



Product Life Cycle Assessment (LCA) as a Tool for Environmental Management

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Abstract: Life Cycle Assessment, included in company environmental management methods, has particular importance in marketing management. Analysis of dangers to the environment through tools such as the LCA method allows for comparisons of alternative company management strategies. LCA is characterised as a technique for environmental management that enables environmental impact assessment of the product, process, industry, and even the comprehensive economic sector. LCA also influences decisions regarding environmental policy modification, but most importantly, it influences a company's marketing activities. The LCA technique is applied the world over with great effectiveness in studying specific phases of a product's life cycles – from 'birth to death'; however, Poland's experience in this domain constitutes continuously developing research areas. The experience of foreign research centres confirms the possibility of applying LCA techniques in supporting environmental risk assessment of innovative technologies where LCA is used to study the environmental impact of a new generation product, i.e. flocculants from polymer wastes. This article presents the results of a study of the effectiveness of applying a new generation of polyelectrolyte (gained from polystyrene waste) in treating industrial wastewater and the LCA environmental impact assessment, which was carried out using SimaPro software. Based on the analysis of the results of the application of sodium salts of sulfone derivatives of polystyrene in the treatment of mine water, it was found that these products significantly reduced the pollution indicators of mine water from KWK1. Accordingly, they provided the basis for the development of technical-scale technology.

Keywords: environmental management, product life cycle assessment, company marketing

1. Introduction

Product Life Cycle Assessment gained significance in the sustainable development of companies in terms of globalisation. Company marketing management is defined as a company's focused activity consisting of adaptation and coordination of basic marketing elements such as product, price, distribution and promotion. Reaching established business goals is attained through product development and other factors. Manufacturers and intermediaries have the tasks of market analysis through market studies, planning and performing adopted strategies, monitoring said company's adopted marketing program and assessing results (Bajdur 2011, Bajdur et al. 2017). The most important elements of a company's marketing management – the continuous process of steering the company – include:

- brand management and advertising,
- shaping client relations,
- shaping company intelligence on pricing,
- shaping pricing policy,
- establishing marketing goals,
- understanding client behaviour in the market,
- market segmentation and identifying buyer needs, preferences and abilities, and,
- developing product marketing strategies.

LCA is already a widely used technique for assessing the potential environmental impact of various municipal waste management options. For large urban agglomerations, this includes both systems assessment (Aghbashlo et al. 2020, Zhou et al. 2011, Gao et al. 2011, De la Rúa Lope et al. 2017). In this view, it can be the basis for decision-making processes in public entities such as central and local governments, to eliminate risks (Lewandowska et al. 2013, Kulczycka et al. 2015, Lelek et al. 2021, Generowicz et al. 2023). LCA analysis is used in many fields, including municipal solid waste management, to evaluate technologies, systems, or processes (Farzad et al. 2017). It makes it possible to compare different management systems in a given



sector and, by identifying the most influential steps, make suggestions for improving environmental performance (Gronba-Chyła et al. 2021, 2022, Alawei 2009). Comparative LCA studies of alternative municipal solid waste management systems in the literature include the use of LCA to compare waste collection systems or the environmental effects of landfilling and incineration and other waste management scenarios (Grzesik et al. 2017, Tunesi 2011, Dong et al. 2018, Mayer et al. 2021, Beylot et al. 2018, Pérez et al. 2021, Generowicz 2020). In a company's contemporary marketing management, as listed above, the most important is to have an appropriately prepared product marketing strategy applying various techniques, such as, for instance, LCA (Alawei et al. 2018). A key to a company's success is a skilful application of marketing management techniques and methods (Ciula et al. 2023, Gaska et al. 2021, Generowicz et al. 2023). To maintain a good market position, companies must stake a long-term innovation development plan enhancing long-term competitiveness also enabling smooth adaptation to dynamically changing market conditions and buyer preferences (Kowalski et al. 2010, Makara et al. 2016, Kwaśnicki et al. 2023). In the example of a new generation of products – flocculants – LCA products can demonstrate their input on a company's development and image (Generowicz 2011, Ciula 2022).

As mentioned, at present, potential products in Poland's market are flocculants extracted from polymer waste and applied to waste treatment. Recent years have indicated a rising volume of waste, and as such, the producer of said waste is tasked with preventing their production and accumulation (Bajdur 2011). Using waste as recycled raw material and rendering such waste harmless at the source of their production is economically and technologically justified (Bajdur et al. 2000a, Bajdur et al. 2000b). Sulfonated polystyrene is used as a flocculant for treating such wastewater (Ozdemir et al. 2023).

Chemical modification of polystyrene waste produces polyelectrolytes with excellent flocculant properties (Bajdur 2011, Bajdur et al. 2017). Polyelectrolytes were applied to mine water treatment. This article presents the application of LCA as an assisting technique in environment risk assessment of the production and application of a new generation of synthetic flocculants. This technique enables an environmental impact analysis of the new 5 polyelectrolytes produced from polymer waste. The LCA analysis performed on the example of polymer waste-derived sulfonates shows the possibilities of applying this technique in assessing environmental risk from innovative technologies in businesses.

The purpose of the LCA analysis was to determine the environmental impact of the process of treating underground water from a coal mine (KWK 1 with certain physico-chemical parameters) using a new type of flocculant - sodium salt of a sulfonic derivative of polystyrene.

2. Materials and Methods

The study was carried out as an ecological life cycle assessment of polyelectrolytes as flocculants from studies of newly synthesised compounds and technologically used in treating underground mine water of bituminous coal mines from mines owned by Katowicki Holding Węglowy S.A. The physicochemical analysis focused on selected indicators of mine water, including sulfates and chlorides, as these compounds should be reduced as required by water-law permits.

The LCA analysis of newly synthesised flocculants utilised to clean mine water followed the guidelines and recommendations in ISO Norms 14040 and 14044. The methodology of said analysis contained 4 phases: establishing goals and range, setting analysis of inputs and outputs, impact assessment of product life, and interpretation of study results, following ISO 14040.

The phase pertaining to life cycle assessment may be performed through various methods associated with computer software for LCA studies. The environmental study results of newly synthesised polyelectrolytes from polystyrene waste are presented. The study applied SimaPro Developer v. 9.4.0.4 software, characterisation developed using EF 3.0 v. 1.03, and a weighted coefficient equal to '1' for every impact category. Upon generating an analysis of input/output sets (LCI), the impact assessment of environmental traces was performed to calculate product traces in said environment, applying all categories and environmental impact models per the selected method. The analysis was carried out using the EF 3.0 method, taking advantage of the SimaPro program along with the database, generally Ecoinvent. EF 3.0 assesses impact as defined by the European Commission. It considers normalising coefficients and weights published in November 2019 by the European Commission.

The study followed the developed life cycle scheme of synthesised polyelectrolytes from polymer waste (expanded polystyrene waste), producing quarter-technical scale flocculants applied in effluent and industrial water treatment (Fig. 1).

3. Set Analysis of Inputs and Outputs

In the input/output set analysis, the system balance was included, and the data inventory was based on the technological assumptions of polyelectrolyte production and their exploitation during mine wastewater treatment. All input and output elements related to the study were defined in the balance analysis phase.

In this phase, the technological scheme for production took into effect equipment selection and the potential use of polyelectrolytes for material and energy balance was included. Next, the data was collected and organised in the inventory tables known as 'status tables'. A complex assessment analysis of the selected product took place.

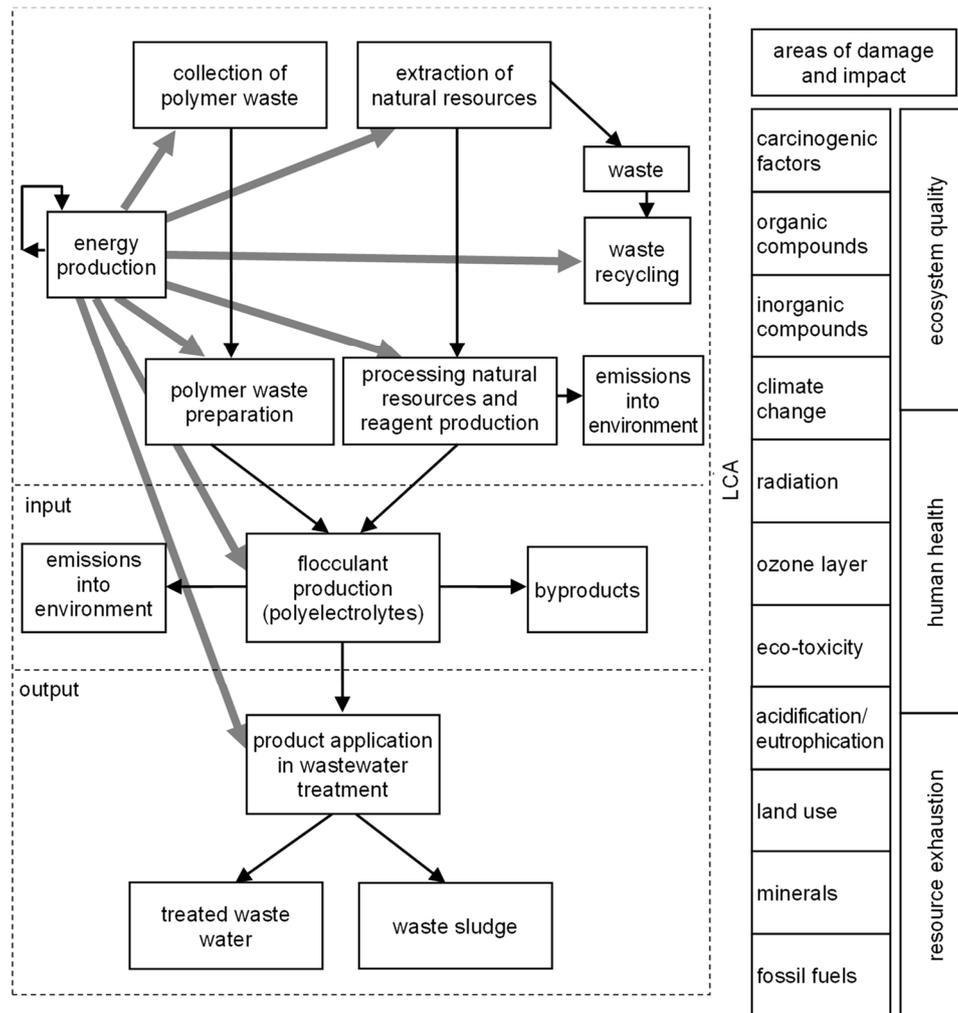


Fig. 1. Synthesised polyelectrolyte life cycle from polymer waste

4. Establishing Goals and Range

Defining the goal and range result from the model characteristics of this technique. The analysis goal was to determine the environmental impact of mine wastewater treatment utilising new types of products. The range of the study included the chemical modification process of a new generation of polyelectrolytes synthesised from polymer waste and then utilising them to enhance the process of industrial wastewater coagulation.

The functional unit for testing was 100 kg of polyelectrolyte extracted during one 24-hour production period. In the analysis of mine wastewater treatment, the functional wastewater volume unit was established as 20,000 m³/day using the newly synthesised polyelectrolyte (Bajdur et al. 2021).

5. Impact Assessment of Product Life and Interpretation of Study Results

The interpretation of the studies in assessing the life cycle of new polyelectrolytes included deducing conclusions from the performed analysis following the initially established goal. Based on results from the analysis of potential environmental impacts during the polyelectrolyte life cycle, synthesised from expanded polystyrene waste and used as a flocculant in treating wastewater.

Based on in-depth literature research, it was concluded there was the possibility of exploiting the process of synthesising polyelectrolytes from polymer waste and other substrates essential to performing syntheses and producing other products possessing flocculant properties. Polyelectrolyte synthesis is performed according to the generally known process of aromatic compound sulphonation. The results produced the basis for generating technological schemes to produce new polyelectrolytes – sodium salt from sulfonated expanded polystyrene waste (PSP).

As in the assumption, the study's range included the modification of the shredded polystyrene waste to gain sulfonated related sodium salts from said waste (PSP) and then utilising the products to enhance the coagulation process for bituminous mine wastewater – KWK1.

After entering the data into the inventory tables for the production processes of potential flocculants made from expanded polystyrene waste, an energy/material balance was developed (Table 1) based on the above method.

Table 1. Energy/material production balance of 100 kg of sodium salts from sulfonated polystyrene*

Input – required raw materials and energy factors	Amount	Unit
Sulfuric Acid	407.76	kg
Calcium Carbonate	301.3	kg
Sodium Carbonate	29.36	kg
Polystyrene Waste	57.6	kg
Electrical Energy	60	kWh
Output – Emissions		
Carbon Dioxide	187.2	kg
Water Vapor	21.3	kg
Water (waste)	78.6	kg

*Calcium sulphate is a by-product (408.9 kg)

After compiling the input/output set analysis (LCI), an environmental trace assessment was performed to calculate environmental trace impact by applying all categories and models pertaining to environmental trace impact following the selected methods.

The analysis was performed using the EF 3.0 method, taking advantage of the SimaPro program with the implemented database – primarily Ecoinvent. EF 3.0 is a method assessing impact accepted by the European Commission. It considers normalising coefficients and weights published in November 2019 by said Commission. Table 2 presents recommended characteristic models where, upon application, it is advised that impact modelling be done within the individual impact categories. The results represented in Table 2 reflect the category set characterised by EF 3.0.

Table 2. Environmental trace impact categories with category indicators and assessment models for recommended levels of environmental trace impact for application needs for the study of environmental traces of products and organisations (Explanations to guidelines of EU, 2022)

Assessment Model for Environmental Trace Impact	Category Indicator for Environmental Trace		Source
Climate change	Bern Model – global warming coefficient, 100 year range	Equivalent Ton of CO ₂	IPCC 2013
Ozone depletion	<i>Environmental Design of Industrial Products, (EDIP)</i> , based on potential Ozone destruction (OPD) over an unspecified period developed by the World Meteorological Organization)	Kilogram equivalent to CFC-11	WMO 2014 + integrated data
Ionising radiation HH	human health impact model	Kilobecquerel equivalent to U ²³⁵ (emission into atmosphere)	Dreicer and others, 1995

Table 2. cont.

Assessment Model for Environmental Trace Impact	Category Indicator for Environmental Trace		Source
Photochemical ozone formation	Model LOTOS-EUROS	Kilogram equivalent NMZO	Van Zelm and others, 2008, in accordance with and application of ReCiPe
Particulate matter	Model PM	Disease incidence	Fantke and others, 2016 in UNEP 2016
Human toxicity, non-cancer	Model USEtox 2.1	Comparative toxic unit for humans (CTU _h)	Fantke and others, 2017), in accordance with Saouter and others, 2018
Human toxicity, cancer	Model USEtox	Comparative toxic unit for humans, CTU _h)	Fantke and others. 2017), in accordance with Saouter and others, 2018
Acidification	Accumulated exceedance	Mol+ equivalent H+	Seppälä and others, 2006, Posch and others, 2008
Freshwater eutrophication	Model EUTREND	Kilogram equivalent P	Struijs and others, 2009, in accordance with application of ReCiPe
Marine eutrophication	Model EUTREND	Kilogram equivalent N	Struijs and others, 2009, in accordance with application of ReCiPe
Terrestrial eutrophication	Accumulated exceedance model	Equivalent N	Seppälä and others, 2006, Posch and others, 2008
Freshwater ecotoxicity	Model USEtox 2.1	Comparative toxic unit for ecosystems, CTU _e	Fantke and others, 2017, in accordance with Saouter and others, 2018
Land use	Soil class indicator according to LANCA	Dimensionless (pt)	De Laurentiis et al. 2019 and LANCA CF version 2.5 (Horn and Maier, 2018)
Water resource depletion	Available Water Remaining Model	equivalent water volume removed from use in m ³	Boulay and others, 2018; UNEP 2016
Resource use, fossils	depleted abiotic reserves – fossil fuels (ADP – mined raw materials)	MJ	Van Oers and others, 2002, as in CML Model 2002, v.4.8
Resource use, minerals and metals	depleted abiotic reserves (final zasoby ADP)	equivalent kg SB	Van Oers and others, 2002, as in CML Model 2002, v.4.8

This set includes 16 categories regarding environmental trace impact, of which 4 – water resource depletion, mineral resource depletion and mined resources, and land use – are categories where environmental problems occur from extraction. The remaining 16 are categories of emissions where compounds are released into the environment and trigger mechanisms thereof.

6. Characterised Indicator Results of Impact Categories

Figure 2 presents the results after the characterisation phase of the 16 categories regarding flocculant impact. The results in all impact categories are scaled to 100%. The data for each category are presented in reference units, e.g. for climate change in kilogram equivalents of CO₂. Of the data presented after characterisation (Fig. 2), it appears that from the impact category, the dominating environmental impacts are from sulfuric acid use and energy consumption. Visible impact also appears with disodium carbonate and calcium carbonate and production emissions. Where potential environmental damage and benefit are shown on one bar, the result is seen as beneficial in that category. Characterisation analysis of the production process resulting from the sulfonation of expanded polystyrene waste indicates a positive impact in the category of resource usage and utilising polystyrene waste.

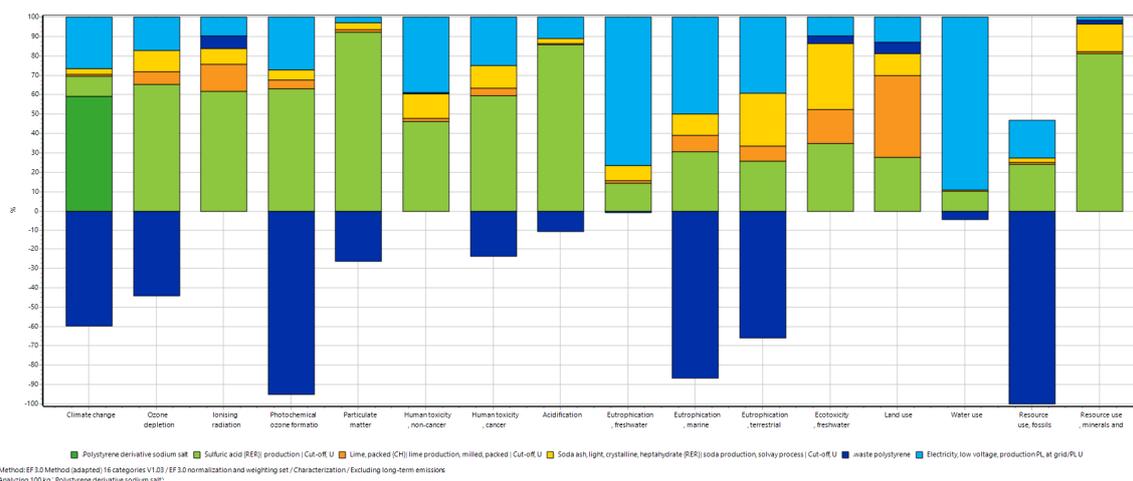


Fig. 2. Results after the characterisation phase for sodium salts resulting from sulfonated polystyrene in reference to a functional unit (own study and the Mineral and Energy Economy Research Institute, Polish Academy of Sciences in Krakow)

7. Weighted Indicator Results for Impact Categories

Figure 3 presents results after the weighting phase in the 16 impact categories. Results in all impact categories are expressed in mPt units, as in mili points. The environmental trace from producing 100 kg of Sodium Salts from sulfonated polystyrene is 40.31 mPt. Inputs to the system whose environmental impact during production is greater than 5% are electric energy (28.5 mPt, 70.7%); sulfuric acid (18.5 mPt, 45.9%); production emissions (4.8 mPt, 12%); sodium carbonate (2.2 mPt, 5.5%); and polystyrene waste as beneficial for the environment (-14.5 mPt, -35.9%). Flocculant production most significantly impacts water use (62%), (this high indicator results from approximately 58% of water being used for electrical energy as adjusted by Ecoinvent for Poland's conditions, which also takes into account hydropower), exploiting reserves, mineral and metal raw materials (9.6%), acidification (12.7%), climate change (8.2%), and particulate matter (8%). In the case of depleted resources, mined raw materials benefitted the environment due to utilising polystyrene waste (-7.6%).

The results after the weighting phase can be presented in a similar bar graph as the characterisation phase; however, in the processes web configuration (Figure 4). The thickness of the arrows indicates the strength of the environmental impact in the production process of sodium salts from sulfonated polystyrene waste as the decidedly potential environmental burden of electricity production and sulfuric acid, and beneficial to the environment is the utilisation of polystyrene waste instead of fresh raw materials – a green arrow and negative value. In the production of flocculants, sulfuric acid was excessively used. Hence, optimising the production process could reduce the acid's negative environmental impact.

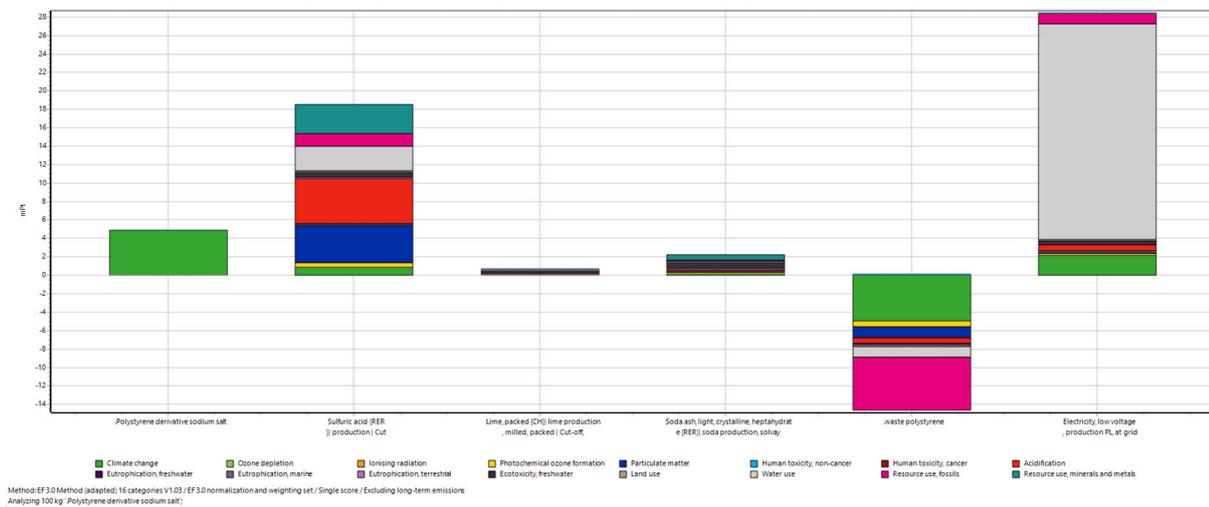


Fig. 3. Results after weighting for sodium salts from sulfonated polystyrene in reference to functional unit (own study and the Mineral and Energy Economy Research Institute, Polish Academy of Sciences in Krakow)

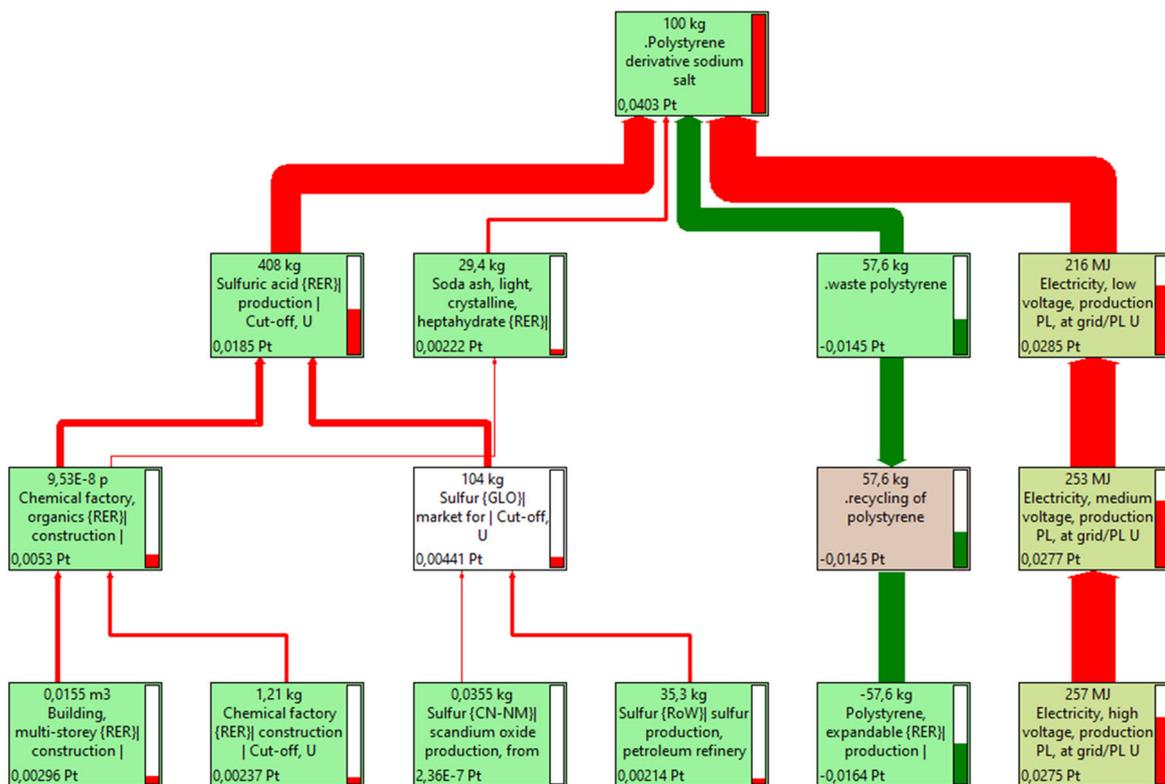


Fig. 4. Environmental trail for the production process of sodium salts from sulfonated polystyrene – process net with regard to the functional unit [Pt] (own study and the Mineral and Energy Economy Research Institute, Polish Academy of Sciences in Krakow).

As results from the raw materials and process tree in the PSP production, a deciding factor of potential environmental burden is the production of sulfuric acid excessively utilised and, at a much lower degree, the consumption of electric energy during the process, as seen in Fig. 4.

Similarly, as in the case of determining the environmental impact of potential product production technologies, an analysis of coal mine wastewater treatment with the use of newly synthesised products was done. The daily volume of wastewater was selected as a functional unit, i.e. 20,000 m³. In the inventory table for the wastewater treatment process, one finds treated effluent, PSP, mixing water, electric energy, and waste sludge after treatment. A deciding factor of potential environmental burden during effluent treatment is the high energy consumption, which raises the emission of SO_x and NO_x.

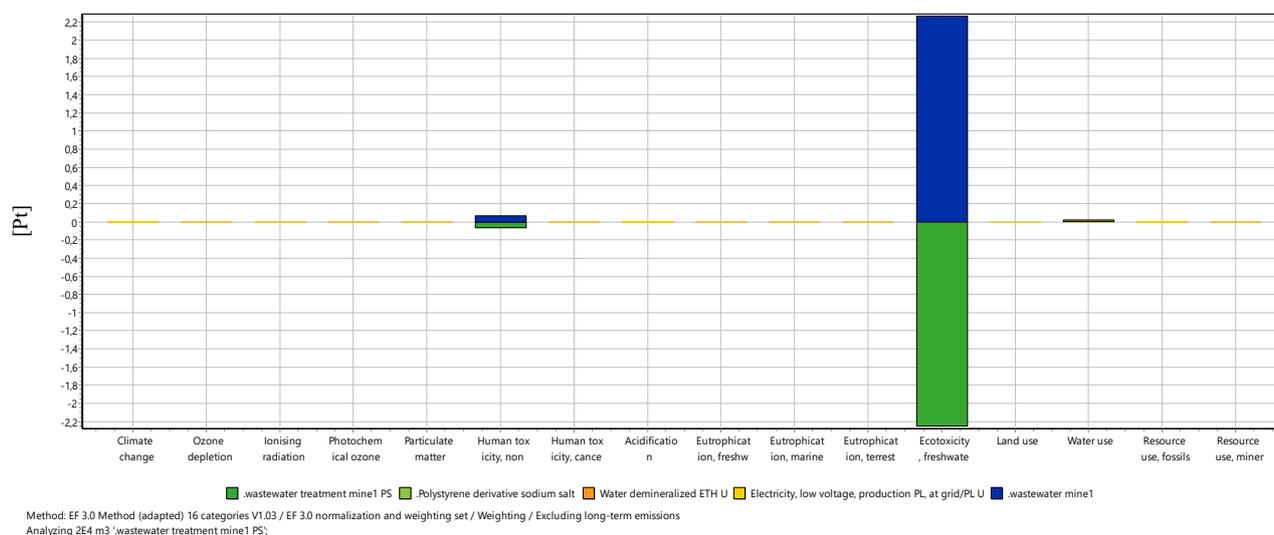


Fig. 5. Results after weighting phase for treatment process of coal mine wastewater with sodium salts from sulfonated polystyrene in reference to the functional unit (own study and the Mineral and Energy Economy Research Institute, Polish Academy of Sciences in Krakow)

Figure 5 was exported from the SimaPro program used in the LCA analysis. The vertical axis shows the value of the potential impact in unit [Pt].

However, the negative indicator value in the mined fuels category indicates a beneficial environmental impact. Since polymer wastes are used to produce new products, it is possible to conserve natural resources such as natural gas or crude oil used to produce polystyrene.

Based on the study results analysis of the product application in the treatment of mine water, it is apparent that the products significantly reduced the indicator degree of polluted mine wastewater. It, in turn, justified the development of technology at a technical scale.

LCA is a reliable method. It indicates not only sources of danger but, above all, is a tool to assess environmental impact, which shows significant positive meaning to recycling. LCA can become a valuable tool for manufacturers in a company's marketing management.

8. Summary and Conclusion

A modern company without marketing management cannot survive in the market and function effectively, as only this type of management will allow a company to reach marketing goals in the long term. In the great role of this type of management, there are several influencing factors, above all, ever-increasing competition and rising costs. In the current business account, market success is more frequently based on the skilful construction of a beneficial company image and the product's brand promotion. In this field, the most essential is the human factor, as in the managers and their skills in their company's marketing management taking advantage of analytical techniques to analyse in real-time the inactions of recipients with Internet services, as well as techniques for managing multi-channel campaigns which involve clientele thanks to interactive digital, mobile or social channels.

LCA results will not replace the need to perform environmental impact assessments, for example, or environmental risk assessment, but constitute a good support technique for reliable and trustworthy research results in the listed areas. In environmental risk management, establishing environmental standards is unavoidable, as is performing basic environmental studies, based on which one can assess environmental risk, i.e. identify dangers and assess exposure to dangerous substances. Of essential meaning is the estimation of health risk being a multi-level procedure enabling the determination of substance impact, e.g., chemicals found in the environment of healthy people, showing that new generations of products are environmentally safe based on reliable and advanced research methodologies. Innovative approaches to the problem of waste management require complex treatment of the issues at hand regarding economics and ecology, as well as civilisation's condition, which seems to be the key to a company's success.

Based on the analysis LCA of the results of using sodium salts of sulfone derivatives of polystyrene in the treatment of mine water, it was found that these products significantly reduced the pollution rates of mine water from KWK1.

Regarding quantitative and qualitative waste indicators, i.e. infrastructure type, industry type, and living standards impact various factors, including residents' habits. Given the above, the specific needs of a given region, such as the problem of waste management, should be resolved individually, reflecting the character of particular wastes. The fact that no process can universally solve all conditions (such as costs, volume reduction, waste mass and environmental impact) should be considered.

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