Supporting Information

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.

Process	**Remarks, data and assumptions**
Dumping WPB into basin	Unloading the collected WPB from the transportation trucks and dumping it into a basin for temporary storage.
Extraction to processor	Grabbing up the WPB from the basin to a conveyor belt (for further processing) using grab hoppers with a power of 15 kW. The energy consumption of this extraction process was calculated to be 0.281 kWh per one FU of the WPB.
Mechanical drilling	The waste lead–acid battery is perforated by driller and the waste electrolyte is discharged.
Electrolyte poured out	The waste electrolyte is collected, purified, and its concentration adjusted before being introduced into the storage tank for sale.
Hydraulic	Cleaning the trucks, basin, and grab hoppers with pressurized spray water. The energy consumption of this washing process is mainly related to the use of water pump with a power of 25 kW; it was calculated to be 0.468 kWh per one FU of the WPB on the basis of the primary data.
Sorting	The reclaimed water consumption is 3377.7 kg in this washing process for disposing of one FU of the WPB. The reclaimed water is from the water recycling system in the wastewater treatment procedure. In addition, the tap water consumption is 30 kg in this washing process for flushing equipment.
Crushing	Carrying the WPB to the crushers using a conveyor belt. The energy consumption of this process mainly results from the use of two crushing and screen machines with a power of 75 kW, and the value was calculated to be 2.808 kWh per one FU of the WPB.
Differential Sorting	Separating the recyclable plastics and clapboards from the WPB using a differential sorting jig. For one FU of the WPB, 52 kg of recyclable plastics and 36 kg of recyclable clapboards can be obtained by this differential sorting process. The energy consumption of the differential sorting equipment with a power of 30 kW was calculated to be 0.562 kWh per one FU of the WPB.
Vibration sieving	Extracting lead block and grid energy by two eddy current separators with a power of 30 kW. For one FU of the WPB, 332 kg of lead block and grid energy can be acquired by this eddy current separation process. The energy consumption of the eddy current separators was calculated to be 1.123 kWh per one FU of the WPB.
Sedimentation in tank	Separating lead pastes (mainly lead sulfate, lead oxide, lead) from the wastewater. For one FU of the WPB, 330 kg of lead pastes are separated. The energy consumption of the filter press system with a power of 25 kW was calculated to be 0.468 kWh per one FU of the WPB.

Note:
1. The data was aggregated by merging the records from the plant's information systems and the interviews of the managing director.
2. The Gabi dataset "*CN: Electricity grid mix ts*" was used to evaluate the environmental impacts due to electricity use.

Table S2. Data and assumptions for modeling the processes of the subsequent procedures after separation.

Procedure	Process	Remarks, datasets and assumptions
Recycling（Plastics & Clapboard）	Washing and Drying	Shredding the recyclable plastic scraps into smaller pieces (below 20 mm) using two shredders, and then the scraps are washed with reclaimed water. The process consumes 130 kg of reclaimed water, resulting in 5.293 kg of wastewater. The Gabi dataset "Shredding" was used to denote the shredding activities. The energy consumption of the shredders was calculated to be 0.936 kWh per one FU of the WPB; in this case, 52 kg of recyclable plastic scraps and 36 kg of recyclable clapboard were gained. The Gabi dataset "Washing (plastic recycling) ts" was used. The energy consumption of the washing machine was calculated to be 0.468 kWh per one FU of WPB. Removing the moisture content from the shredded plastic pieces and clapboard using a hot air dryer with a power of 25 kW; vapor is fully reclaimed using fume extractors. The energy consumption of the hot air dryer was calculated to be 0.468 kWh per one FU of WPB. The Gabi dataset "CN: Electricity grid mix ts" was used assess the environmental impacts of electricity usage.
	Pelletizing	Processing the plastic pieces using a twin-screw extruder; around 5 g of non-methane hydrocarbon is generated during extruding the plastic content in one FU of the WPB. The Gabi dataset "GLO Plastic extrusion profile (unspecific)" was used. The energy consumption of the extruders was calculated to be 1.872 kWh per one FU of WPB. Granulation of the extruded plastic strands using a pelletizer with a power of 10 kW. The energy consumption was calculated to be 0.187 kWh per one FU of the WPB, and the Gabi dataset "Granulator" was used.
	Packing	Packing up the plastic pellets in bags of 25 kg using a packing machine with a power of 10 kW. For one FU of the WPB, 52 kg of plastic and 36 kg of clapboard pellets are packed. The energy consumption of the packing machine was calculated to be 0.187 kWh to dispose one FU of WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.
Waste Electrolyte Treatment	Collection	Collecting 244.933 kg of waste electrolyte and 5.067 kg of leachate and putting in the acid storage pit.
	Neutralization	Putting 5 kg of sodium hydroxide into the acid storage pit for neutralization.
	Purification	The main components of the waste electrolyte are sulfuric acid and lead sulfate. Purified diluted sulfuric acid solution is produced using membrane concentration and purification equipment with a power of 100 kW. As a result, 95.733 kg of sulfuric acid and 8.875 kg of sodium sulfate are produced. After purification, the supernatant is reused to clean the plastic shell and the sludge is put into a smelting furnace for crude lead-making after the filter press. The energy consumption in the Waste Electrolyte Treatment was calculated to be 1.872 kWh per one FU of the WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.
	Adjust density	Adjusting the concentration as needed and selling it as a pickling agent. The process results in 150.392 kg of wastewater. The sodium sulfate liquid is returned to the sodium sulfate crystallization cooling tower of the preliminary desulfurization procedure.
Preliminary Desulfurization	Filtration and Pressurization	Pressing the lead pastes and filter lead sludge. Mixing the materials including 330 kg of lead pastes and 65.667 kg of sodium carbonate with reclaimed water for 2–3 minutes in a mixer, making the solids well distributed in the sludge. The materials are stirred for the low-temperature

		desulfurization reaction. Sodium carbonate is purchased from suppliers, lead pastes are acquired from the separation procedure and lead sludge is acquired from the wastewater treatment procedure. The process generates 308.18 kg of desulfurized lead paste and 87.487 kg of sodium sulfate. The energy consumption of the two filter press systems with a power of 25 kW was calculated to be 0.936 kWh per one FU of WPB. The energy consumption of the filtration and purification system with a power of 12.5 kW was calculated to be 0.234 kWh per one FU of WPB. The energy consumption of the reactor system with a power of 100 kW was calculated to be 1.872 kWh per one FU of WPB. The following chemical reactions take place in the reaction system: $Na_2CO_3 + PbSO_4 \rightarrow Na_2SO_4 + PbCO_3 \downarrow$ The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.
	Evaporative Crystallization	The process generates 96.362 kg of sodium sulfate in the crystallization system for sale, including 8.875 kg sodium sulfate from waste electrolyte treatment procedure and 87.487 kg of sodium sulfate from filtration and pressurization process. The reclaimed water consumption is 19280 kg in this process for disposing one FU of the WPB. The reclaimed water is from the water recycling system in the wastewater treatment procedure. In addition, the tap water consumption is 359.6 kg for water vapor. The energy consumption of the crystallizer with a power of 33 kW was calculated to be 0.618 kWh per one FU of WPB. The energy consumption of the drying system with a power of 65 kW was calculated to be 1.217 kWh per one FU of WPB. The energy consumption of the filling system with a power of 30 kW was calculated to be 0.562 kWh per one FU of WPB. In addition, the energy consumption of the process also was calculated to be10^6 kJ per one FU of WPB for 359.6 kg of steam produced by the boiler system. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage. The Gabi dataset "*CN: Steam ts*" was used to assess the environmental impacts of electricity usage.
	Centrifugation	The process generates 18790 kg of reclaimed water and 849.6 kg of wastewater. The energy consumption of centrifugation with a power of 60 kW was calculated to be 1.124 kWh per one FU of WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.
Crude Lead Making	Feeding	Putting 308.18 kg of desulfurized lead paste coming from the Preliminary Desulfurization procedure and 1.609 kg of lead mud acquired from the Wastewater Treatment procedure into an oxygen-enriched side blown furnace, and then adding reducing agent 21 kg of coke powder and 57 kg of iron filings. In addition, 4.39 kg of reclaimed lead smock and 0.04 kg of lead dust from the Dust Removal and Desulfurization procedure. The energy consumption of the equipment with a power of 30 kW was calculated to be **0.562 kWh** per one FU of WPB. The Gabi dataset *"CN: Electricity grid mix ts"* was used to assess the environmental impacts of electricity usage.
	Heat up for melting	Six oxygen-enriched side blown furnaces with a power of 26.25 kW each are used to melt these materials. The melting temperature is 950 °C.The furnace uses natural gas as fuel. The natural gas consumption is calculated to be 85 m^3, equivalent to 60.979 kg per one FU of WPB where the density of natural gas is assumed to be 0.717 kg/m^3. The energy consumption of this process was calculated to be **2.948 kWh** per one FU of WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.

	Smelting	The production cycle is about 6 hours. During this period the following chemical reactions take place in this process: $2PbO + C \xrightarrow{\Delta} 2Pb + CO_2 \uparrow$ $PbO_2 + C \xrightarrow{\Delta} Pb + CO_2 \uparrow$ $PbCO_3 \xrightarrow{\Delta} PbO + CO_2 \uparrow$ $PbO + Fe \xrightarrow{\Delta} Pb + FeO$ The smelting process needs three gas holding furnaces whose fuel is natural gas. The natural gas consumption was calculated to be 2 m^3, equivalent to 1.435 kg per one FU of WPB where the density of natural gas is assumed to be 0.717 kg/m^3. Both oxygen-enriched side blown furnaces and gas holding furnaces provide thermal energy with oxygen-enriched burning. The oxygen consumption was calculated to be 15030 km^3, equivalent to 143.186 kg per one FU of WPB. The energy consumption of three gas holding furnaces with a power of 15 kW was calculated to be **0.842 kWh** per one FU of WPB. For one FU of WPB, 261.64 kg of crude lead, 89.572 kg of ferrous oxide, 126.838 kg of smelting slag and 3.638 kg of lead smock and dust are generated. The main ingredients of lead smock and dust are SO_2, NO_2, lead dust, and lead smock, which are collected and sent to the Dust Removal and Desulfurization procedure for disposal further. The smelting slag is poisonous waste, and its components are lead, iron sulfide, and calcium oxide. The slags are sent to a qualified unit for disposal further.
	Unwind	The unwind process has two lead dust purification systems with a power of 20 kW each. The energy consumption of this process was calculated to be 0.749 kWh per one FU of WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.
Refining	Impurity removal	First, crude lead melting is carried out to remove copper. Then, 261.64 kg of crude lead from the Crude Lead Making procedure and 332 kg of lead block and grid energy are put into eight gas refining furnaces for further refinement. The gas refining furnaces consume natural gas. The natural gas consumption was calculated to be **75 m^3**, equivalent to **53.805 kg** per one FU of WPB where the density of natural gas is assumed to be 0.717 kg/m^3. Then, the sulfur addition method is carried out to remove copper. Adding 0.127 kg of sulfur to the lead solution generates lead sulfide, and the lead in the lead sulfide is quickly replaced by copper to produce cuprous sulfide. Cuprous sulfide is insoluble in lead at operating temperature, and its density is small. It floats on the surface of lead liquid as a solid, and forms sulfide slag and is removed. For impurity elements such as Sb, Sn, As, etc., the temperature of the lead liquid in the refining pot is controlled within a certain range, and 6.97 kg of sodium nitrate ($NaNO_3$) and 5 kg of sodium hydroxide (NaOH) are added to oxidize the impurities in the lead solution, and the resulting slag phase is separated from the lead, thereby removing impurities such as Sb, Sn, As, etc. The following chemical reactions take place in this process: $Pb + S \xrightarrow{\Delta} PbS$ $PbS + Cu \xrightarrow{\Delta} Pb + CuS$ $Sb + NaOH + NaNO_3 \xrightarrow{\Delta} Na_2SbO_3 + NO_2 \uparrow + H_2O \uparrow$ $Sn + NaOH + NaNO_3 \xrightarrow{\Delta} Na_2SnO_3 + NO_2 \uparrow + H_2O \uparrow$ $As + NaOH + NaNO_3 \xrightarrow{\Delta} NaAs_2O_4 + NO_2 \uparrow + H_2O \uparrow$
	Alloying	According to the specifications of the product, the impurity elements in the crude lead can be selectively removed (Sb, Sn, Cu, S, Ca, Al, etc.)

Casting	and other elements are added according to the alloy standards, and the alloy elements such as calcium, selenium, antimony, and tin are adjusted to generate lead alloy required by customers. The process generates 541.33 kg of lead ingot for sale for one FU of WPB, which consumes 4160 kg of reclaimed water for casting and cooling, and generates 4000 kg of reclaimed water and 160 kg of wastewater. In addition, 63.243 kg of refining slag and 1.164 kg of lead smock and dust are generated. The main ingredients of lead smock and dust are SO_2, NO_2, lead dust, and lead smock, which are collected and sent to the Dust Removal and Desulfurization procedure for further disposal. The refining slag is poisonous waste, and its components have lead and copper sulfide. The slags are sent to a qualified unit for further disposal. The lead casting process needs two ingot casting machines with a power of 350 kW each. The energy consumption of this process was calculated to be **13.104 kWh** per one FU of WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.

Table S3. Wastes generated from the disposal of one FU of WPB.

Waste	Quantity [kg]
Slag	190.081
Lead Dust	0.678
Sodium Salt	0.530
SS	1.983
Smoke	0.044

Table S4. Emissions generated from the disposal of one FU of WPB.

Emission	Quantity [g]
SO_2	208
NO_2（NO_x）	114
NH_3	1.49
COD	2
CO_2	53720
NH_3-N	0.20
Non-methane hydrocarbon	5

Table S5. Data and assumptions for modeling the processes in the waste disposal procedures.

Procedure	Process	Remarks, datasets and assumptions
Wastewater Treatment	Reclaimed water recycling	Reclaimed water from separation, preliminary desulfurization, etc., is treated in the reclaimed water recycling system. The circulating water system needs to add 151.2 kg of tap water for one FU of WPB. The energy consumption of the reclaimed water recycling system with a power of 50 kW was calculated to be **0.936 kWh** per one FU of WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.
	Neutralization	For wastewater from separation and other disposal procedures, 2.837 kg of sodium hydroxide (NaOH) and 1.914 kg of flocculant PAM are put into wastewater for the neutralization reaction and to condition the wastewater in regulating tanks.
	Precipitation	After the precipitation process, the wastewater enters a coagulation sedimentation tank, with 1.609 kg of sludge paste filtered and removed. From this, 28838.933 kg of reclaimed water is acquired The energy consumption of the two pumps with a power of 12.5 kW each was calculated to be **0.468 kWh** per one FU of WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.
Dust Removal and Desulfurization	Dust removal	This process uses a workshop dust-containing exhaust gas collection system with a power of 33 kW and a flue gas dust removal system with a power of 55 kW. Dust is collected into a bag filter, with a dust removal efficiency over 98%. The minimum trapped particle size is less than 0.1 μm. The energy consumption of the dust extraction process was calculated to be **1.648 kWh** per one FU of WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage. The Gabi dataset "*Dust*" was used to assess the environmental impacts. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage.
	Desulfurization in tower	After bag dust removal and desulfurization in the desulfurization tower, it is discharged into the air through a 50 m exhaust pipe. The main equipment involved in this process is an exhaust gas treatment system with a power of 30 kW, a desulfurization filtration purification system with a power of 12.5 kW, and an air compressor with a power of 22 kW. The energy consumption of the process was calculated to be **1.207 kWh** per one FU of WPB. The Gabi dataset "*CN: Electricity grid mix ts*" was used to assess the environmental impacts of electricity usage. The Gabi dataset "*Dust*" was used to assess the environmental impacts.

Table S6. Electricity, natural gas and water consumption in the disposal of one FU of WPB.

Procedure	Electricity consumption [kWh]	Natural gas consumption [m^3]	Water consumption [kg]	
			Tap water	Reclaimed water
Fragmentized Separation	**5.710**	0	30	3,377.7
Recycling (plastics and clapboard)	4.118	0	0	130.0
Waste Electrolyte Treatment	1.872	0	0	0
Preliminary Desulfurization	6.561	0	359.6	19,280.0
Crude Lead Making	5.101	87	0	0
Refining	13.104	75	0	4,160.0

Dust Removal and Desulfurization	2.855	0	0	1,200.0
Wastewater Treatment	1.404	0	151.2	0

Table S7. Secondary products derived from the disposal of one FU of the WPB.

Product	Quantity [kg]
Sulfuric Acid	95.73
Sodium Sulfate	96.36
Recycled plastics	51.96
Recycled clapboards	36.00
Ferrous Oxide	89.57
Lead Ingot	541.33

Table S8. Data and assumptions for the modeling of the avoided primary materials and energy.

	Primary Product	Dataset	Source
Lead Ingot	Primary Pb	"*GLO electrolytic refining of primary lead*"	EI
Plastics	Primary PC	"*Polypropylene granulate (PC) mix*"	Gabi
	Primary HDPE	"*Polyethylene High Density Granulate (HDPE/PE-HD) Mix*"	Gabi
	Primary ABS	"*Acrylonitrile butadiene styrene (ABS)*"	Gabi
Sulfuric Acid	Primary Sulfuric Acid	*"CN: Sulfuric Acid"*	Gabi
Sodium Sulfate	Primary Sodium Sulfate	*"CN: Sulfuric Sulfate"*	Gabi
Clapboards	Primary Paper	"*RER kraft paper production, unbleached*"	EI
Ferrous Oxide	Primary Ferrous Oxide	*"CN: Ferrous Oxide"*	Gabi

Table S9. Top three procedures and their contributions to the value of each midpoint category.

Category	1st Procedure	2nd Procedure	3rd Procedure
ALOP	Preliminary Desulfurization (55.43%)	Crude Lead Making (27.23%)	Refining (9.77%)
GWP	Crude Lead Making (54.18%)	Refining (17.90%)	Preliminary Desulfurization (17.05%)
FDP	Crude Lead Making (53.41%)	Refining (31.26%)	Preliminary Desulfurization (8.60%)
FETP	Crude Lead Making (58.83%)	Refining (28.14%)	Preliminary Desulfurization (8.63%)
FEP	Crude Lead Making (65.59%)	Refining (16.10%)	Preliminary Desulfurization (13.13%)
HTP	Crude Lead Making (65.51%)	Refining (32.14%)	Preliminary Desulfurization (1.35%)
IRP	Crude Lead Making (63.78%)	Preliminary Desulfurization (12.51%)	Refining (10.47%)
METP	Crude Lead Making (59.58%)	Refining (26.05%)	Preliminary Desulfurization (8.71%)
MEP	Crude Lead Making (35.88%)	Refining (25.26%)	Preliminary Desulfurization (15.06%)
MDP	Preliminary Desulfurization (38.69%)	Refining (25.72%)	Crude Lead Making (23.72%)
NLTP	Crude Lead Making (42.89%)	Refining (22.51%)	Preliminary Desulfurization (17.23%)
ODP	Crude Lead Making (35.03%)	Refining (20.77%)	Preliminary Desulfurization (15.21%)

PMFP	Crude Lead Making (56.98%)	Preliminary Desulfurization (17.01%)	Refining (12.32%)
POFP	Crude Lead Making (51.96%)	Refining (15.77%)	Preliminary Desulfurization (14.18%)
TAP	Crude Lead Making (43.59%)	Preliminary Desulfurization (26.52%)	Refining (16.64%)
TETP	Crude Lead Making (36.08%)	Refining (25.84%)	Transportation (22.26%)
ULOP	Crude Lead Making (37.99%)	Transportation(34.72%)	Preliminary Desulfurization (11.87%)
WDP	Crude Lead Making (54.00%)	Wastewater Treatment(14.93%)	Preliminary Desulfurization (11.95%)

Table S10. Top three procedures and their contributions to the value of each endpoint category.

Category	1st Procedure	2nd Procedure	3rd Procedure
EQ	Crude Lead Making (47.39%)	Preliminary Desulfurization (20.48%)	Refining (19.16%)
HH	Crude Lead Making (61.23%)	Refining (27.74%)	Preliminary Desulfurization (6.75%)
RE	Crude Lead Making (52.86%)	Refining (31.09%)	Preliminary Desulfurization (9.21%)
Total	Crude Lead Making (57.20%)	Refining (28.10%)	Preliminary Desulfurization (8.79%)