

Article

Comparative Analysis of Meat Bone Meal and Meat Bone Combustion Using the Life Cycle Assessment Method

Zygmunt Kowalski ¹, Magdalena Muradin ^{1,2} , Joanna Kulczycka ^{3,*}  and Agnieszka Makara ⁴

¹ Mineral and Energy Economy Research Institute, Polish Academy of Sciences, 31-261 Cracow, Poland; zkow@meeri.pl (Z.K.); muradin@meeri.pl (M.M.)

² Institute of Management, Poznan University of Economics and Business, 61-875 Poznan, Poland

³ Faculty of Management, AGH University of Science and Technology, 30-067 Cracow, Poland

⁴ Faculty of Chemical Engineering and Technology, Cracow University of Technology, 31-155 Cracow, Poland; agnieszka.makara@pk.edu.pl

* Correspondence: kulczycka@meeri.pl; Tel.: +48-12-632-22-45

Abstract: LCA analysis with 16 impact categories was used for the comparison of two developed combustion technologies: Scenario I—the combustion of meat bone meal produced from all types of meat waste; Scenario II—the combustion of meat bones from the production of meat products. The key hotspots determined were electricity and natural gas consumption, covering as much as 98.2% of the total influence on the environment in Scenario I and 99.3% in Scenario II. Without taking into account the environmental burdens avoided, the LCA analysis showed that Scenario I was assessed to have 71.2% less environmental impact. The avoided burdens approach changed the relationship between the two scenarios. The absolute value score for the overall environmental impact shows that Scenario II can be more environmentally beneficial than Scenario I; however, Scenario I allowed the elimination of all types of Polish meat waste, and Scenario II could only be carried out in meat production units for the elimination of meat bone waste and by-products from meat processing (i.e., 23% of the total meat waste produced in Poland).

Keywords: meat bone meal; meat bone; meat waste; life cycle assessment; combustion



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1. Introduction

Meat is an essential component of food and is consumed all over the world. Meat production increased to 340 million tons in 2018, more than three times the amount produced 50 years ago, mainly due to population growth and a global increase in wealth [1]. Livestock farming and animal waste production have a high influence on the environment in terms of GHG emissions, land use, and water consumption. The utilization and proper management of animal waste has resulted in a decrease in its impact on the natural environment [2].

The work [3] presented a systematized system for the calculation of the amount of waste produced, which was worked out to the macro level for Europe. The value chain including EU meat production and meat waste in 2011 was as follows (Mt/y):

- available meat, 61.7;
- total meat waste, 14.2 (23%), of which primary production comprised 0.5 (0.81%), processing and manufacturing comprised 2.9 (4.7%), retail and distribution comprised 1.7 (2.7%), consumption in households comprised 7.3 (11.8%), and food services comprised 1.7 (2.7%).

The meat available in Poland amounted to 4.204 Mt/y [4]. The quantity of meat waste calculated according to [3] was estimated to be 0.967 Mt/y, of which the amount of waste from meat primary manufacturing and processing was 0.232 Mt/y (24.0% of the total amount of meat waste). Meat waste mostly contains organic parts, water, and phosphorus compounds. Phosphorus recovery from meat waste is included in the waste utilization,

agricultural, and circular economy strategies of many countries [5–7], and research in this regard has been carried out for many years [5,6]. One potential strategy used is the thermal utilization of meat waste [8].

Meat waste produced in the EU is most often processed into meat bone meal (MBM). The European Union manufactures 4.5 Mt/y MBM, which is consumed mainly as bio-fuel [9–11]. This, depending on the method used, permits the production of energy and has enabled GHG emissions to decrease to 1t CO₂eq. per 1 t MBM. Incineration of a natural fuel for energy production is avoided [11].

The co-incineration of MBM and sewage sludge mixture has been proposed to recover energy from these materials, as well as the use of the obtained ash, as a high-quality hydroxyapatite, as a substitute for phosphate rock [12]. The combustion of MBM and other meat by-products in industrial rotary kilns was described by [13–15].

The thermal utilization of bone, off-site recycling, and the use of the ash produced—which contains high-purity hydroxyapatite—as a substitute for natural phosphoric ores are examples of pollution prevention options [16–18]. Generally, bones contain 70% of inorganic and 30% of organic compounds. Biological apatite is nonstoichiometric HA with a Ca/P molar ratio greater than 1.67. Apatite is a component of bones, enamel, dentine, and other tissues (urinary stone, tooth scale, and mineralized soft tissue) [19]. Depending on the quality of the raw material, the product from the calcination of meat bone (MB) should contain on average up to 16% P. Such phosphorus content in the hydroxyapatite ash is in the typical range of this element in phosphorus raw materials, which contain 13–17% P [19–21].

Such technologies confirm the possibility of the implementation of the circular economy methodology in industrial practice, enabling the use of the value contained in raw materials and recycled waste to the greatest possible extent [16]. In accordance with the circular economy concept, energy recovery by incineration is also beneficial. This has also resulted in the life cycle value chain of products holding the maximum possible value and quality while also being energy efficient [16,17].

The present study uses Polish MBM and an MB combustion unit as the subjects of research. The aim is to compare the impact on the environment of MBM and MB combustion units using a comparative LCA evaluation using the ILCD 2011 Midpoint procedure and to identify hotspots. The following two different scenarios were analyzed: Scenario I—the combustion of MBM produced from all types of meat waste; Scenario II—the combustion of MB and other meat processing and manufacturing by-products from the production of meat products.

2. Methodology

2.1. Scope and Goal of the Assessment

LCA assesses the total influence of the analyzed product on the environment, including its emissions, resources, energy use, and production over its entire life cycle [22]. The LCA estimation was made according to the ISO standard [22] and the ILCD 2011 Midpoint + V.1.09 procedure, which indicates a consolidated midpoint/endpoint system with the use of 16 impact categories [23–25]. The ILCD method makes the proper application of the characterization coefficients possible for environmental impact evaluation in accordance with the guidelines of the ILCD handbook. The ILCD final effect of the assessment determining the impact on the environment is the calculated “eco-indicator” [26,27]. The ILCD weight indexes were supposed to be 1. This assumption resulted in the equal treatment of all environmental impact categories. The calculations were performed with the SimaPro Developer v. 9.1.1.1 LCA software [28].

The function of the system was to convert a defined quantity of meat wastes to 1 ton of hydroxyapatite containing phosphorus. Therefore, the functional unit was assumed to be 1 ton of hydroxyapatite ash produced. The scope of the study included all operations related to meat waste combustion and hydroxyapatite ash use (i.e., from gate to gate). The boundaries of the study included incineration in rotary kilns, the afterburning of exhaust

gases, and steam production in a hydroxyapatite production chain. Excluded from the scope of the study were the construction, maintenance, and restoration of the combustion unit because of their minimal influence on the result.

2.2. Allocation

In this study, the inputs of MBM and MB were considered as wastes and the producer was allocated to primary production. Therefore, the environmental burdens coming from those operations were eliminated from the system boundaries and allocated to the meat production process. The main environmental benefits appear in phosphorus recovery, but the system provides the production of steam as a by-product, which is a carrier for the heat used in meat production. The avoided burdens approach was examined in terms of heat production from steam in both scenarios.

2.3. Scenarios Analysed

The comparative analysis was based on MBM and MB combustion using two different scenarios of their thermal processing. The material streams flow and the system boundaries are presented in Figure 1.

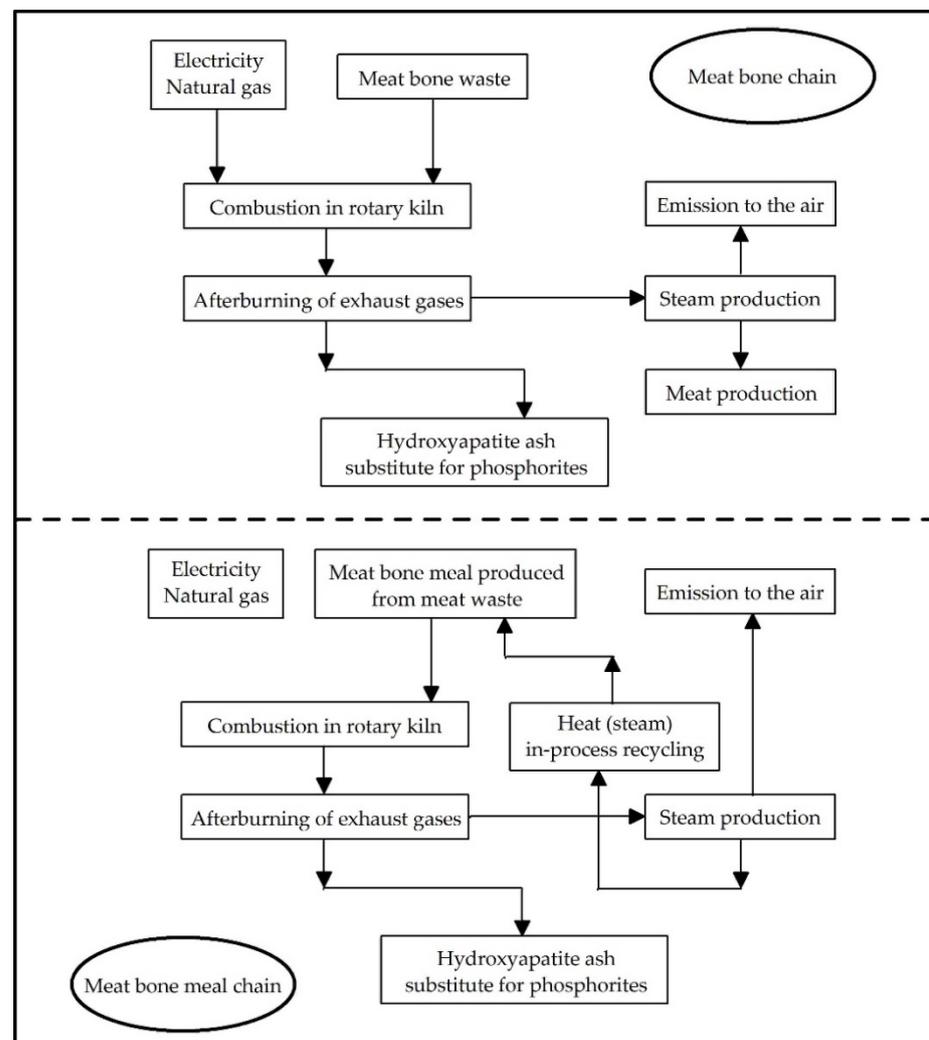


Figure 1. Meat bone meal and meat bone chains: system boundaries and material streams.

2.3.1. Scenario I

MBM is produced from all types of meat waste. Scenario I involved the combustion of MBM in the Farmutil Company. In 2019, Farmutil developed and launched their own

MBM incineration unit with a capacity of 4 t/h. A flow-sheet of the MBM combustion process is presented in Figure 1 [15,29]. The calcination of MBM in a rotary kiln involves the full incineration of the MBM organic fraction. This is achieved with not less than 20% excess air relative to the stoichiometric quantity needed for the total oxidation of the organic compounds. The thermal processing of MBM includes such operations as drying-degassing, the burning of charred organic material, and the calcination of hydroxyapatites. The co-current rotary kiln is alimeted with MBM in measured quantities using screw conveyors. The measured MBM combustion heat was 18.5 GJ/t on average.

HA ash received from the rotary kiln and exhaust gas from afterburning in a stationary furnace are transported to the warehouse. There is provision for the possible recycling of HA ash into the kiln. In addition, the heat of the exhaust gases from kilns is used in the production of technological steam in steam boilers. The flue gas after the steam-producing boiler is cleaned by first dry dedusting in bag filters, next wet dedusting in scrubbers, and then by being discharged into the air.

MBM requires calcination at temperatures of up to 950 °C and ash containing almost pure hydroxyapatite $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ was obtained from MBM thermal decomposition. Under these conditions, the hydroxyapatite grains were well crystallized with no traces of melting. X-ray diagrams indicated trace contents in the HA phase of $\text{Ca}_3(\text{PO}_4)_2$, CaCO_3 , SiO_2 , and Fe_2O_3 . The phosphorus content in the produced ash was on average 39.0% P_2O_5 and the Ca content was on average 32.5%. The P content in HA ash was much higher in relation to the phosphorites with which it was compared, where it was up to 33.8% P_2O_5 [30].

MBM typically contains (%): 8.0–10.0 CaO; 5–6 P; 6.0–8.0 N; 0.5–0.6 SiO_2 ; 0.01–0.02 F; 0.5–1.0 K; and 1.5–2.0 Na. As, Cu, Pb, Cr, Ni, and Ag ranged from 0.001 to 0.0001%. Table 1 shows the contents of P_2O_5 and the significant components and impurities important for the production of phosphoric acid and phosphorus fertilizers from MBM and MB ash [15,29]. These results show that MBMA has a very high P_2O_5 content and is at the same time a pure raw material containing very low amounts of iron and aluminum compounds ($\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$)/ $\text{P}_2\text{O}_5 < 0.0003$) and other impurities; thus, the production of phosphoric acid and phosphoric fertilizers from MBMA allowed us to obtain higher-quality products.

Table 1. Content of P_2O_5 and basic impurities in MBM and MBMA.

Material Type	Content (%) or Ratio (%)							
	P_2O_5	Al_2O_3	Fe_2O_3	$(\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3)/\text{P}_2\text{O}_5$	MgO	MER ¹	Cd (ppm)	X_{Cd} (mg Cd/kg P_2O_5)
MBM	9.6	0.0	0.005	0.0005	0.13	1.405	0.002	0.02
MBMA	41.0	0.0	0.014	0.0003	0.33	0.839	0.014	0.03

¹ Minor Element Ratio MER = $100 \times (\sum (\text{Al}_2\text{O}_3, \text{Fe}_2\text{O}_3, \text{MgO}))/\text{P}_2\text{O}_5$ (%).

2.3.2. Scenario II

Scenario II involved a production unit for the thermal processing of MB waste. This derives exclusively from primary meat production and takes place directly in the meat factories. The Polish meat production is 4.204 Mt/y [4]. The amount of meat waste calculated according to [3] was estimated to be 0.967 Mt/y, which was utilized mostly for MBM production [10,29]. The quantity of waste from primary meat manufacturing containing waste bone in Poland was assessed to be 0.232 Mt/y (24.0% of the meat waste amount). Its combustion allows the user to obtain 71,118 t/y of HA ash, a substitute for phosphate rock.

The calcination of bone waste from meat primary production allows the user to obtain white powdered ash, a homogeneous raw material with an average bulk density of 1.25 t/m³. Its main crystalline phase is hydroxyapatite $\text{Ca}_5(\text{PO}_4)_3\text{OH}$. X-ray diagrams showed traces of $\text{Ca}_3(\text{PO}_4)_2$, CaCO_3 , SiO_2 , and Fe_2O_3 phases in the product. The molar ratio of Ca/P is 1.67 and the ash contains 17.0% P (P_2O_5 —39.0) and 46.4% Ca (CaO—65.0), and the share by size fraction (%) is: <0.01 mm—39.8; 0.01–0.16 mm—15.2; 0.16–0.25 mm—18.1;

0.25–0.5 mm—16.9; and >0.5 mm 10.5%. The 0.01–0.5 mm fraction forms the HA product, and oversized and undersized ash is reused in the calcination process (in-process recycling) [18].

The charge used in the rotary kiln contained ground pork bones with a size of 3–5 cm and a bulk density of 0.655 kg/dm³, containing 35.0–45.0% H₂O and a dry mass (%) of: organic matter 36.5, fat 15, proteins 20.0, P 10.0, and Ca 28.0. The Cd, Hg, As, Cr, Pb, and Cu content in MB waste is lower than 0.1 ppm [18].

The mass ratio of recycled HA and bone waste was 1:1. The processing of MB waste in a rotary kiln concerns the full incineration of the organic fraction of meat waste using not less than 20% of additional air at a temperature of 950 °C. The ash produced using thermally decomposed semi-finished MB products is practically pure hydroxyapatite [29,31]. Exhaust gases are after-burned in a stationary chamber kiln, and the heat recovered from flue gases is used for steam production in steam boilers. Flue gas from the boilers is cleansed in bag filters and then released through a chimney into the air. Dust from the bag filters and the boiler is recycled into a rotary kiln. The content of impurities in the flue gases emitted was (ppm): inert dust—30; SO_x—50; NO_x—150; organics as C—10; ∑ Pb, Zn, Cr, As, Co, Ni—traces; PCDD/PCDF—0.05 ppb; Hg—none; HCl, HF—traces [31].

2.4. Inventory Data

The inventory data of raw materials were taken from the Ecoinvent database v. 3.3 [31] for European conditions. Empirical data for unit processes and input-output calculations were based on both scenarios of the thermal processing of MBM and MB. The raw material consumption figures and emissions to air for the compared two scenarios are shown in Table 2. The inputs of MBM (144 t/d) and MB (48 t/d) were considered to be wastes; therefore, environmental burdens were allocated to the meat production process. The quantity of recycled hydroxyapatite was used to maintain the proper combustion conditions. No wastewater or solid wastes are generated in the process.

Table 2. Life Cycle Inventory (LCI) for both MBM and MB scenarios (units/day).

Input/Output	Units	Scenario I	Scenario II
<i>Inputs</i>			
MBM and MB wastes	t	144.0	48.0
electricity medium voltage, country mix, PL	MWh	2.88	3.51
tap water	m ³	3.6	20
natural gas	Nm ³	3240	9239
Recycled hydroxyapatite			
<i>Outputs</i>			
hydroxyapatite ash	t	36	14.4
calculated for P ₂ O ₅	t	14.04	5.616
heat from steam	GJ	148.8	342.24
<i>Outputs—emissions to air</i>			
inert dust (PM)	kg	0.0324	0.3318
SO ₂	kg	0.162	0.5530
NO _x	kg	0.648	2.2119
CO	kg		0.1106
HCl	kg	0.0324	Nd
HF	kg	0.00324	Nd
heavy metals	kg	0.00162	
metals and zinc	kg	0.0162	
organic compounds as C	kg		0.1106
dioxins and furans	kg	0.000324	0.0006

The after-burned exhaust gases are relatively clean due to the relatively low calcination temperatures used, which reduced the formation of nitrogen oxides in the incineration processes, and the efficient exhaust gas treatment designed for the MBM and MB incineration units [32].

3. Results and Discussion

3.1. General LCA Results

The Life Cycle Impact Assessment (LCIA) allowed the comparison of the results from two scenarios after the characterization and normalization stages. In addition, two approaches were chosen for using the steam generated in the combustion process to feature the potential environmental benefits of both scenarios. The first approach covers the situation where the steam is treated as a by-product of the process and the environmental benefits are not considered. This approach includes only the results of the phosphorous recovery. In the second case, the avoided burdens of steam production were taken into account. It was considered that the heat recovery from steam production would be used in the meat production, thus reducing the consumption of fossil fuels.

The midpoint results of each impact category for both scenarios after the characterization stage are shown in Table 3.

Table 3. Life Cycle Impact Assessment results: midpoint characterization stage.

Impact Categories *	Units	Scenario I	Scenario II
Climate change (CC)	kg CO ₂ eq	3.55E+01	5.37E+02
Ozone depletion (OD)	kg CFC-11 eq	4.12E−05	3.19E−04
Human toxicity, non-cancer effects (HT NCE)	CTUh	1.76E−05	9.43E−05
Human toxicity, cancer effects (HT CE)	CTUh	5.89E−06	3.04E−05
Particulate matter/Respiratory inorganics (PMF)	kg PM2.5 eq	−9.22E−02	5.92E−02
Ionizing radiation human health effects (IR HH)	kBq U235 eq	−1.23E+01	−5.48E+00
Ionizing radiation effects (interim) (IR E)	CTUe	−7.82E−07	2.21E−05
Photochemical ozone formation (POF)	kg NMVOC eq	1.09E−01	1.90E+00
Acidification (AD)	mol H+ eq	1.73E−01	3.17E+00
Terrestrial Eutrophication (TE)	mol N eq	4.36E−02	4.49E+00
Freshwater eutrophication (FE)	kg P eq	6.54E−02	2.88E−01
Marine eutrophication (ME)	kg N eq	1.62E−03	4.19E−01
Freshwater eco-toxicity (FET)	CTUe	3.95E+02	2.94E+03
Land occupation (LO)	kg deficit	−6.90E+01	5.73E+02
Water resource depletion (WRD)	m ³ water eq	1.13E+00	6.57E+00
Mineral, fossil and ren resource depletion (FD)	kg Sb eq	−1.22E−02	−1.02E−02

* Category names according to [33].

The greatest impact of both scenarios was observed in 3 of the 16 categories, including ‘climate change’ (CC), ‘freshwater eco-toxicity’ (FET), and ‘water resource depletion’ (WRD) (Table 3). In these three categories, Scenario II results in greater impacts than Scenario I. Scenario II also results in a significant impact in the ‘land occupation’ category (2.94E+03 kg C deficit).

Scenario I showed greater impact in almost all categories. Scenario II only produced a greater impact in the FD category. Comparing the categories where the environmental effect is below zero, Scenario I resulted in greater benefit in the LO category. Scenario II featured potential benefits in the PMF, IR E, and LO categories. Figure 2 shows the percent contribution of both scenarios I and II for the 16 impact categories. The smallest difference between the scenarios is observed in the IR HH category.

The normalization data (Figure 3) show that the quality structures of the influence on the environment differ from the characterization results and that the HT CE impact category is predominant for both scenarios.

The final normalization results (Figure 3) indicate that Scenario II of the MB combustion had the greatest environmental influence. Scenario I of meat and bone meal combustion was characterized by a lower impact. The categories with the highest impact scores were HT NCE and FET for Scenario I and Scenario II; however, Scenario I exhibits a lower impact in all categories. The total impacts of HT CE, HT NCE, and FET categories included above 90% of the summarized impacts in both scenarios. The HT CE category received 67% of the total impacts in Scenario I and 58% in Scenario II.

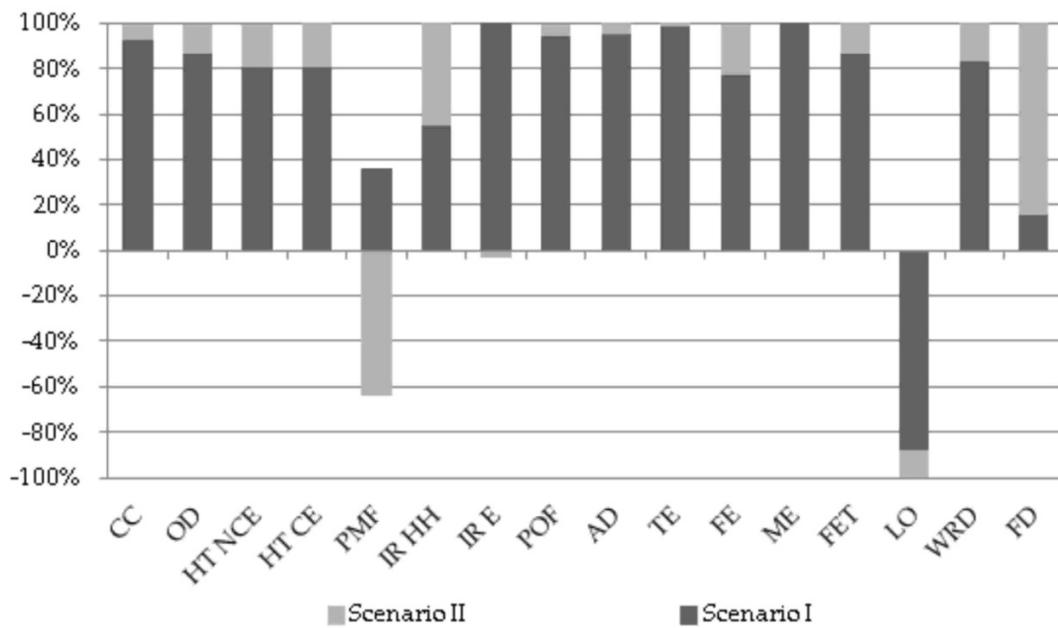


Figure 2. The contribution (%) of both scenarios to the characterization results by impact category based on the SimaPro calculations. Category name abbreviations as in Table 3.

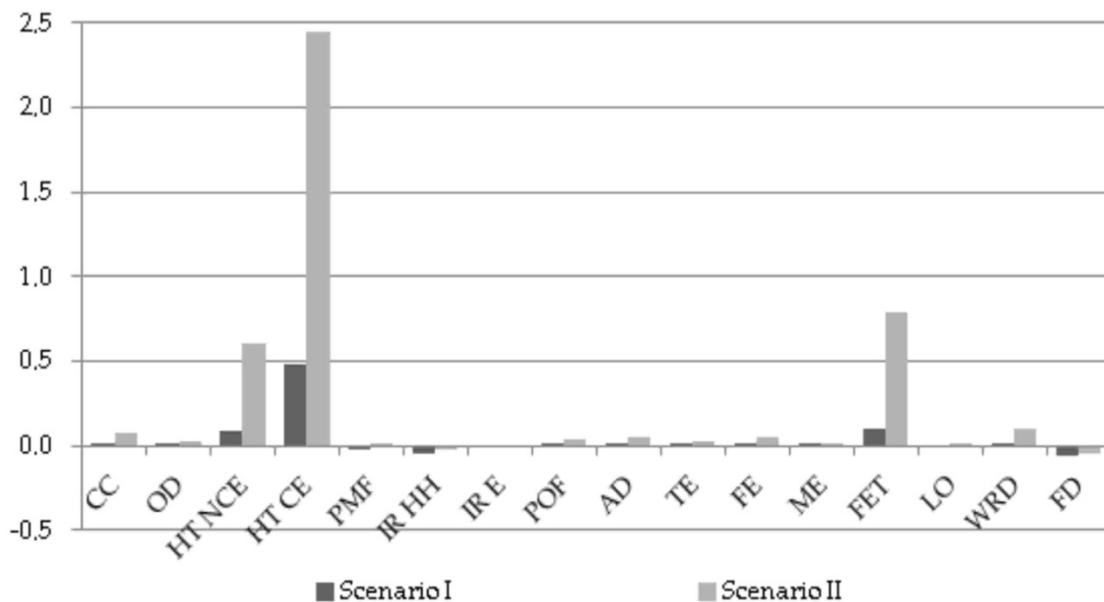


Figure 3. Scenario I and II normalization results by impact category. Category name abbreviations as in Table 3.

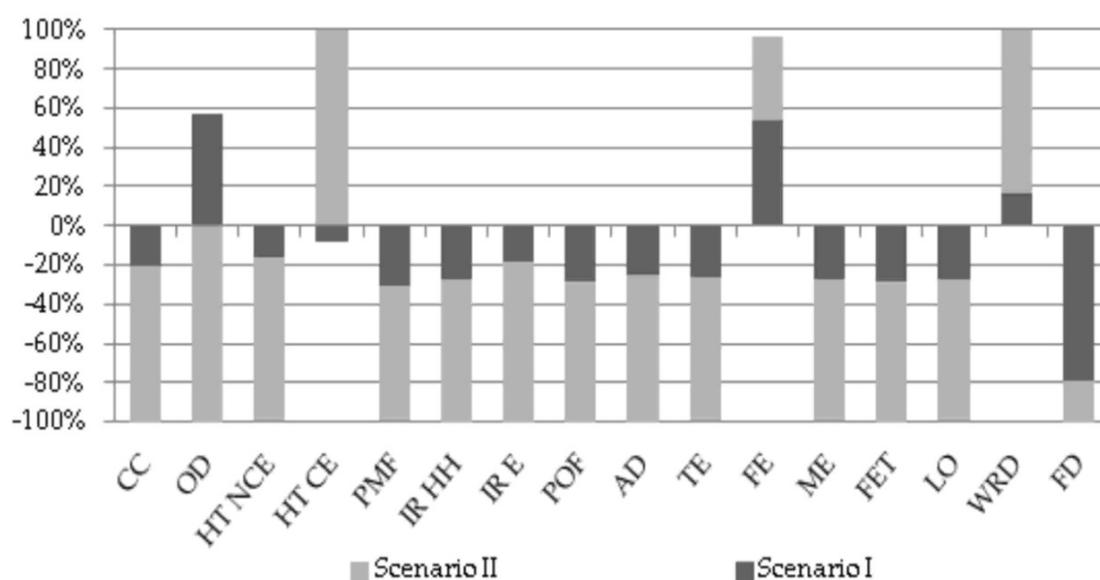
3.2. Avoided Burdens Approach

The approach of the avoided environmental burden arising from the steam production was also analyzed. The environmental benefits of reuse in the meat production of recovered energy change the holistic structure of the impact of both scenarios. The greatest impact was observed in 2 of the 16 categories, including ‘freshwater eutrophication’ (FE) and ‘water resource depletion’ (WRD) (Table 4). Considering the avoided burdens approach, both scenarios generate impact values below zero in almost all categories except for OD, HT CE, FE, and WRD. In two categories, HT NCE and WRD, Scenario II results in greater impacts than Scenario I; in the OD and FE categories, Scenario I features higher impact values than Scenario II (Figure 4).

Table 4. Life Cycle Impact Assessment results: midpoint characterization stage with the avoided burdens approach.

Category *	Units	Scenario I	Scenario II
Climate change (CC)	kg CO ₂ eq	−3.90E+02	−1.91E+03
Ozone depletion (OD)	kg CFC-11 eq	−1.09E−05	1.91E−05
Human toxicity, non-cancer effects (HT NCE)	CTUh	−1.04E−05	−6.62E−05
Human toxicity, cancer effects (HT CE)	CTUh	2.01E−07	−2.35E−06
Particulate matter/Respiratory inorganics (PMF)	kg PM2.5 eq	−2.35E−01	−7.62E−01
Ionizing radiation human health effects (IR HH)	kBq U235 eq	−3.10E+01	−1.13E+02
Ionizing radiation effects (interim) (IR E)	CTUe	−8.74E−05	−4.76E−04
Photochemical ozone formation (POF)	kg NMVOC eq	−5.85E−01	−2.10E+00
Acidification (AD)	mol H+ eq	−1.25E+00	−5.01E+00
Terrestrial Eutrophication (TE)	mol N eq	−2.14E+00	−8.09E+00
Freshwater eutrophication (FE)	kg P eq	2.28E−02	4.28E−02
Marine eutrophication (ME)	kg N eq	−2.03E−01	−7.58E−01
Freshwater eco-toxicity (FET)	CTUe	−3.11E+02	−1.11E+03
Land occupation (LO)	kg deficit	−4.81E+02	−1.79E+03
Water resource depletion (WRD)	m ³ water eq	9.09E−01	5.31E+00
Mineral, fossil & ren resource depletion (FD)	kg Sb eq	−1.33E−02	−1.69E−02

* Category names according to [33].

**Figure 4.** The contribution (%) of both scenarios to the characterization results by impact category with the avoided burdens approach. Category name abbreviations as in Table 3.

In comparison with the other categories where the impact is below zero, Scenario II resulted in lower impact values in almost all categories apart from the FD category. The percent contributions of both scenarios I and II (in %) in the presented impact categories are shown in Figure 4. The greatest differences between the two scenarios are observed in the OD and HT CE categories.

The normalization results with the avoided burdens approach (Figure 5) showed that the quality structures of the influence on the environment were similar and the WRD impact category was predominant. The lowest scores can be attributed to the IR HH, FET, and FD categories for Scenario I and the IR HH, HT NCT, and FET categories for Scenario II.

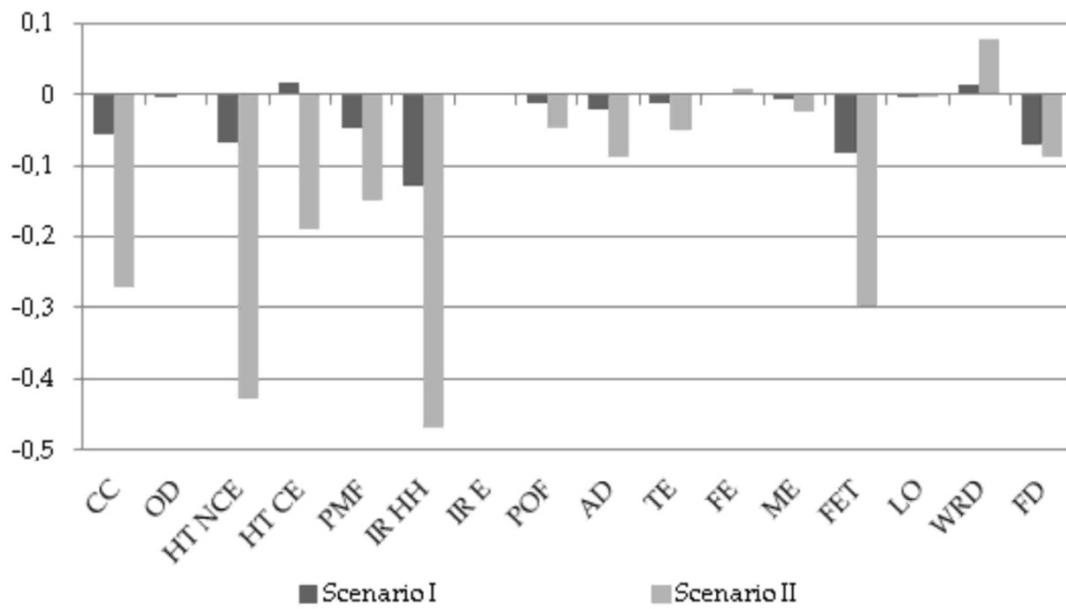


Figure 5. Scenario I and II normalization results by impact category with the avoided burdens approach. Category name abbreviations as in Table 3.

3.3. Determination of Key Process Figures

The normalization results indicated that the basic consumption figure for all scenarios was electricity consumption, resulting in the greatest impact scores in Scenarios I and II (Figures 6 and 7).

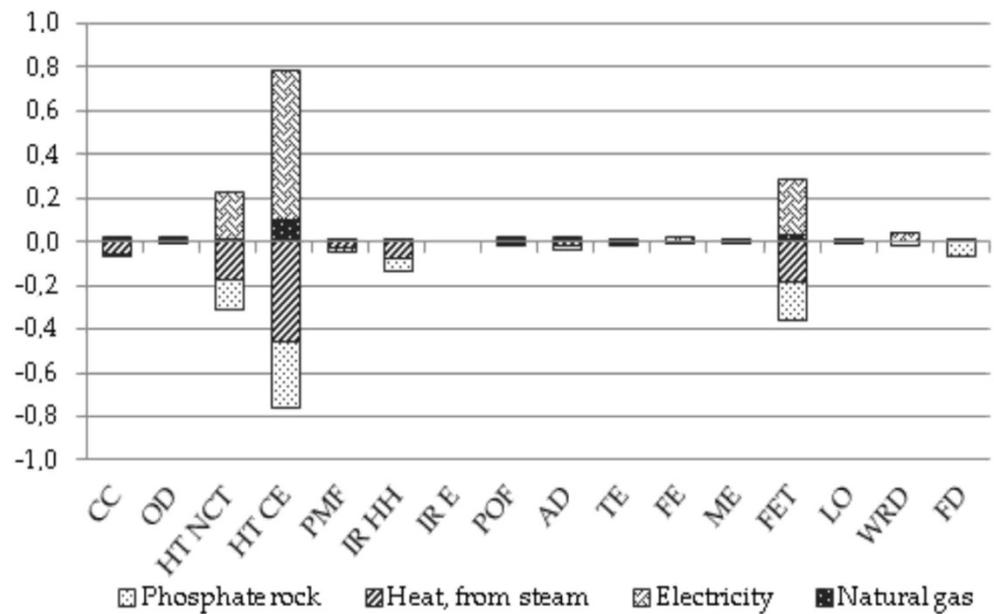


Figure 6. Normalization scores for Scenario I. Category name abbreviations as in Table 3.

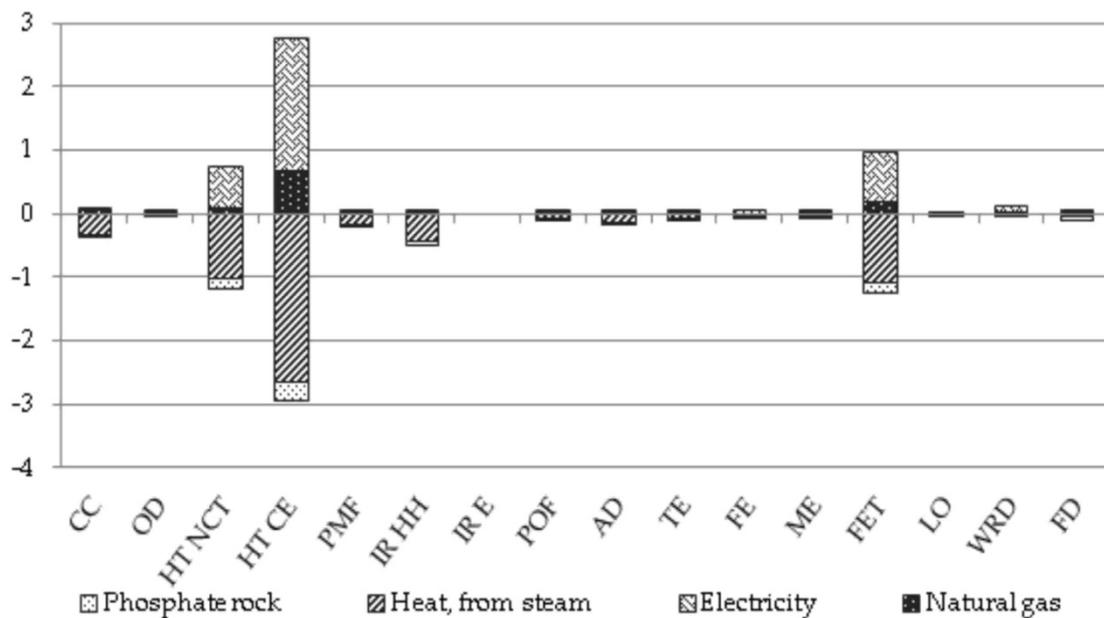


Figure 7. Normalization scores for Scenario II. Category name abbreviations as in Table 3.

All of the environmental impacts resulting from electricity and natural gas consumption are outweighed by the benefits of heat and phosphorous recovery. Electricity consumption included 87.1% of the overall environmental influence in Scenario I and 76.5% in Scenario II. The second contributor is natural gas consumption, which is responsible for 11.1% and 22.8%, respectively (Table 5).

Table 5. Contributions of consumption figures to the total impact indicator: normalization scores.

Contribution to the Overall Impact	Units	Water Consumption	Electricity Consumption	Natural Gas Consumption	Other	Heat from Steam Avoided	Phosphorous Recovery Avoided
Scenario I	%	0.1	87.1	11.1	1.7	−74.5	−58.3
Scenario II	%	0.6	76.5	22.8	0.1	−123.5	−16.8

The avoided burdens corresponding to the heat generation from steam contributes 74.5% for Scenario I and −123.5% for Scenario II towards the overall impact. The phosphorous recovery reduced the total influence on the environment by −58.3% for Scenario I and −16.8% for Scenario II.

4. Conclusions

Two scenarios of meat waste thermal utilization were assessed using the LCA method: I—the combustion of MBM produced from all types of meat waste; II—the combustion only of MB and other meat processing and manufacturing by-products from the production of meat products.

The ‘excluding avoided environmental burdens’ approach LCA results showed that Scenario II had the greatest environmental influence. Scenario I was characterized by a 71.2% lower impact. Electricity and natural gas consumption figures were determined for two scenarios, as the key hotspots accounted for 98.2% of the total environmental score in Scenario I and 99.3% in Scenario II.

The avoided burdens approach results in changing the balance between both scenarios. The absolute value score of the overall environmental impact shows that proper MB combustion (Scenario II) can be more environmentally beneficial than MBM combustion.

In general, Scenario I can be used for the elimination of all types of Polish meat waste. Scenario II can only be implemented in meat production units to deal with MB and other meat waste and by-products from meat processing and manufacturing. The quantity of

these types of meat products is estimated to be 10% of total meat waste. However, LCA analysis showed that this solution could be environmentally attractive for some meat producers.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

MBM	meat bone meal
MB	meat bones
MBMA	meat bone meal ash
MBA	meat bone ash
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
ILCD	International Reference Life Cycle Data System
CE	circular economy

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