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Article

Environmental Impact Assessment of the Dismantled Battery: Case Study of a Power Lead–Acid Battery Factory in China

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Abstract: With the increase in battery usage and the decommissioning of waste power batteries (WPBs), WPB treatment has become increasingly important. However, there is little knowledge of systems and norms regarding the performance of WPB dismantling treatments, although such facilities and factories are being built across the globe. In this paper, environmental performance is investigated quantitatively using life cycle assessment (LCA) methodology for a dismantled WPB manufacturing process in Tongliao city of Inner Mongolia Province, China. The functional unit was selected to be one metric ton of processed WPB, and the average data of 2021 were used. The results indicated that WPB dismantling treatments are generally sustainable in their environmental impacts, because the life cycle environmental effects can be neutralized by the substitution of virgin products with recycled counterparts. Of all the processes of dismantlement, Crude Lead Making, Refining, and Preliminary Desulfurization, were the top three contributors to the total environmental burden. The results of the sensitivity analysis showed that increasing photovoltaic power, wind power, and natural gas usage may significantly reduce the burden on the environment. On the basis of our findings, some suggestions are put forward for a policy to promote environmental green growth of WPB treatment. Although this paper is aimed at the power lead–acid battery, the research method is also of significance for the power lithium-ion battery, and we will conduct relevant research on the disassembly process of the power lithium-ion battery in the future.

Keywords: dismantled manufacturing; LCA; workflow analysis; waste power battery; disposal of used lead–acid batteries

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1. Introduction

The rapid pace of the development of new energy vehicles will lead to a much speedier rate of waste power battery (WPB) generation. Therefore, the disposal of WPBs is becoming a topic attractive to public investors, as well as receiving intensive attention from academics [1,2]. Conventionally, the primary practice is a lack of specific treatment, with only simple treatment to obtain valuable resources, landfill for materials that are not easy to handle, or remelting taken directly considering the disposal cost, regardless of the impact of the waste on the environment [3,4]. Environmentally friendlier alternative options have increasingly been applied to dispose of WPBs. Therefore, an integrated approach for WPBs is gaining increased popularity; such a dismantling model strategy is supposed to exhibit superior environmental performance and higher energy efficiency [5–7]. Most of the waste treatment models in the literature have focused only on the applications of a certain process; for example, the suggestion in [8], in which the life cycle performance evaluation for dismantled manufacturing is underexamined because the complex design of such a system might lead to higher costs, making this strategy economically unsustainable. Research regarding the recycling of spent lithium-ion batteries has provided meaningful references for this study [9]. Despite sustainability evaluation being a research hotspot, according to our best knowledge, no one has examined the environmental performance of life cycle dismantling processes in an integrated manufacturing method.

To fill the aforementioned knowledge gaps, the life cycle assessment (LCA) method is applied to evaluate the environmental performance of dismantled WPB manufacturing. LCA is an effective method and tool for quantifying different WPB treatments' environmental impacts, offering possibilities to promote the sustainability of WPB treatments [10–12]. The dismantled WPB remanufacturing center is in a state-of-the-art factory in Tongliao city of Inner Mongolia Province, which was designed to produce power batteries for new energy vehicles in 2016. The construction of the plant started at the beginning of 2017 and was finished in December 2018, and the trial operation took place in 2019. Afterwards, the equipment and facilities were fully put into use with complete capacity production on 1 January 2020. Our scientific research is on the basis of the operational data of 2021, the management information systems, and communication with the relevant department managers of the plant, which are the real data coming from the actual operation of the enterprise. At the same time, the public datasets—for example, GaBi and EcoInvent (EI)—are used as supplements. Because of the rich information resources, our research work overcomes the difficulty of limited data. It is well known that the availability of data severely affects research work on WPB disposal. Through a literature search, we learned that other related research works only investigated the environmental performance on "waste-to-energy and resource" technologies for the separation of lead compounds and sulfates from the WPB [13–15].

Our work overcomes the difficulties of data limitation and achieves effectiveness with sufficient details. We propose a first quantitative analysis and assessment of the environmental impact for every detailed process of WPB dismantling treatment. From the perspective of methodology, the LCA application is much more complete and comprehensive than in other correlational studies of WPB treatment. The life cycle inventory database of battery disposal would be further enriched by our research work. We provide recommendations to reduce the environmental burdens of the studied WPB dismantlement processes, as such integrated dismantlement treatments have been practiced across the globe. In this manuscript, the data are collected from a real-world case of the dismantled WPB disposal processes. We therefore provide very detailed information about flows of mass and energy in the dismantling processes of WPB. These data are valuable in waste disposal procedure modeling for other researchers. Moreover, the WPB disposal processes system displayed in our research could be a meaningful reference on waste management modeling. The study results also could provide some useful references on implementing remanufacturing before process optimization.

2. Methods and Data

Typically, the LCA method is applied in accordance with ISO 14040 series standards, where four basic steps are included. The four basic steps are "goal and scope definition", "inventory analysis", "impact assessment", and "final interpretation". In this study, the environmental impact evaluation was carried out with the help of both GaBi ts Professional Academy (version 8.6.0) and EI (version 3.4) software; the selection of the software was due to the fact that these tools are applicable to model WPB treatments and WPB manufacturing processes such as Fragmentized Separation, Preliminary Desulfurization, Smelting, and Battery Production.

2.1. Goal and Scope Definition

This work has two major objectives:

To evaluate the balance of quality of the WPB disposal processes that occur in the studied WPB center, with the assistance of the material flow analysis (MFA) approach;

To assess the environmental performance of WPB disposal processes that take place in the studied site. Further quantitative results about the contributions of each WPB dismantling process to the total environmental impact are given.

The findings of our study can be applied to support the decisions that are concerned with the implementation and promotion of dismantled WPB workshops, as well as determining possible improvements for related disposal procedures.

Referring to some extensive literature about the evaluation of the lifecycle environmental impact of WPB systems [16], the functional unit (FU) is defined as one metric ton of gathered WPB that is to be processed by the studied power battery dismantling center. The material of dismantled power batteries is for sale or used for power battery manufacturing. The FU can also be defined as one metric ton of dismantled WPB and purchased components that are to be processed by the studied power battery manufacturing center. The FU is also applicable to gathered WPB that is to be processed by the studied power battery dismantling center.

The components of one FU of gathered WPB were calculated on the basis of company operating data in 2021, seen in Table 1.

Table 1. Average components of one FU of the gathered WPB.

	Lead Paste	Lead Block and Grid	Waste Plastics	Waste Clapboard	Waste Electrolyte
wt.%	33.0	33.2	5.2	3.6	25.0

The zero-burden assumption principle is adopted in this paper. The principle is extensively applied in WPB research for defining system boundaries including all the related procedures, as shown in Figure 1. The system boundaries are suited to the LCA method especially. In system boundaries, there are nine processes: (1) Transportation, (2) Separation, (3)Recycling (Plastics and Clapboard), (4) Waste Electrolyte Treatment, (5) Preliminary Desulfurization, (6) Crude Lead Making, (7) Refining, (8) Dust Removal and Desulfurization, and (9) Wastewater Treatment. Further, the previously mentioned processes are classified into four generic phases:

(a) Transportation. This stage only has the first procedure. In this stage, the WPB is transported from the WPB collecting entrance to the plant.

(b) Separation. This stage only includes the second procedure. In this stage, the WPB is firstly pre-processed and separated, from which some intermediate products are consequently derived.

(c) Processing. This stage consists of the procedures from the third procedure to the seventh procedure. In this stage, the intermediate products are further processed and turned into the final products.

(d) Disposal. This stage has two procedures: the eighth procedure and ninth procedure. In this stage, the undesirable outcomes are treated. These undesirable outcomes, such as dust, exhaust gas, and wastewater, are produced from the dismantled WPB disposal processes.

Initially, all the collected WPBs are transported to the dismantling and manufacturing plant. After WPB transportation, these WPBs are subjected to the "fragmentized separation" process. From these procedures of the separation process, the preliminary outcomes are obtained, such as lead block, grid, waste plastics, waste clapboard, lead paste, lead sludge, and waste electrolyte. Some of these preliminary outcomes are treated in the corresponding procedures. In Figure 1, products labeled as "final products" are sold or reused in the remanufacturing processes. The processes of smoke and dust treatment and wastewater treatment are explained in detail, because the equipment related to environment protection was installed at the beginning of the factory's construction.

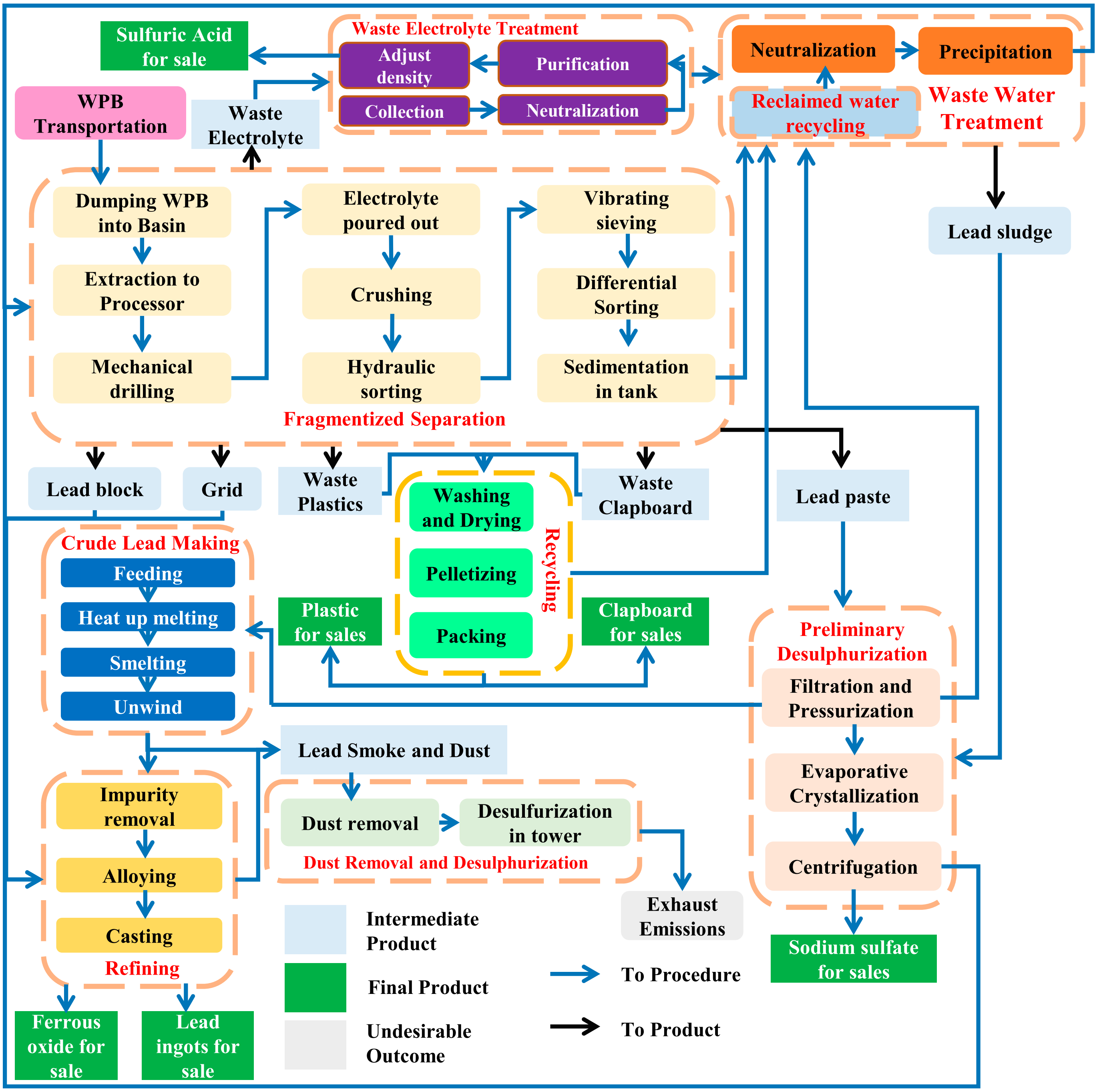


Figure 1. The WPB disposal processes system boundaries.

Based on our previous research work about municipal solid waste (MSW) treatment [17], the multi-functionality work is discussed by extending the system boundaries to include the production of primary materials and energies. These materials and energies would be replaced by counterpart secondary materials and energies recovered from the WPB dismantling processes. Similar to the composition of WPBs (seen in Table 1), both the materials and energies of the inputs and outputs are calculated in accordance with the average values of the operation data acquired from 1 January 2021 to 31 December 2021 for all treatment processes. Details of the life cycle inventory (LCI) data are presented in the following subsection.

2.2. Inventory Analysis

As previously mentioned, not only primary data but also secondary data are used in this research work. The primary data incorporate the records from the plant's management information systems and the interviews with relevant department managers. The secondary data are derived from reference to the public LCI database of GaBi and EI (version 3.4), which covers a wide range of materials, energies, and procedures for WPB treatment. The following subsection elaborates on the data and assumptions that are employed to model the WPB dismantling processes in the studied center.

2.2.1. Transportation

The WPBs are collected from waste battery recycling points in the Northeastern provinces and eastern Inner Mongolia of China. Twelve garbage trucks are used to carry the WPB from four major acquisition points to the treatment factory. The four acquisition points include three points in the capital city of the Northeastern provinces and one point in Tongliao city of Inner Mongolia. The detailed geographic information of WPBM center is presented in Figure S1 (seen in the Supplementary Materials).

Based on actual operation data, it is supposed that these WPBs are evenly distributed among the above four recycling points and the distance traveled by the trucks is 1,802,854 km per year. In the GaBi database, "CN Transport, truck (50 t total cap., 47.3 t payload)" is utilized to estimate the "transportation" effects on the environment.

2.2.2. Separation

The "Separation" process is crucial for WPB dismantling treatment. "Separation" greatly affects the subsequent processes and outputs. In this studied plant, the WPB separation procedure consists of nine subprocesses (seen in Figure 1). The detailed datasets and assumptions are presented in Table S1 (seen in the Supplementary Materials). The obtained material information is presented in Table 2 from one FU of the WPBs.

Table 2. Weight and purpose of separated materials from one FU of the WPBs.

Material Obtained	Weight (kg)	Application Description
Lead Paste	330	Lead Ingot Making
Lead Grid	332	Lead Ingot Making
Recyclable Plastics	52	Plastic Recycling
Recyclable Clapboard	36	Clapboard Recycling
Lead Sludge	5.067	Lead Ingot Making
Waste Electrolyte	244.993	Sulfuric Acid Preparation

2.2.3. Processing

After the "Separation" process, most of the separated material is subjected to the subsequent "Processing" procedure. "Processing" includes plastic recycling, clapboard recycling, sulfuric acid preparation, by-products of sodium sulfate and ferrous oxide production, and lead ingot making. The detailed datasets and assumptions are presented in Table S2.

2.2.4. Disposal

In the studied integrated WPB treatment plant, two disposal procedures, i.e., wastewater treatment, and dust removal and desulfurization, are used to dispose of the wastes, which are shown in Table S3, and the emissions from the aforementioned disposal processes are presented in Table S4. The detailed datasets and assumptions for these disposal procedures are presented in Table S5. Specifically, we summarize the consumptions of energy and water for all procedures (seen in Figure 2) in Table S6.

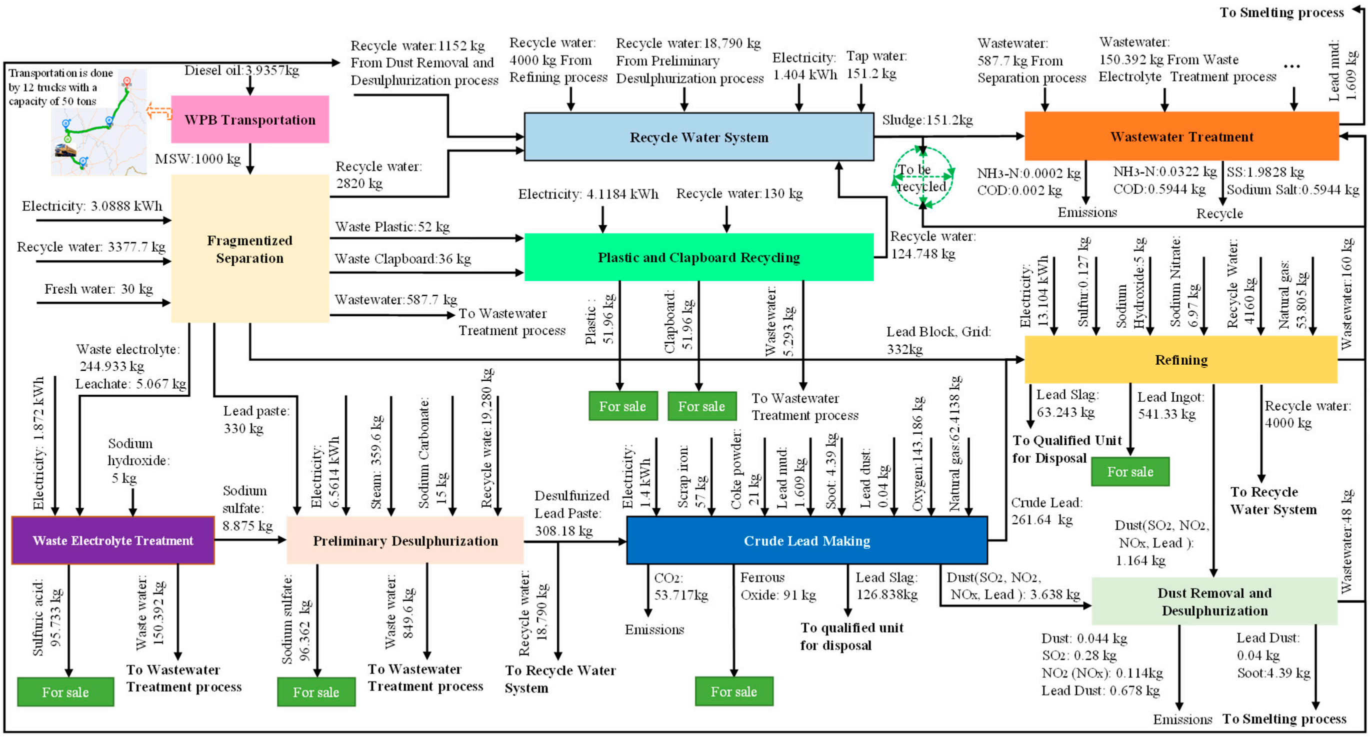


Figure 2. Quality and energy flows in one ton of WPB processing at the dismantling plant.

2.2.5. Substitution

Referring to other case studies of WPB treatment [18], the secondary products derived from this integrated WPB treatment plant are assumed to be substitutes for the original counterparts in Table S7. For the recycled materials, such as lead, plastics, and clapboard, their substitution ratios are all set to a 1:1 proportion. Perhaps these recycled materials are slightly inferior in terms of quality grade to the corresponding primary product. For sulfuric acid, its substitution ratio is determined from the comparison of its concentration or purification value and that of the primary waste electrolyte; the overall substitution ratio of lead is kept at 1:1. The detailed LCI data are presented in Table S8 for avoidable primary products.

2.3. Effect Evaluation

The ReCiPe method is a coordinated lifecycle impact assessment (LCIA) modeling tool. ReCiPe 2016, a new commonly used version, is applied to estimate the environmental effects for WPB dismantling treatments at both midpoint and endpoint levels. In terms of midpoint indicators, the following commonly used characterization factors are used in this paper through a top-down approach according to ISO recommendations. These midpoint indicators and their dimensions are listed as follows: agricultural land occupation (ALOP, in m^2a), global warming potential (GWP, in kg CO_2-Eq), fossil depletion (FDP, in kg oil-Eq), freshwater ecotoxicity (FETP, in kg 1,4-DCB-Eq), freshwater eutrophication (FEP, in kg P-Eq), human toxicity potential (HTP, in kg 1,4-DCB-Eq), ionizing radiation (IRP, kg U235-Eq), marine ecotoxicity potential (METP, in kg 1,4-DCB-Eq), marine eutrophication potential (MEP, in kg N-Eq), metal depletion (MDP, kg Fe-Eq), natural land transformation (NLTP, in m^2), ozone depletion potential (ODP, in CFC-11-Eq), particulate matter formation potential (PMFP, in kg PM10-Eq), photochemical oxidant formation potential (POFP, in kg NMVOC), terrestrial acidification potential (TAP, in kg SO_2-Eq), terrestrial ecotoxicity potential (TETP, in kg 1,4-DCB-Eq), urban land occupation (ULOP, in m^2a), and water depletion (WDP, in m^3). For the endpoint indicators, four damage categories are calculated and discussed. These four endpoints are ecosystem quality (EQ, in points), human health (HH, in points), resources (RE, in points), and the total impact (Total, dimensionless). It is worth mentioning that both midpoints and endpoints only serve to evaluate potential damage rather than actual environmental impact.

For characterization at the midpoint level, the formula is

$$I_m = \sum_i Q_{mi} m_i \tag{1}$$

where *mi* is the magnitude of intervention *i* (e.g., the mass of CO_2 released to air), Q_{mi} is the characterization factor that connects intervention *i* with midpoint impact category *m*, and I_m is the indicator result for midpoint impact category *m*.

The way to proceed for characterization at the endpoint level starts from the intermediate midpoints. The formula is

$$I_e = \sum_m Q_{em} I_m \tag{2}$$

where I_m is the indicator result for midpoint impact category *m*, Q_{em} is the characterization factor that connects midpoint impact category *m* with endpoint impact category *e*, and I_e is the indicator result for endpoint impact category *e*.

2.4. Sensitivity Analysis

Changes in inputs or assumptions cause fluctuations in results. Therefore, sensitivity analysis is used to evaluate the fluctuations. Here, our attention focuses on the refining procedure, because the refining procedure is the most intensive for energy consumption and ranks the second in the volume of water used among all the disposal processes. Further, we consider sodium sulfate, a by-product of the preliminary desulfurization procedure, as sodium sulfate is sold as an industrial raw material. Preliminary desulfurization is the procedure that consumes the most water, the second largest in terms of electricity, and consumes much more steam. Thus, the sensitivity analysis should be performed to investigate the following three aspects: (1) WPB source separation ratio, (2) sodium sulfate replacement, and (3) usage of photovoltaic power in the integrated WPB treatment plant. We demarcate the initial setting point as the base scenario.

2.4.1. Source Classification Ratio of WPBs

At present, the Chinese government is actively pushing ahead green and sustainable manufacturing in all industries, especially in WPB recycling. Source governance is considered an effective method for WPB treatment. To estimate the impact on environmental performance for increasing the source classification ratio (SCR) of WPBs, we assume that the SCR is set to 10%, 30% and 50% in weight. In other words, 10%, 30%, and 50% in weight of the WPBs are processed directly with no separation.

2.4.2. Sodium Sulfate Substitution

Sodium sulfate is regarded as an important industrial material, the making of which realizes not only the low-temperature desulfurization of lead sulfate, which is environmentally friendly, but also the process of economic value growth. To investigate the impact of the sodium sulfate economic value, we here assume that the price of sodium sulfate is 346.82 CNY/ton according to the average price in the local market.

2.4.3. Usage of Photovoltaic Power

The use of green and clean energy, including wind and solar, is widely advocated in China, despite its supply being heavily influenced by the weather conditions [19,20]. To investigate the environmental impact of photovoltaic power replacements, we here assume that photovoltaic power is used to replace natural gas as heating energy in the smelting process and the refining process, and electricity in the integrated dismantled WPB treatment plant. In addition, photovoltaic power can be used to generate electricity power for dismantled WPB manufacturing. In this case, it is supposed that all the electricity in the factory is provided by photovoltaic power with a conversion efficiency of 70% considering the weather, day and night in all kinds of different conditions.

3. Results

3.1. Material Balance and Energy Balance

Combined with LCI data compiled in the previous subsection and other information, the mass flows and energy flows for disposing one FU of the WPBs were calculated and are described in Figure 2. According to Figure 2, the top three electricity consumers are refining, preliminary desulfurization, and fragmentized separation. Although the electricity energy consumption for the procedure of crude lead-making is ranked in fourth position of all procedures of WPB dismantling, it uses the highest amount of natural gas energy. Refining uses the largest amount of electricity energy and the second highest amount of natural gas energy. Preliminary desulfurization uses the second highest amount of electricity and a high amount of steam for sodium sulfate crystallization. Fragmentized separation uses the third highest amount of electricity and high amounts of tap water and reclaimed water. Consistent with our previous LCA study, plastic recycling is ranked fifth for electricity consumption. For reclaimed water, the main users are preliminary desulfurization, refining, and fragmentized separation. However, tap water is principally used in the process of preliminary desulfurization, recycling the water system, and separation. Comparatively, tap water consumption is far less than reclaimed water consumption for WPB dismantling treatment, due to internal water recycling.

Out of all the processes, refining is the process with the highest energy intensity, accounting for 13.104 kWh per one FU of WPBs, followed by preliminary desulfurization, fragmentized separation, crude lead-making and recycling (plastics and clapboard), whose electricity consumptions are 6.561, 5.710, 5.101, and 4.118 kWh, respectively, per one FU of WPBs. The most water-intensive procedure is preliminary desulfurization, consuming 19,639.6 kg per one FU of WPBs, followed by refining, fragmentized separation, dust removal, and desulfurization, whose water consumptions are 4160.0, 3407.7, and 1200.0 kg, respectively, for disposing one ton of WPBs.

3.2. Total Environmental Achievements

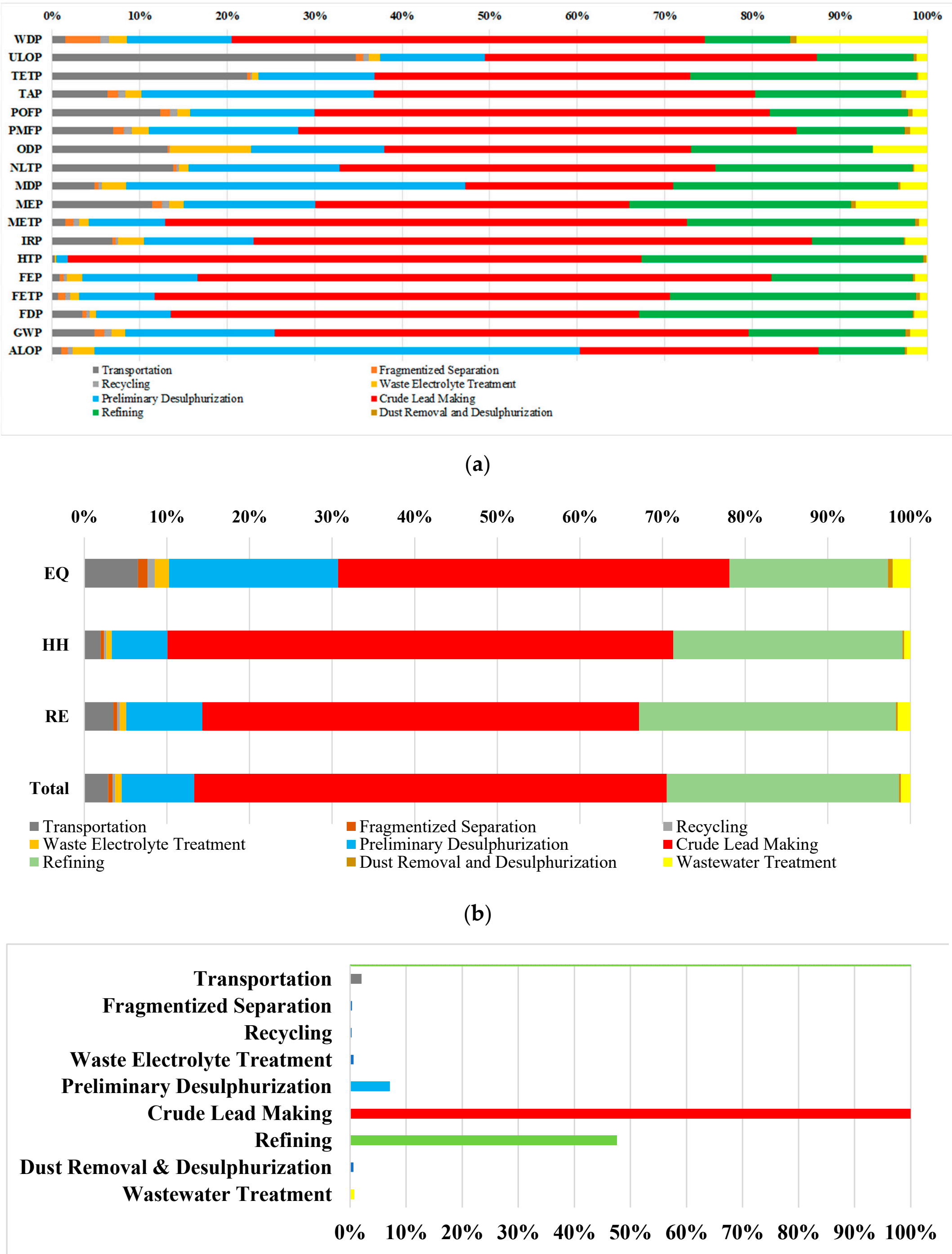
The underlying environmental effects related to one ton of dismantled WPBs are summarized in Table 3, with measurements in terms of midpoint and endpoint indicators selected from ReCiPe 2016. The data analysis results are reported by the contribution of midpoints and endpoints to the WPB disposal processes in Figure 3. Further, the top three contributors are summarized in Tables S9 and S10, according to the values of the midpoint and endpoint indicators.

Table 3. Indicator values of the disposal of one ton of WPBs.

	Category	Value	Unit of Measurement (UoM)
Midpoint	ALOP	13.61804792	m^2a
	GWP	528.8701177	kg CO_2-Eq
	FDP	296.6366039	kg oil-Eq
	FETP	14.76361101	kg 1,4-DCB-Eq
	FEP	0.238595722	kg P-Eq
	HTP	3133.759531	kg 1,4-DCB-Eq
	IRP	29.1974986	kg U235-Eq
	METP	12.25284895	kg 1,4-DCB-Eq
	MEP	0.615142614	kg N-Eq
	MDP	15.57298361	kg Fe-Eq
	NLTP	0.076092593	m^2
	ODP	3.76907×10^{-5}	kg CFC-11-Eq
	PMFP	1.089223377	kg PM10-Eq
	POFP	1.740287176	kg NMVOC
	TAP	2.17274774	kg SO_2-Eq
	TETP	0.075203026	kg 1,4-DCB-Eq
	ULOP	7.368844859	m^2a
	WDP	1.401757654	m^3

Table 3. *Cont.*

	Category	Value	Unit of Measurement (UoM)
Endpoint	Ecosystem quality	9.573223828	points
	Human health	62.37041674	points
	Resources	36.26269081	points
	Total	108.2063314	points



(c)

Figure 3. Contributions of WPB dismantling processes involved: (**a**) midpoint indicators selected from ReCiPe 2016, (**b**) endpoint indicators selected from ReCiPe 2016, and (**c**) endpoint single score by means of final scores based on Pts.

From Figure 3 and Table S9, crude lead-making is the greatest contributor to the impact values of the selected midpoints. A total of 16 out of the 18 selected midpoint indicators rank highest except for ALOP and MDP. Crude lead-making leads all other processes in four endpoint indicators; that is, EQ (47.39%), HH (61.23%), RE (52.86%) and Total (57.20%). Additionally, crude lead-making is the second highest contributor to the value of ALOP (27.23%) and the third largest contributor to the value of MDP (23.72%). This is probably ascribed to the reason that crude lead-making consumes the most natural gas with 87 m^3, and much more electricity with 5.101 kWh, for one FU of WPBs. In the crude lead-making procedure, the smelting furnace adopts an oxygen-enriched side-blown furnace, which requires a large amount of oxygen. As coke powder is used as a reducing agent to prevent lead oxidation, a high amount of carbon dioxide is produced in this process.

Refining is the second high contributor to the midpoint indicators GWP (17.90%), FDP (31.26%), FETP (28.14%), FEP (16.10%), HTP (32.14%), METP (26.05%), MEP (25.26%), MDP (25.72%), NLTP (22.51%), ODP (20.77%), POFP (15.77%), and TETP (25.84%), which is mainly attributed to the electricity and natural gas that are used in the procedure. Refining uses electricity (13.104 kWh), natural gas (75 m^3), water (4160 kg of reclaimed water), sodium nitrate (6.970 kg), sodium hydroxide (5.000 kg), sulfur (0.127 kg) and electricity energy (6.561 kWh) per disposal of one FU of WPBs. Currently, China's electricity structure is mainly based on coal power, which causes the deletion of fossil fuels and emissions of CO_2 and SO_2. Therefore, upgrading processing units and equipment has become popular and effective in easing the related environmental burden.

Preliminary desulfurization is a much greater contributor to the values of the midpoint impact categories selected. A total of 17 out of the 18 selected midpoint indicators are ranked in the top three, except TETP which ranks fourth. Preliminary desulfurization is the largest contributor to the values of ALOP and MDP. Preliminary desulfurization is the second highest contributor to the values of IRP (12.51%), PMFP (17.01%), and TAP (26.52%). Preliminary desulfurization shows the highest environmental burden, due to consuming sodium carbonate (65.667 kg), steam (359.600 kg), water (19,280 kg of reclaimed water), and electric energy (6.561 kWh) per disposal one FU of WPBs.

Wastewater treatment is the second largest contributor to the value of WDP (14.93%), mainly attributed to the circulating water system replenishment of 151.2 kg of fresh water per disposal of one FU of the WPBs in the procedure. Of the processes that are included in the wastewater treatment process, biochemical treatment is proved to be the highest environmental burden, on account of sodium hydroxide (2.837 kg), flocculant PAM (1.914 kg) and electrical energy (1.404 kWh) per disposal of one FU of WPBs. Except for the above, the environmental impact can primarily be attributed to the emission of SS, COD, non-methane hydrocarbon, NH_3-N, and sodium salt. Biological treatment exhibits remarkable potential in reducing eutrophication and human toxicity. Thus, the biological treatment of wastewater is an effective method and is widely adopted to treat reclaimed water.

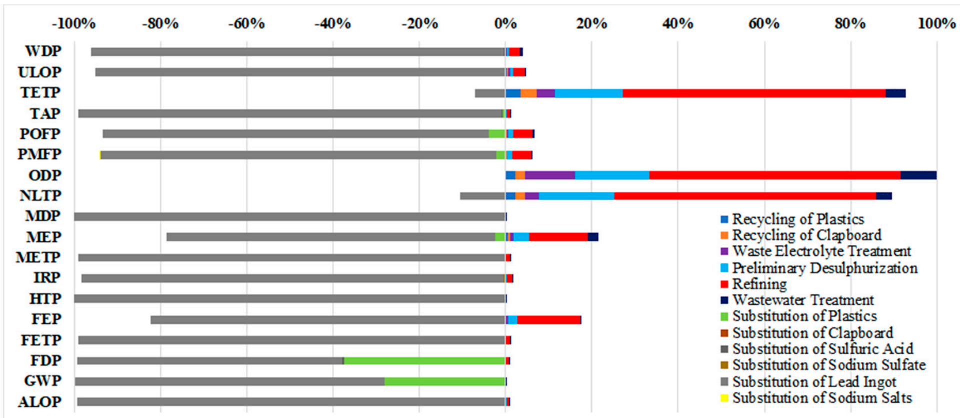
Transportation takes the third position in the value of the midpoint indicator TETP (22.26%) and occupies the second largest share in the value of midpoint indicator ULOP (34.72%). This might be due to the consumption of 3.9357 kg of diesel oil per disposal of one FU of WPBs. The mean distance from the four WPB recycling points to the WPB treatment plant is 284.25 km and the plant treatment capacity is 150,000 tons per year. Thus, using new energy truck transportation route optimization tends to be effective in reducing the related environmental burden.

The other procedures including fragmentized separation, recycling, waste electrolyte treatment, dust removal, and desulfurization have a limited impact on the values of all the indicator categories selected.

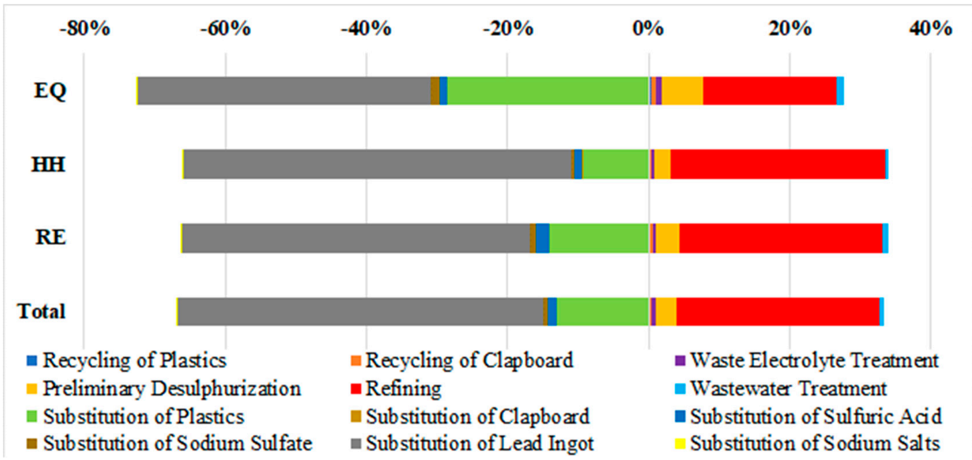
The endpoints expressing environmental impact are stacked together to obtain the data of each WPB treatment process, as shown in Figure 3c. From Figure 3c, the top three WPB processes are crude lead-making, refining, and preliminary desulfurization in the endpoint single score.

3.3. Secondary Product Substitutions

According to Section 2.2.5, recovered products are supposed to substitute for their counterparts. We have calculated and present the environmental performance of secondary substitutional products in Figure 4. The environmental impact is allocated to secondary products obtained from the corresponding procedures in the dismantling of WPBs. Referring to the literature [21], the environmental burden and environmental benefits are arranged on the right and left in Figure 4, respectively. The above-mentioned environmental burden refers to the production of recycled products, and the above-mentioned environmental benefits refer to the savings resulting from the acquisition of relevant alternative or substitution materials. Generally, as shown in Figure 4, the environmental burden could almost be counteracted by the environmental benefits in the performance of most midpoint indicators, except TETP, ODP, and NLTP. The top two contributors of environmental benefits are secondary lead ingot and plastics, contributing to 96.9% of the total environmental savings. Compared to lead ingot and plastics, other substitutions provide a relatively small contribution.



(**a**)



(**b**)

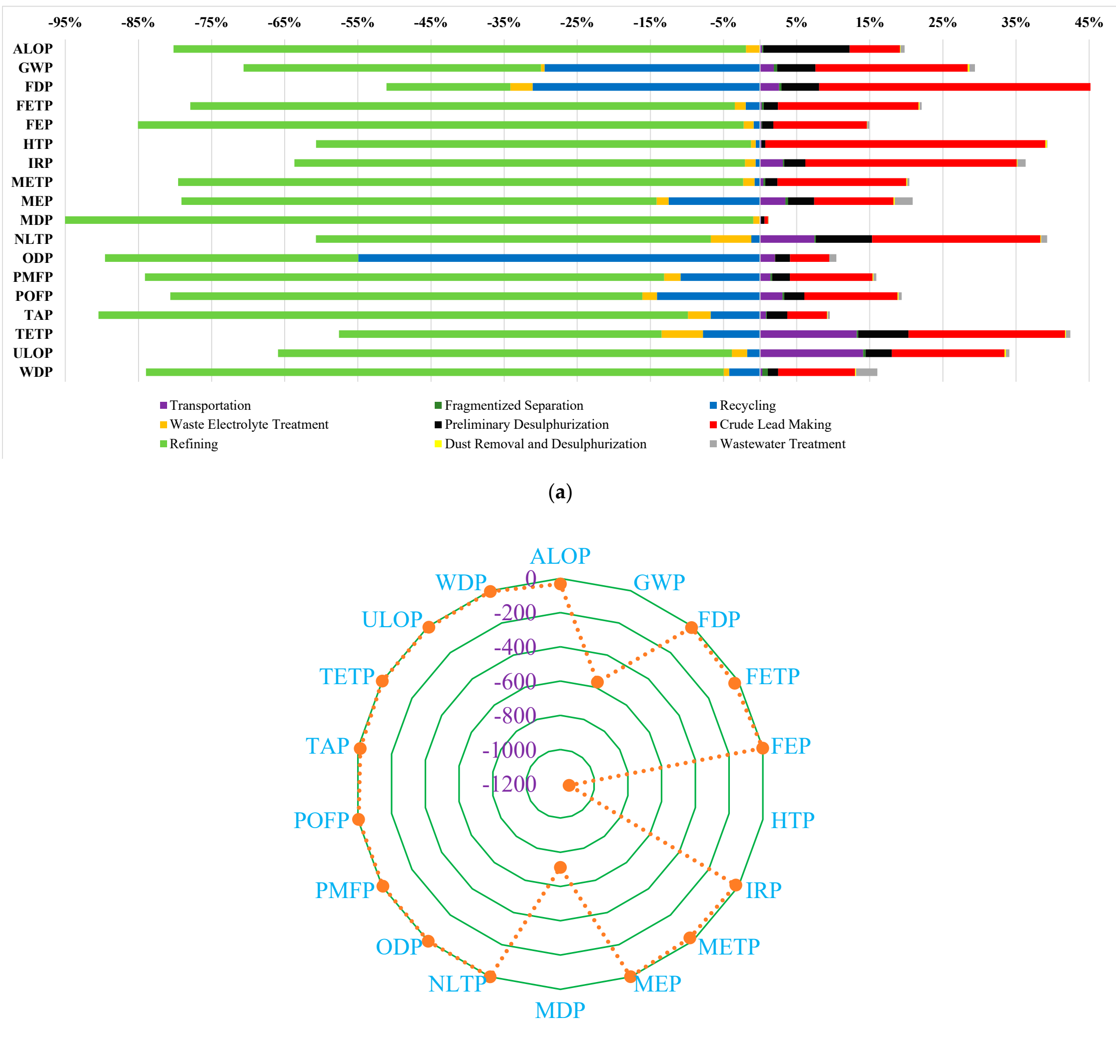
Figure 4. Contributions of the secondary product substitutions, in accordance with (**a**) midpoint indicators selected from ReCiPe 2016 and (**b**) endpoint indicators selected from ReCiPe 2016.

The potential environmental gains in the replacement of primary lead ingot with secondary lead ingot contribute the biggest share in the environmental impact for the midpoint indicator categories. In the 18 midpoint indicators, 15 indicators exceed 95%, except GWP (71.9%), FDP (61.9%), and ODP (32.2%). Moreover, lead ingot substitution also shows a large contribution to the values of the endpoint impact indicators HH (83.3%), RE (74.7%), and Total (77.5%). This could be due to the large consumption of energy and volume of materials in producing conventional lead ingot, particularly in the smelting process, in which large amounts of natural gas and oxygen are consumed; at the same time, a large amount of carbon dioxide is produced in the crude lead-making procedure.

Recycled plastics contribute the greatest share to the value of the midpoint indicator ODP (67.8%) and contribute the second highest share to the values of the endpoint indicators EQ (39.5%), RE (21.3%), and Total (19.4%). Moreover, environmental savings of these secondary substitutions take second place in the values of midpoint indicators FDP (37.6%) and GWP (28.0%). The environmental benefits gained are due to avoiding the use of crude petroleum for fabricating virgin plastics.

From Figure 4, using recovered lead ingot and recycled plastics to replace their primary counterparts could bring obvious environmental gains to many indicators. However, the environmental benefits are negligible for the substitution of sulfuric acid, sodium sulfate, recycled clapboards, and ferrous oxide.

From Figures 3a and 4a, which show the combined contributions of the dismantled WPB disposal processes and the contributions of the secondary product substitutions, the iterative process in terms of the environmental impact of the midpoint indicators was obtained, as shown in Figure 5.



(a)

(b)

Figure 5. Environmental impact of the considered alternatives: (**a**) iterative process midpoint indicators and (**b**) radar chart of midpoint indicators of the total disposal procedures.

From Figure 5, considering secondary product substitutions, the procedures such as refining, recycling, and waste electrolyte treatment can bring noticeable environmental savings to multiple indicators. The environmental impact of the total of all disposal procedures display benefits, with GWP and MDP having the most significance of all the midpoint indicators. This could be ascribed to the fact that both high energy consumption and high material consumption are required in producing conventional lead ingot. Metal depletion could be markedly mitigated by using recovered materials as substitutes for their primary counterparts.

3.4. Results of Scenario Analysis

The current situation is that the electricity consumed in waste battery treatment comes from the market group for electricity, which is considered as the base scenario. Subsequently, a few scenarios have been constructed according to the different types of energy supply situation including hard coal power, natural gas, wind power, and photovoltaic power. Therefore, the values of all the midpoint indicators can be compared by ratio of every energy type and basic energy source type (grid energy). After the scenario analysis, it can be concluded that the environmental impact of different forms of energy varies considerably in terms of sensitivity to midpoint indicators. Therefore, the battery factory can prioritize the main factors that are sensitive to environmental impact to achieve maximum environmental benefits.

The potential environmental effects of the dismantling treatment of one ton of WPBs were evaluated and are shown in Figure 6 under the different types of energy supply, where the values of all midpoint indicators are compared with those in the base scenario (market group for electricity).

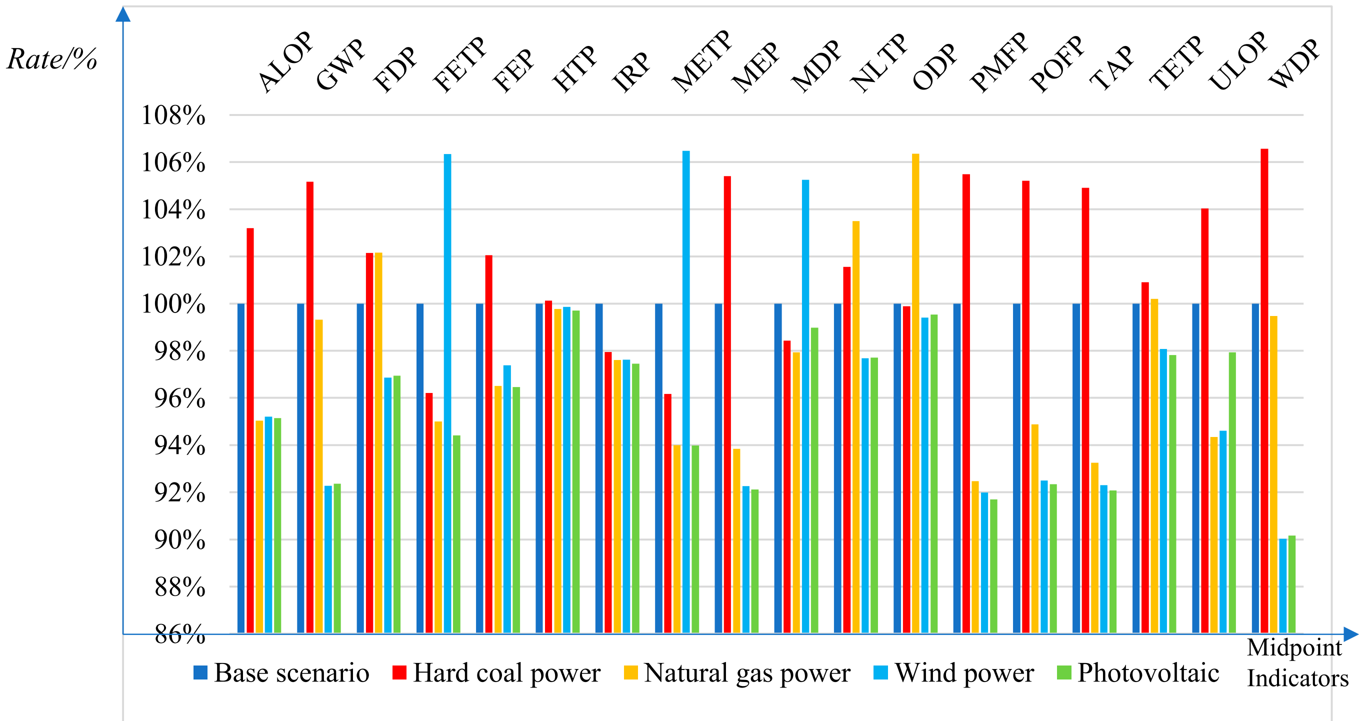


Figure 6. Environmental effects for disposing of one ton of WPBs under different types of energy supply.

As can be seen from Figure 6, different energy types cause different variations in each indicator. This different environmental impact may be interpreted by the inherent properties of each energy source. Compared with other energy sources, photovoltaic power has the largest environmental benefits. For all the 18 midpoint indicators, photovoltaic power exhibits much better environmental performance than the base scenario. Wind power shows the second largest environmental benefits; there are 15 midpoint indicators that exhibit much better results than the base scenario except FETP, METP, and MDP. Wind power generation could bring pollution to fresh water, and the manufacturing of the whole machine—as well as the blades, fasteners, converters, wind turbines, etc. required for the whole machine—consumes a high amount of metal. Natural gas also has obvious environmental benefits; there are 14 midpoint indicators that exhibit much better results than the base scenario, except FDP, NLTP, ODP, and TETP. Natural gas exhibits the least greenhouse gas and SO_2 emissions compared with coal. The values of GWP and TAP could be greatly decreased when replacing natural gas with photovoltaic power. The utilization of photovoltaic power could offer an attractive opportunity to minimize the global warming impact from fossil fuel consumption. Using photovoltaic power and wind power instead of hard coal power and natural gas can largely reduce the environmental effects of FDP. Replacing electricity and natural gas with photovoltaic power would obtain maximum gains in terms of MEP, PMFP, POFP, TAP, and WDP, because electricity from photovoltaic power is environmentally more sustainable than electricity from the grid, which is due to a higher proportion of fossil fuel generation in the grid [22,23]. For other indicators such as ODP, HTP, and TETP in the midpoint categories, energy replacements only impart a minor impact on their values. Therefore, possible environmental impact mainly depends on the decision of the WPB factory in using different types of energy supply.

3.5. Identification of Uncertainty

In this study, the sources of uncertainty are primarily related to emission factors and inputs, such as material amounts and electricity and water consumption, which could contribute to the output variable of the model significantly. Moreover, the uncertainty associated with the input data and the model structure adds to an overall uncertainty of LCA outputs. Generally, uncertainty sources come from occasional, epistemic, and other causes, which are listed in detail in Table 4.

Table 4. Different sources and induced factors that cause uncertainty in LCA for WPB dismantling treatments.

No.	Sources	Induced Factors
1	LCI data of electricity	Different percentages of renewable energy generation in the electricity grid will lead to different environmental impacts due to electricity use.
2	Emissions: including SO_2, NH_3, lead dust	Different emission standards and different proposal technologies will lead to different emissions.
3	Amounts of secondary products, including plastics, clapboard, etc.	Ingredients of WPBs in different models and the amounts used will affect the amounts of secondary products.
4	Amounts of sulfuric acid, sodium sulfate, and lead ingot being made	Different desulfurization and smelting processes will lead to different types of by-products. Due to the market acceptance of these kinds of by-products, the WPB treatment plant may choose to manufacture different types of by-products, which will lead to different environmental impacts.
5	Utilization rate of photovoltaic power	Photovoltaic power storage costs and convenience directly affect its utilization, which will lead to different environmental impacts.
6	Type and quantity of wastewater treatment chemicals	Different chemicals for wastewater treatment have different environmental impacts.
7	Diesel oil consumption	The transportation routes, power of the vehicle, and parameters of the vehicle, such as size and rated power, to collect WPB will affect the fuel consumption for WPB transportation.

4. Discussion

Results for dismantling treatment were compared with results for remelting treatment in the WPB plant with the purpose of probing different impact performances for different

WPB treatments. Referring to the previous literature [24] and GaBi data, the impact data of WPB dismantling treatment (the current work) and WPB remelting treatment were compared and are shown in Table 5.

Table 5. Comparison of the environmental impact of dismantling treatment and remelting treatment for disposal of WPB.

Midpoint	Dismantling	Remelting
ALOP	13.618	43.585
GWP	528.870	654.089
FDP	296.637	160.553
FETP	14.764	37.788
FEP	0.239	1.053
HTP	3133.760	4195.199
IRP	29.197	42.747
METP	12.253	35.228
MEP	0.615	1.479
MDP	15.573	717.858
NLTP	0.076	0.094
ODP	0.000	0.000
PMFP	1.089	4.029
POFP	1.740	4.854
TAP	2.173	14.431
TETP	0.075	0.075
ULOP	7.369	12.087
WDP	1.402	5.833

From Table 5, it can be seen that dismantling treatment has obvious advantages over remelting treatment in all eighteen indicators except FDP and TETP, which is probably attributed to the recovery and remanufacturing of some materials in integrated dismantling treatment. In addition, with dismantling treatment, there are significant savings in energy consumption and emissions. With the separation process, a large number of raw materials can be directly sold and used for material substitution. This greatly reduces the environmental effects of the whole process. For example, the recovery of plastics and clapboard replaces the primary production of those materials to offset the environmental burden. The manufacturing of sulfuric acid, sodium sulfate, ferrous oxide, and lead provides many credits for integrated dismantling treatment so that the impact assessment values appear much more advantageous in most impact categories, as shown in Figure 7.

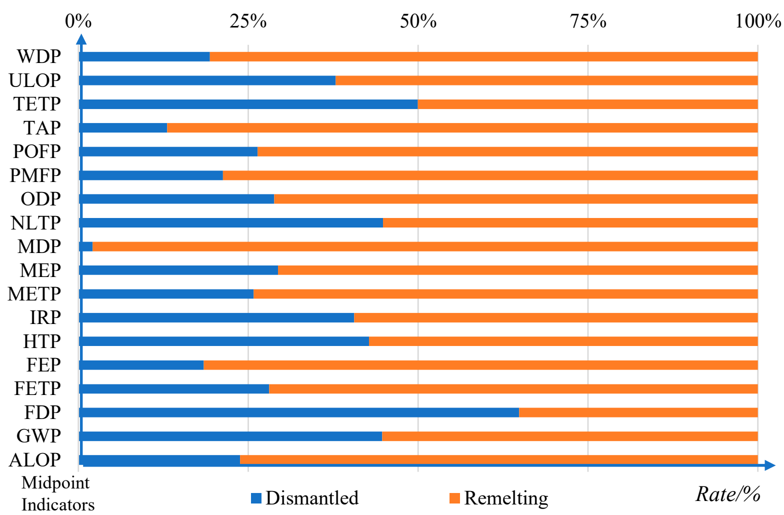


Figure 7. Comparison of the environmental impact of dismantling and remelting for the disposal of WPBs.

For FDP, dismantling treatment is obviously inferior to remelting. The high value of FDP may be due to the consumption of natural gas and diesel used in the crude lead-making, refining, and transportation processes. There is no advantage in integrated dismantling treatment on the TETP. The reason may be that in the use of both sulfuric acid and steam during the conversion process, the factory studied in this paper uses 359.6 kg of steam per one FU of WPBs in the preliminary desulfurization procedure.

Figure 7 also implies that dismantling treatment offers more environmental benefits than the traditional method of remelting. Compared to the average levels in existing literature, the dismantling mode shows much lower environmental effects in most midpoint indicators. This could also be attributed to the substitution of plastic and lead ingot.

5. Conclusions

The environmental performances of the dismantled WPB treatment factory were quantitatively evaluated for the purpose of revealing the sustainability of remanufacturing, which could provide some references for employing waste battery treatments. With operational data and interviews with managers in 2021, energy flows and material flows have been depicted for the studied treatment center. Applying LCA methodology, the environmental impact has been assessed for specific disposal procedures and processes, from which the following conclusive marks are derived:

Refining consumes the most electricity power (35.12%) and preliminary desulfurization consumes the largest amount of reclaimed water (68.50%) and tap water (66.49%).

Refining, crude lead-making, and preliminary desulfurization belong to the procedures with the greatest environmental effects due to electricity consumption; crude lead-making also consumes a high amount of natural gas. Wastewater treatment and dust removal and desulfurization are the largest contributors to parts of the midpoint indicators for the utilization of flocculant PAM, sodium hydroxide, and electricity and for the emissions of SO_2, NO_2 (NO_x), smoke, and lead dust. Transportation also has a large share of the value of some midpoint indicators, which might be due to the longer average distance from the WPB recycling points to the WPB treatment plant. Thus, using a new energy truck and transportation route optimization tends to be feasible and effective in alleviating the related environmental burden.

Lead, plastics, and sulfuric acid are the top three contributors to the environmental benefits of material substitutions.

Photovoltaic power usage could reduce the environmental burden in WPB dismantling treatments.

To promote an environment-friendly society, every consumer needs to have good environmental awareness. So, consumers should send their used waste batteries to the battery recycling point and must not discard these waste batteries casually. With the aim towards a factory operation business, because a lot of electricity is used in waste battery treatment, it is newly encouraged that reducing the use of grid power by increasing photovoltaic power, wind power, and natural gas usage can reduce environmental burdens to a larger extent.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr11072119/s1, Figure S1: An aerial view of the selected WPBM center (marked by the red box) in the city of Horqin Left Rear Banner, Inner Mongolia Province, China, taken by Google Map. * The red dots represent the waste battery recycling points; Table S1: Data and assumptions for modeling the processes in the Fragmentized Separation procedure; Table S2: Data and assumptions for modeling the processes of the subsequent procedures after separation; Table S3: Wastes generated from the disposal of one FU of WPB; Table S4: Emissions generated from the disposal of one FU of WPB; Table S5: Data and assumptions for modeling the processes in the waste disposal procedures; Table S6: Electricity, natural gas and water consumption in the disposal of one FU of WPB; Table S7: Secondary products derived from the disposal of one FU of the WPB; Table S8: Data and assumptions for the modeling of the avoided primary materials and energy; Table S9: Top three procedures and their contributions to the value of each midpoint category; Table S10: Top three procedures and their contributions to the value of each endpoint category.

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