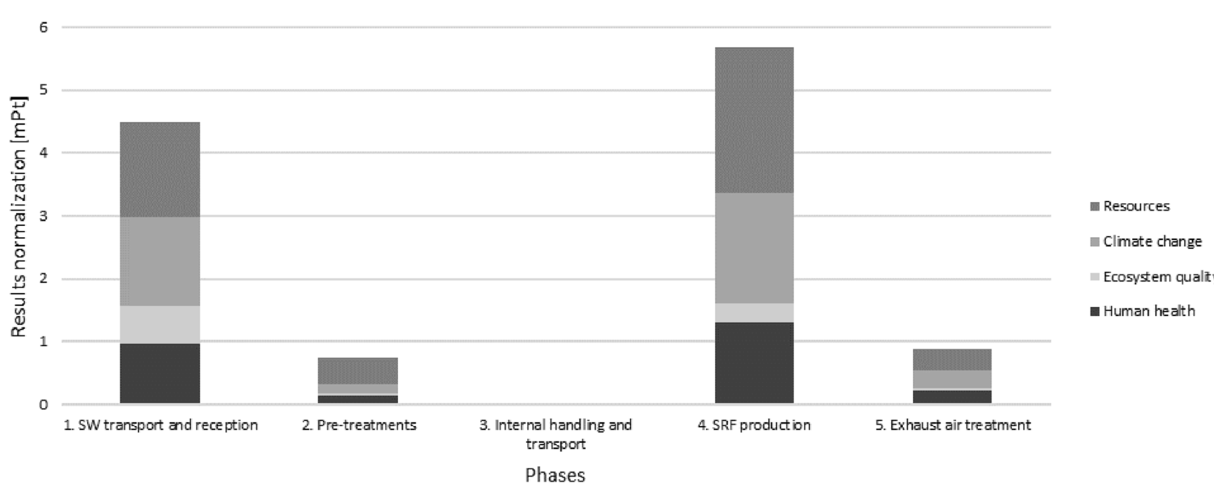
The third and last scenario considers the change of LCV_{SRF} and biogenic sources of carbon emissions. The higher the biogenic carbon content, the lower the fossil CO_2 emissions from SRF combustion, the LCV, and the coke replacement rate. A final analysis defines the maximum and minimum environmental benefits that the SRF gives due to coke replacement in a worst- and best-case scenario (cement kiln located near to the SRF production facility site).

Best- and worst-case scenarios were finally evaluated: in the favourable scenario, minimum travel distances, maximum amount of biogenic content in the SRF, and renewable energy use are considered. In the unfavourable case, maximum travel distances (about 1500 km far – ex. from Bari-Italy to Wien-Austria), minimum amount of biogenic content in the SRF, and non-renewable energy use are considered (100 % from coal).

In the end, the interpretation of the results will provide information about the environmental benefits for introducing renewable energy sources for the operation of the facility, the maximum distances (road



(a)



(b)

Fig. 2. Normalization of the environmental impact indicators (without avoided impacts): (a) mid-point, and (b) end-point categories.

trip) that can be travelled to still obtain carbon credits, and the quantity of biogenic and non-biogenic fractions that need to be contained in the SRF to gain maximum environmental benefits. The optimistic and pessimistic impact gives the maximum and minimum impacts that can be generated by SRF production and consumption in cement kilns.

3. Results and discussion

3.1. Environmental profile – Upstream and core LCA

Research outcomes are reported in Fig. 2. These results take into consideration processes from Phase 1 to Phase 5. Globally, the system contributes for about 11.82 mPt. In terms of midpoint (Fig. 2a), the most significant category is non-renewable energy (4.59 mPt), followed by global warming (3.59 mPt), and respiratory inorganics (2.32 mPt). At the same time, terrestrial ecotoxicity (0.84 mPt), non-carcinogens (0.20 mPt), and carcinogens (0.12 mPt), are categories also affected by the system. Phase 4 substantially influences the non-renewable energy category, contributing for about 50 % of the impact. The use of shredders to produce SRF is the biggest cause of impact in this category. The second phase that mainly affect this category is Phase 1 - SW transport and reception, contributing for about 32 % of the impact. Transport also contributes to the global warming, with CO_2 emission due to fuel consumption, for about 39 %.

The analysis of end-point categories allows detecting the Phase that contributes the most to the general impacts generated within the SRF production stage (Fig. 2b). The main contributor is the SRF production – Phase 4 (5.69 mPt), followed by SW transport and reception – Phase 1 (4.49 mPt). In particular, SRF production contributes to resources depletion for about 64 % of the impact, and climate change (48 %). Similarly, SW transport and reception influences on resources depletion, for about 41 % of the impact, and climate change (39 %). These end-point categories are influenced by the consumption of non-renewable energy sources. Therefore, to mitigate the climate change, the local company shall focus future efforts and investments in minimizing the impact in the SRF production phase (Phase 4) and not, for example, to convert internal vehicles into electric ones.

3.2. Impacts characterization – System expansion LCA

In terms of normalized end-point categories, results of the full-LCA (Phase 1 to Phase 7) highlight that all categories are negative and, globally, −535.51 mPt can be obtained. Therefore, impacts related to human health (-281.05 mPt), climate change (-110.63 mPt), resources depletion (-108.43 mPt), and ecosystem quality (-35.40 mPt) are compensated by the substitution of carbon coke. Human Health is the most important endpoint mitigated since contributes for about 52 % of total normalized endpoints. On balance, coke substitution provides environmental outcomes that justify the production and use of SRF since more than 99 % of impacts are avoided. The contribution analysis in terms of characterized midpoint categories is reported in Table 2.

These outcomes take into consideration the whole SRF life cycle. In terms of global warming potential (GWP), about 35.6 $kgCO_2$-eq are generated by the SRF production phase, plus 4.61 $kgCO_2$-eq if residues management is considered. However, these impacts are compensated by coke substitution, for a net value of about −1.1 tCO_2-eq. In particular, all impact indicators are compensated due to coke substitution, with an average savings of about 16,500 MJ of non-renewable energy, 2.27 kg PM2.5-eq of respiratory inorganics, and 55,800 kg TEG of terrestrial ecotoxicity, which are the most important impacts detected within the normalization procedure.

3.3. Scenarios analysis

3.3.1. Renewable energy sources at the treatment plant

The outcomes of the analysis are reported in Fig. 3. Results show that the use of non-renewable energy (energy scenario 1) increase the environmental impacts of about 95 % (71.99 kg CO_2-eq) compared to the baseline scenario. At the same time, the use of renewable energy from photovoltaic panels (energy scenario 2) reduces the impacts to about 19.75 kg CO_2-eq, halving the GWP (100 year). Therefore, moving from baseline scenario to renewable energy, the impact to the climate change can be reduced for about 46 %. This result shows that the change of energy source can substantially mitigate the carbon footprint of SRF production, and this strategy can be implemented by industry owners to reduce the carbon footprint of SRF production activities.

3.3.2. Transportation distances – From treatment plant to cement kilns

Road transportation distances from the SRF treatment plant to cement kilns contribute to the global environmental impact of the system within the whole life cycle. The results of the analysis are reported in Fig. 4. The analysis shows that the contribution to the GWP with transportation distances equal to zero contribute for about −1288.3 kg CO_2-eq. This is the typical scenario of northern Europe, where SRF mechanical treatment plants are located near the cement kiln (Sarc et al., 2019). The maximum distance that can be traveled by transportation trucks to still obtain environmental benefits is of about 6000 km. It turns out that very long distances should be travelled to achieve negative impacts.

It is an unlikely scenario, because beyond 1500 km transportation can be assumed by train or ship that gives lower environmental impacts compared to road trucks (Kim and Van Wee, 2009). On one hand, these results confirmed that the production and transportation of SRF always pays off as long as it replaces carbon coke. On the other hand,

Table 2
Contribution analysis. Characterized environmental impact indicators per FU at mid-point category. Numbers in bold refer to the higher impacts related to each impact indicator; Indicators in bold refer to the most important indicators identified in the results normalization phase.

Indicators	Units	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Total
Carcinogens	kg C_2H_3Cl-eq	9.37 E-02	1.86 E-02	3.54 E-04	**1.67 E-01**	2.42 E-02	−1.48	−1.31 E + 02	−1.32 E + 02
Non-carcinogens	kg C_2H_3Cl-eq	2.82 E-01	2.01 E-02	1.08 E-03	1.77 E-01	2.91 E-02	**3.15 E-01**	−1.05 E + 01	−9.67
Respiratory inorganics	kg PM2.5-eq	8.29 E-03	1.38 E-03	3.20 E-05	**1.17 E-02**	2.04 E-03	−3.79 E-02	−2.26	−2.27
Ionizing radiation	Bq C-14 eq	1.17 E + 02	3.30 E + 01	4.47 E-01	**2.79 E + 02**	4.31 E + 01	−1.26 E + 02	−1.13 E + 03	−7.88 E + 02
Ozone layer depletion	kg CFC-11-eq	2.56 E-06	7.36 E-07	9.87 E-09	**3.05 E-06**	4.00 E-07	−4.53 E-07	−7.89 E-05	−7.26 E-05
Respiratory organics	kg C_2H_4-eq	**6.46 E-03**	9.33 E-04	2.49 E-05	4.54 E-03	5.25 E-04	−3.35 E-02	−3.04	−3.06
Aquatic ecotoxicity	kg TEG water	1.42 E + 03	2.61 E + 02	5.50	**2.48 E + 03**	3.86 E + 02	−2.59 E + 03	−2.51 E + 05	−2.49 E + 05
Terrestrial ecotoxicity	kg TEG soil	**9.42 E + 02**	5.31 E + 01	3.67	3.99 E + 02	5.99 E + 01	−1.06 E + 03	−5.62 E + 04	−5.58 E + 04
Terrestrial acid/nutri	kg SO_2-eq	1.30 E-01	2.62 E-02	5.01 E-04	**2.48 E-01**	3.86 E-02	−3.98 E-01	−1.23 E + 01	−1.22 E + 01
Land occupation	m2org.arable	4.97 E-01	2.99 E-02	1.94 E-03	**5.15 E-01**	8.53 E-02	−4.17	−1.41 E + 01	−1.71 E + 01
Aquatic acidification	kg SO_2-eq	**3.43 E-02**	8.33 E-03	1.32 E-04	7.58 E-02	1.19 E-02	−7.36 E-02	−3.39	−3.33
Aquatic eutrophication	kg PO_4 P-lim	1.33 E-03	3.58 E-04	5.08 E-06	**2.28 E-03**	3.32 E-04	−3.78 E-03	−2.48 E-01	−2.47 E-01
Global warming	kg CO_2-eq	1.40 E + 01	1.33	5.40 E-02	**1.74 E + 01**	2.78	4.61	−1.14 E + 03	−1.10 E + 03
Non-renewable energy	MJ primary	2.28 E + 02	6.54 E + 01	8.75 E-01	**3.54 E + 02**	4.99 E + 01	−4.08 E + 02	−1.68 E + 04	−1.65 E + 04
Mineral extraction	MJ surplus	**1.89 E-01**	1.69 E-02	7.09 E-04	1.79 E-01	3.33 E-02	−1.33	−2.80	−3.71

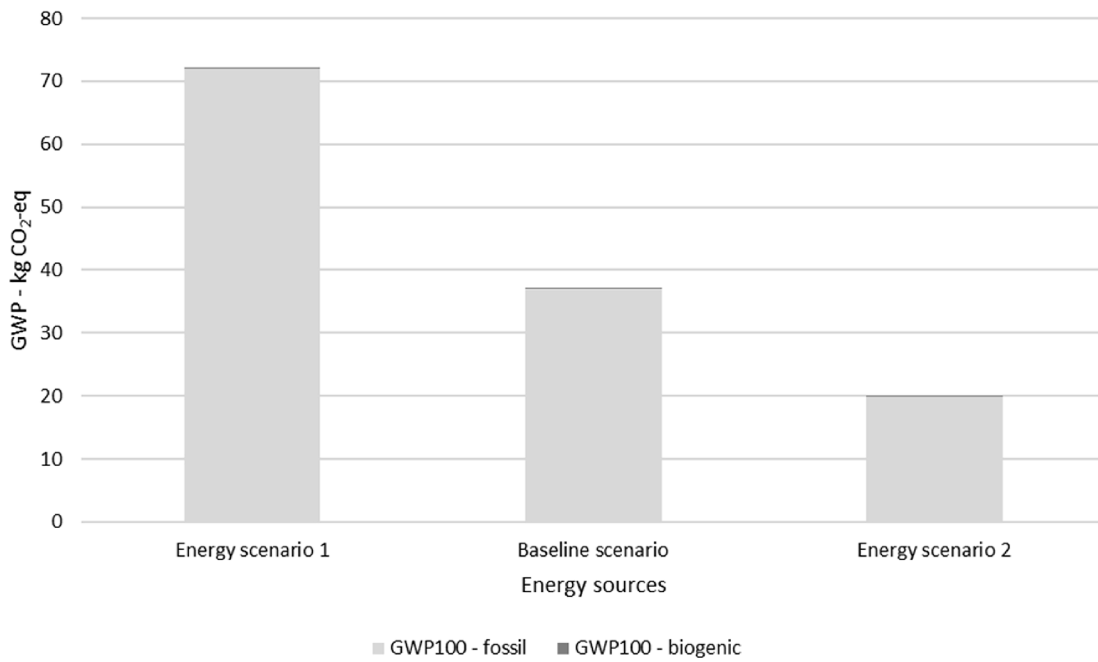


Fig. 3. Variation of GWP considering three different energy sources scenarios (non-renewable energy – energy scenario 1, baseline, and renewable energy – energy scenario 2).

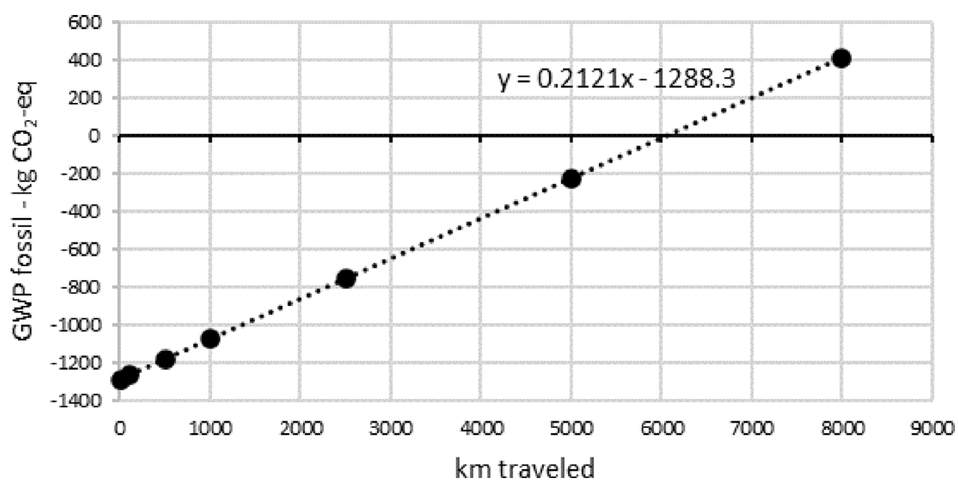


Fig. 4. Variation of global warming potential (GWP) due to different transportation distances travelled by trucks.

transportation should be considered since it might mitigate environmental benefits and reduce carbon credits obtained by the cement industry. These results also indicate that, in remote areas where cement kilns are not available, the strategy to select waste to make SRF and sell it to foreign countries or to cement plants located far away is still preferable.

3.3.3. Biogenic carbon sources vs. Coke replacement rate

SRF characterization can increase or reduce the environmental benefits that can be obtained due to coke substitution. The trend of the carbon footprint (fossil) function of the paper content is presented in Fig. 5. Results refer only to Phase 7 and data were obtained by theoretically changing SRF composition and LCV.

The light grey line shows how fossil CO_2-eq emission decrease thank to the increase of paper and cardboard waste combustion. The trend is nonlinear due to the simultaneous reduction of the LCV that decrease the carbon coke substitution rate. The replacement rate ranges from 0.455 to 0.826 due to the lower LCV of paper, which is about 12.5 MJ kg^{-1} (Ferronato et al., 2022b), compared to the plastic mix available in the SRF (about 24.7 MJ kg^{-1} – primary data). At the same time, the dark grey line shows the CO_2-eq saved due to coke substitution. The trend is linear, and benefits decrease while paper and carboard waste contents increase. This is due to the lower substation rate.

Therefore, the coke substitution rate decreases when the paper content rise, mitigating the positive effects due to coke substitution. At the same time, the fossil CO_2-eq emissions decrease with a non-linear behavior when paper content increase, from –233.48 $kgCO_2$-eq with zero paper content to −1358.21 $kgCO_2$-eq with 90 % paper and carboard. This is due to the increase of biogenic carbon emissions during the SRF combustion phase (excluded from Fig. 5), despite the reduced coke substitution rate.

On balance, the net maximum benefit can be obtained when SRF contains about 80 % of paper and cardboard, achieving about −1752.03 kg CO_2-eq saved due to coke substitution (extraction and combustion). This result suggests that higher biogenic contents mean higher avoided impacts, despite the reduction of the LCV. On the other hand, coke

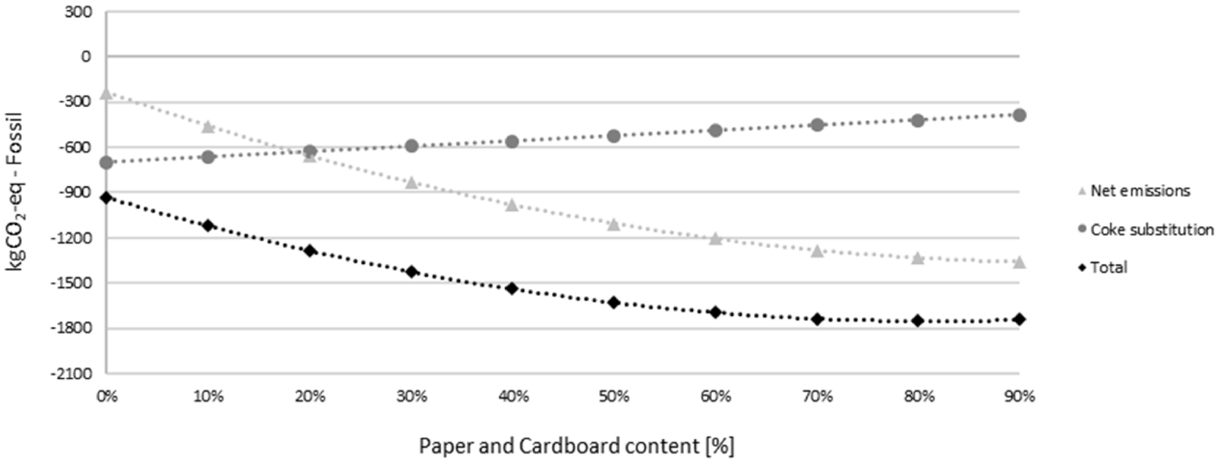


Fig. 5. Net CO_2 - Fossils emissions avoided due to Coke substitution at the cement kiln (extraction and combustion) – Phase 7.

substitution always provides environmental benefits by reducing the GWP and compensating environmental impacts due to plastic waste combustion.

3.3.4. *Best- and worst-case scenarios*

This analysis considers all processes from Phase 1 to Phase 7. The outcomes of the analysis are reported in Fig. 6. The worst-case scenario considers an SRF biogenic content equal to 3 % (0 % paper content, and 3 % wood content), LCV of SRF equal to about 24.44 MJ kg^{-1}, transportation distances of about 1500 km, and use of non-renewable energy sources (electricity production by hard coal). The best-case scenario involves and SRF with about 83 % of biogenic carbon content, LCV of SRF equal to 14.70 MJ kg^{-1}, and transportation distances of about 6 km, with the use of renewable energy sources for electricity production.

Results show that avoided impacts range from −542.09 kg CO_2-eq for the worst-case scenario to about −1729.05 kg CO_2-eq in the best-case scenario. Moving from worst-case scenario to baseline scenario, climate change is reduced by about 124 %. Similarly, moving from baseline scenario to best case scenario, climate change is reduced by about 44 %. Therefore, from the worst to the best scenario, GWP can decrease for about 218 %. On one hand, these results suggest that SRF production and consumption is always beneficial, also considering a non-favorable case: coke substitution is always the preferable choice. On the other hand, the results obtained in the best scenario highlights how internal strategies can maximize GWP reduction and, therefore, the increase of carbon credits.

On one hand, the best-case scenario suggests locating cement kilns near SRF mechanical treatment plants, producing electricity from renewable sources, and increasing the quantity of biogenic waste fractions like paper and cardboard. Therefore, for future strategies, cement plants can be located near big cities (around 80 km far), and close to mechanical treatment plants that can produce the SRF required by the plant. In addition, waste fractions should contain higher amounts of cardboard, that can suggest moving towards a zero plastic-packaging strategy.

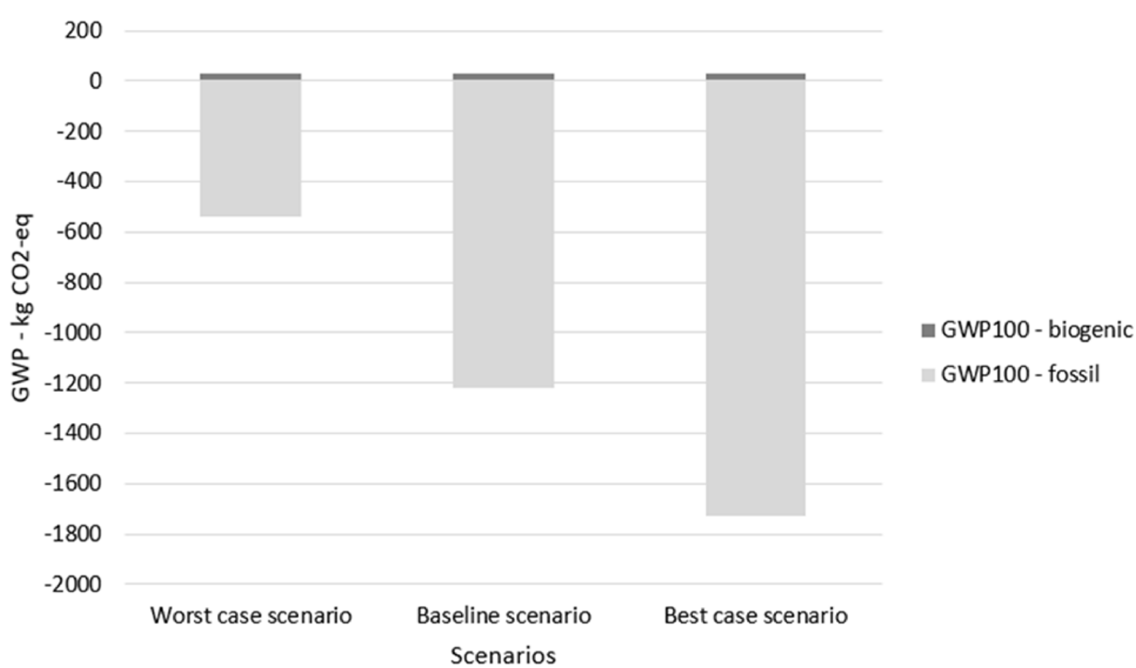


Fig. 6. Variation of GWP in SRF life cycle (worst-case, baseline, and best-case scenario).

4. Conclusions

This study shows that producing SRF from mechanical treatment and separately collected waste is a potentially green choice if SRF contributes to avoid coke production and consumption. The SRF production process contributes to about 35.6 kg CO_2-eq per ton of SRF. However, the avoidance in coke extraction and combustion contributes to a maximum of −1752.03 kg CO_2-eq savings with about 80 % of SRF biogenic carbon content and treatment plants located close to the cement kiln. It means that the transportation and production phase contributes to about 2 % of the impacts potentially avoided due to coke substitution.

The research suggests that one ton of SRF produced allows substituting from 455 to 826 kg of coke, that means an average carbon footprint of about −542.09 to −1729.05 kg CO_2-eq in the worst- and best-case scenario. Transportation might affect the benefits due to coke replacement. However, the study demonstrated that transportation trucks should travel for more than 6000 km to obtain negative impacts, which seems quite unrealistic. This is a good result also for developing countries where hard coal is still used as main source of energy and SRF mechanical treatment plants are still not implemented: environmental benefits exist also for cities where cement plants are located far from the waste treatment site.

The research provided a novel contribution to the literature by providing results of an attributional LCA of SRF production facility in Italy and a scenario analysis that involves important parameters that affect the global warming potential like transportation distances, biogenic carbon contents, and use of non-renewable energy. The outcomes contribute to underline the importance to replace carbon coke with SRF in cement kilns. This is important for countries that are building new carbon neutral strategies and for members of the European Union to foster the green transition. Therefore, the study recommends producing SRF from non-recyclable waste obtained from mechanical treatment plants and separate collection at the source to mitigate the global carbon footprint and to achieve carbon neutrality in Europe and at a global level.

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CRediT authorship contribution statement

Navarro Ferronato: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chiara Giaquinta:** Writing – original draft, Visualization, Software, Investigation, Formal analysis. **Fabio Conti:** Supervision, Project administration, Funding acquisition. **Vincenzo Torretta:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Authors’ contribution

All authors contributed to the study conception and design. Data collection was in charge of Chiara Giaquinta and Navarro Ferronato. The data analysis was carried out by Navarro Ferronato and Chiara Giaquinta. Field work was in charge of Navarro Ferronato and Chiara Giaquinta. The study has been supervised by Navarro Ferronato and Vincenzo Torretta. The first draft of the manuscript was written by Navarro Ferronato and Chiara Giaquinta, and all authors commented on earlier versions of the manuscript. All authors read and approved the final manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.02.029.

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