H2020 Work Programme "Smart, green and integrated transport"
GV-06-2017 – Physical integration of hybrid and electric vehicle batteries at pack level aiming at increased energy density and efficiency

D7.4 - Comparative study and calculation tool for EV battery recycling processes

Lead Contractor: Accurec Recycling GmbH

Author(s): Zhangqi Wang

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This report includes comparative study of the state-of-the-art lithium-ion battery recycling technology by Accurec (ACC). Based on the collected data, a smart calculation tool for EV battery recycling process has been developed.

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Document History

Date	Version	Name	Changes
24-03-2020	1	ZW (ACC)	Version 1
09-04-2020	2	BP (RSC)	Revision version 1
17-04-2020	3	ZW (ACC)	Version 2
03-06-2020	4	IC (CID)	Final review: minor text formatting

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1 Introduction

The main objectives of WP7 are to qualify the developed batteries in a regulatory and environmental way and to develop specific and optimized recycling and/or reuse processes for the battery production aimed to electric vehicles.

All the different materials/components to be used in WP2, WP3, WP4 and WP5 will be assessed through their safety, environmental friendliness, sustainability and eco-efficient performances. Eco design analysis will be also performed to keep the environment key parameters under control following ISO Standard. This will be traduced into three main parts which are regulatory assessment, environmental impact assessment and recycle/reuse analysis.

This Work Package has the following aims:

- Technical, economic and environmental optimization of the product (eco-design)
- Define an industrially optimized recycling process for the whole battery module.
- Evaluate the possible reutilization of the different battery components for further uses

Ref. Task 7.3: Battery pack recycling study

Task Leader: ACC

Involved partners: RSC

Once it is defined which raw materials, components and manufacturing processes are most suitable and sustainable for the project, the recycling of all different components has to be addressed. Thus, the state-of-the-art battery recycling technology (from dismantling to cell recycling) will be reviewed in terms of costs, materials and energy efficiency and environmental impacts for each process step. These steps can include different pyro- or hydrometallurgical (pyrolysis, leaching) approaches, as well as mechanical processing (crushing, sieving). In that way, main cost drivers will be identified and evaluated using a sensitivity analysis.

The material output of each recycling process step will be analyzed and possible outlets evaluated to enhance the economic effectiveness. All collected data will be summarized in an extendable database, which can be used for setting up a software calculation tool for deriving the best combination of recycling process steps for EV batteries (in terms of costs, efficiency, footprint) based on the input material.

A smart recycling calculation tool will be developed based on all collected data for the iModBatt battery pack.

2 Work performed

2.1 Comparative study of the state-of-the-art recycling technology

ACC has firstly carried out a comparative study of the state-of-the-art recycling technologies. The industry available recycling processes were reviewed with respect to their process costs, environmental impacts, materials and energy consumptions etc.

2.2 Calculation tool for EV battery recycling

After that, ACC devoted to developing a smart calculation tool for EV battery recycling. The collected and reviewed data were summarized and integrated into a smart calculation tool, which is able to simulate the recycling process of iModBatt battery pack. Detailed material flow in recycling process can be explained by the calculation tool.

3 Results and discussion

3.1 Comparative study of the state-of-the-art recycling technology

The lithium-ion battery is a highly assembled system which stores or releases specific amount electric energy during charging or discharging. As Figure 1 shows, the structure of a lithium-ion battery is very complex. A lithium-ion battery is composed of several components which are described in detail in Figure 1. During manufacture process, all these components are assembled into a limited volume. However, as a recycler, the objective is to separate and refine these components for secondary use.

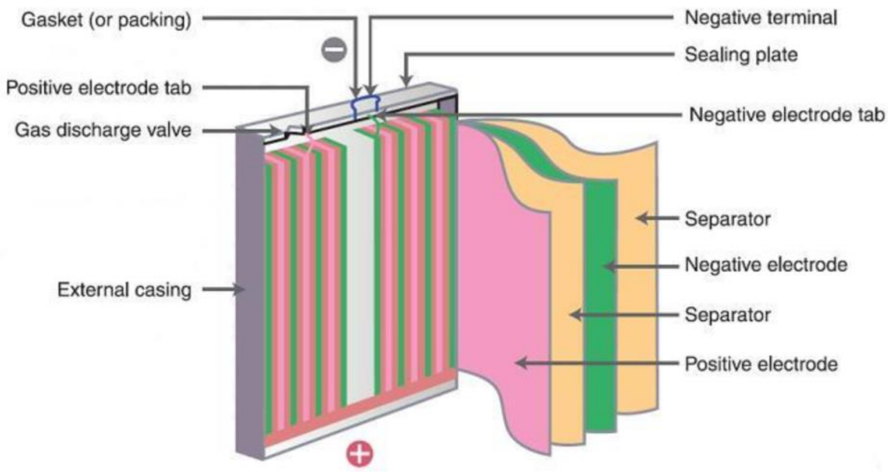


Figure 1 Basic structure of the single cell of lithium-ion battery [1]

Although it is estimated that hundreds of thousand tons of electric vehicle batteries are needed to be recycled in the near future, the number of recycling facilities is still limited worldwide, and the recycling industry is still developing. A brief overview of current recycling facilities globally is listed in Table 1 according to our internal data. The details of the recycling processes will be discussed later. As seen in Table 1, the treatment capacity and recycling processes are different at different companies. The companies are ranked by their (estimated) treated capacities in Table 1. Only 6 companies treat end-of-life lithium-ion batteries at industrial scale (over 800 tons/year) and other companies only have pilot-scale capacity. Regarding recycling techniques, the choices are diverse with different technical requirements, safety risks, and final products etc. Regarding products, these companies are classified into two groups. The 1st group only conducts pretreatment and separate several components of a battery (with blue background) and the 2nd group perform pyro/hydrometallurgy, extracting and refining chemical elements like cobalt, nickel. Regarding recycling efficiency and technical requirement, recycling processes can be classified into several paths. The details will be discussed below.

Table 1 lithium-ion battery recycling facilities worldwide

	Company	Country	Scale	Process applied	Estimated capacity tons/year	Announced capacity tons/year
1	SungEel	Korea	industrial	Mechanical pretreatment + pyrometallurgy + hydrometallurgy	6000	N/A
2	UMICORE	Belgium	industrial	Pyrometallurgy + hydrometallurgy	4000	7000
3	ACCUREC	Germany	industrial	Pretreatment: thermal + mechanical	2000	3000
4	BRUNP	China	industrial	Mechanical pretreatment + hydrometallurgy	1000*	10000
5	GEM	China	industrial	Mechanical pretreatment + hydrometallurgy+chemical synthesis	1000*	30000
6	Nickelhütte Aue	Germany	industrial	Pyrometallurgy + hydrometallurgy	800**	1000
7	RECUPYL	France	pilot	Pretreatment: mechanical, Inert N_2 shredding	650**	800
8	JX Nippon	Japan	pilot	Thermal +mechanical pretreatment + pyrometallurgy + hydrometallurgy	500*	5000
9	EDI	France	pilot	Pretreatment: mechanical	500**	N/A
10	Retrieve	US	pilot	Pretreatment: aqueous-mechanical	300**	N/A
11	SNAM	France	pilot	Pretreatment: thermal	300**	N/A
12	AkkuSer	Finland	pilot	Pretreatment: mechanical	100**	N/A
13	Sony & Sumitomo	Japan	pilot	Thermal pretreatment +pyrometallurgy + hydrometallurgy	150**	N/A
14	Glencore	Canada	industrial	Pyrometallurgy + hydrometallurgy	0	N/A
15	Batrec	Switzerland	pilot	Pretreatment: mechanical	0	N/A

*: facility mainly recycle E-waste and capacity of end-of-life batteries estimated.

**: insufficient information, capacity estimated.

N/A: information not available

Glencore and Batrec have stopped their activities due to safety reasons.

In the 1st group, companies like Accurec, Recupyl, Retrieve, SNAM, AkkuSer, EDI conduct only pretreatment without further metallurgical treatment. Companies in 2nd group have either pyrometallurgy and/or hydrometallurgy processes. The company with the largest treatment capacity in 1st group is Accurec, whose recycling processes will be discussed in detail.

Accurec Recycling GmbH is a battery recycling company founded in Mülheim an der Ruhr, Germany in 1995. In the beginning, Accurec was dedicated to recycle Ni-Cd batteries. From 2007-2018, Accurec has intensively engaged in research activities regarding lithium-ion battery recycling. In 2016, a lithium-ion battery recycling plant was established in Krefeld. With completion of recycling process chain and expansion of capacities, Accurec is a continuously growing company. In 2018, Accurec has treated around 2500 tons of lithium-ion batteries and its capacity is expected to grow in the future.

Accurec's recycling process of lithium-ion batteries consists in thermal pretreatment and subsequent mechanical pretreatment. In this process, Accurec applies in the first step a thermal pretreatment furnace, specifically rotary kiln furnace, to crack and pyrolyze organic components at temperature of maximum 600 °C. This thermal pretreatment can also deactivate lithium-ion batteries independent on the state of charge. Off-gases are washed and cleaned under alkaline environment; only clean air is emitted into the atmosphere. Thereafter, organic-free materials are shredded in atmosphere by a rotating roll crusher into small pieces. A mixture of steel, copper, aluminum pieces with larger particle size and electrode powder with small particle size are obtained after crushing. In the end, the mixture is separated mechanically via screening and magnetic separation. The final products from Accurec are active mass, ferrous metal (steel casing) and non-ferrous metal (copper, aluminum). The active mass is sold to other companies for further metallurgical treatment, recovering metals.

Other company in the 1st group has similar recycling process. The key point of pretreatment is to deactivate battery and separate different components which can be sold as products. Thus, deactivating end-of-life lithium-ion battery in a safe process is essential for pretreatment, since the batteries still contain residual energy, which could cause severe fire incident. Unlike other batteries, lithium-ion batteries often blow up during the recycling process due to radical oxidation when lithium metal produced from battery overcharge sustains a mechanical shock from exposure to the air. Companies like RECUPYL and Retrieve use Inert gas shredding or aqueous mechanical separation technology to avoid battery being contacted to oxygen or air. SNAM uses thermal pretreatment to deactivate lithium-ion batteries which is similar to Accurec's process. Other companies like AkkuSer and EDI use rather a simple way to deactivate batteries. Although lots of efforts are made to ensure a safety process during recycling, fire incident still happened. As a result, some companies like Betrec and Glencore have to stop their activities due to accidents.

In 2nd group, companies usually have larger capacity/scale and the recycling process extents to the deep recovery of metals from end-of-life lithium-ion batteries. Those companies are Umicore, Brunp, GEM, JX Nippon, Nickelhütte Aue, SungEel, Sony & Sumitomo. Here Umicore's process will be discussed in detail since it has the largest capacity in Europe.

Umicore N.V. is a multinational material processing group headquartered in Brussels, Belgium. The company was merged by four companies in the mining and smelting industries in 1989. Unlike Accurec, Umicore has relative wide business divisions, including Energy Materials, Recycling, Catalysis, and Performance Materials. Although lithium-ion battery recycling is only a small part of Umicore's main business, in 2011, a new recycling plant with a capacity of 7000 ton/year was established in Hoboken, dedicating lithium-ion and nickel–metal hydride battery recycling.

The recycling process is mainly a smelter, where lithium-ion (and NiMH) batteries are directly fed into a smelting furnace (see Figure 2). Here, the state of charge of the battery is not important since everything is melted at high temperature. Batteries and additives of slag formers, coke and limestone are fed into the smelting furnace. The smelter generates following output fractions:

• Off-gas emission

• Slag: containing Al, Li, Mn, rare earth elements from NiMH, etc.

• Metal alloy: containing Cu, Co, Ni

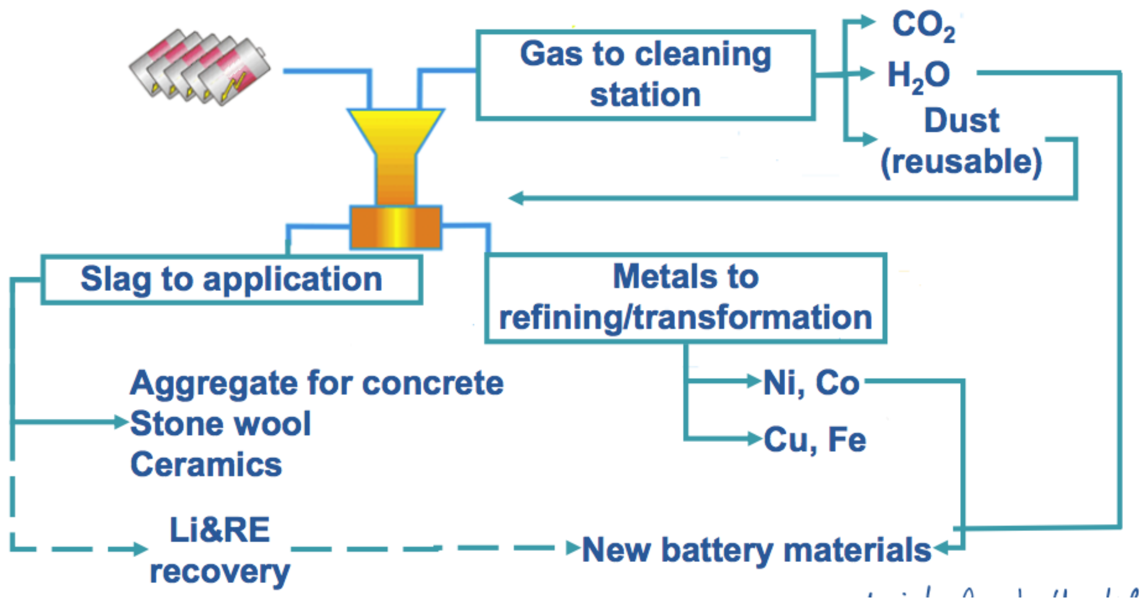


Figure 2 Flow chart of lithium-ion & NiMH battery recycling process at Umicore [2]

More details about the smelting process are described here. Based on the reactions occurring as a result of the gradual temperature increase in the process, the smelter can be divided into three zones [3]:

1) In the upper zone, the batteries are heated by hot gases rising through the furnace. The temperature of batteries in this zone typically remains under 300°C which allows the electrolyte to be slowly evaporated.

2) Batteries are then transferred downwards in the furnace until they reach the so-called plastic pyrolysis zone. In this zone, the temperature can be as high as 700°C, allowing plastics to be removed from battery packs. The heat energy released from this step contributes to heating the gases which subsequently rise towards the upper zone.

3) In the lower zone, smelting and reduction of the remaining material take place. The materials are transformed into two fractions: slag and alloy. The slag is mainly composed of oxide compounds containing a light-weighted element such as aluminum, silicon, calcium and to some extent iron. Lithium also ends up in the slag fraction in the form of lithium oxide. The slag can be used for construction or concrete industry. The alloy fraction is composed predominantly of heavy metal such as iron, copper, cobalt, and nickel. The temperature of the recovered alloy fraction is between 1200°C and 1450°C upon extraction from the furnace.

The organics as well as carbon, which account for around 30 wt.% of a battery, are used as combustible compounds and a reducing agent for metal oxides. It is said that the energy released during these reduction reactions provides sufficient energy to heat up the smelter. A gas cleaning system captures or discomposes volatile organic compounds (VOC's) and dioxins in the off gas.

A metallic alloy with a high concentration of copper, cobalt, and nickel is yielded, after the smelting process [4]. The metal alloy is then granulated and further refined in a hydrometallurgical process which is carried out in another Umicore's facility in Olen [5]. There, precious metal e.g., copper, cobalt, nickel is recovered by progressively hydrometallurgy method. The detail of this hydrometallurgical process is summarized by a Japanese thesis [6] as Figure 3 shows.

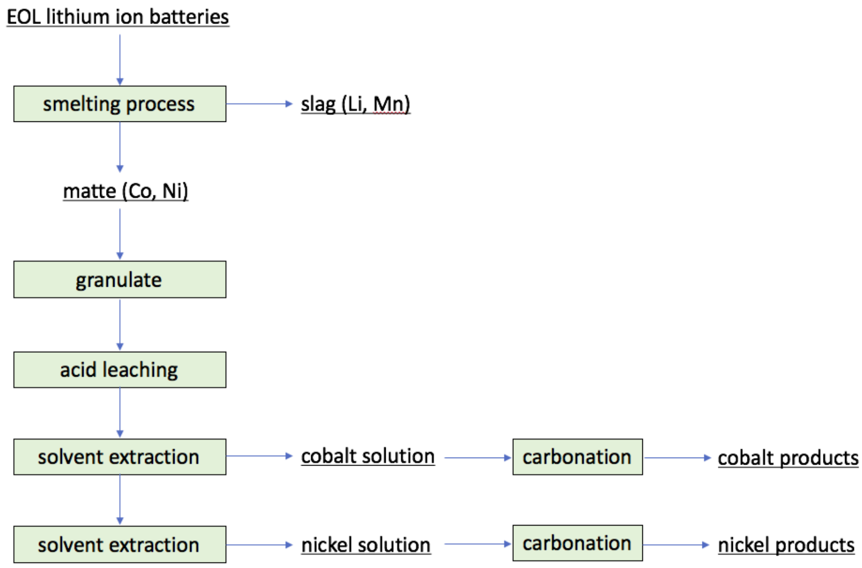


Figure 3 Recycling process of waste lithium-ion battery (Umicore Co.)

In the end, final products such as nickel/cobalt hydroxide, lithium metal oxide are shipped to Asian countries like China, Japan, and Korea where most of the lithium-ion batteries are manufactured, in order to close the loop for copper, nickel, and cobalt. The smelting facility in Hoboken has a designed capacity of 7000 t/a, but exact capability of annual treated end-of-life battery tonnages is estimated to be around 3000-4000 t/a.

Except Nickelhütte Aue, all other companies in the 2nd group have thermal or mechanical pretreatment before their pyro/hydrometallurgy processes. The disadvantage of the process without pretreatment is that steel, aluminum, and copper also have to be melted even they are in metallic state and can be separate before pyrometallurgy. As a result, these components are melted and mixed with precious metals from the cathode and considered as an impurity. Unlike Umicore, SungEel and JX Nippon both use thermal or mechanical pretreatment to deactivate end-of-life batteries and extract active mass. During pretreatment, steel casing, copper, and aluminum current collector are separated, leaving mainly cathode material and graphite in the active mass. The subsequent hydrometallurgy process includes acid leaching and solvent extraction, which is similar to Umicore's process. The main difference between Umicore and SungEel/JX Nippon is that some components like steel, aluminum, and copper are extracted before pyro/hydrometallurgy process. As a result, the lithium concentration in slag fraction from SungEel and JX Nippon after pyrometallurgy is higher, while iron concentration in matte is lower than that from Umicore's process.

As seen in Table 1, although different companies have different recycling processes, the principle of each recycling process step is similar. The available process steps are limited to thermal pretreatment, mechanical pretreatment, pyrometallurgy and hydrometallurgy. Considering that the products from 1st group will be further treated by pyrometallurgy and hydrometallurgy process, here, we propose four possible recycling routes as Figure 4 shows. It should be mentioned here the proposed four recycling routes cannot represent all possible recycling routes, but those process have the most possibility to be qualified in industrial scale.

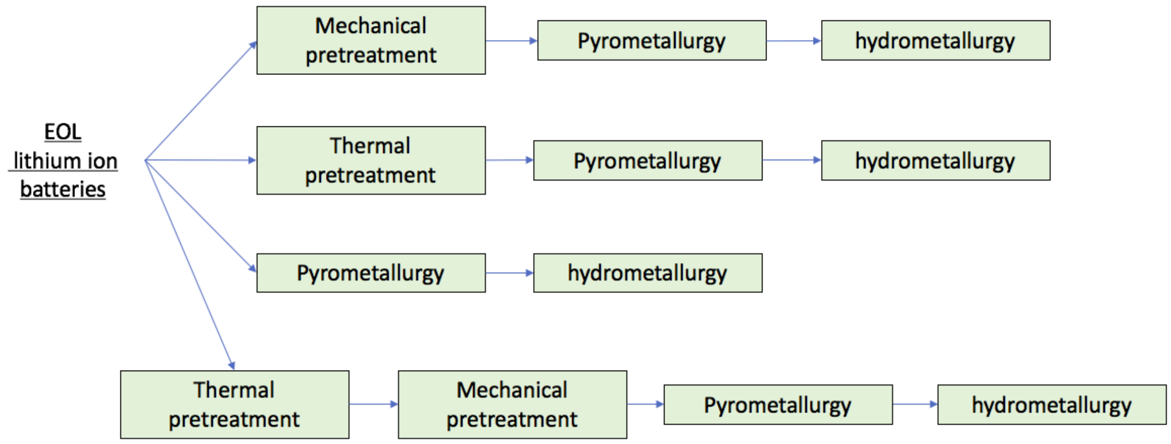


Figure 4 possible recycling processes for end-of-life lithium ion batteries

Route 1: end-of-life lithium-ion batteries undergo mechanical pretreatment with N_2 inert gas or aqueous environment, separating steel, copper, aluminum and active mass. Off-gas needs to be treated before emitting into the atmosphere. The separated active mass gets through pyrometallurgy, obtaining slag and matte. The matte experiences hydrometallurgy process to recover metals such as cobalt and nickel.

Route 2: end-of-life lithium-ion batteries undergo thermal pretreatment, removing plastic and organic impurities. The deactivated batteries get through pyrometallurgy, obtaining slag and matte. The matte experiences hydrometallurgy process to recover metals such as cobalt and nickel.

Route 3: end-of-life lithium-ion batteries are directly put in a furnace, experiencing pyrometallurgy process, resulting slag and matte material. The matte undergoes hydrometallurgy process to recover metals such as cobalt and nickel.

Route 4: end-of-life lithium-ion batteries undergo first thermal pretreatment to be deactivated then get through mechanical pretreatment, separating steel, copper, aluminum and active mass. After that, the separated active mass is getting though pyrometallurgy process, resulting in a slag and matte material. The matte undergoes hydrometallurgy process to recover metals such as cobalt and nickel.

The main differences of the 4 processes are what and how the pretreatment is. However, the late treatment of the 4 processes is the same pyrometallurgy and hydrometallurgy. The throughput and materials for the pyrometallurgy and hydrometallurgy process is depending on pretreatment, different. Several aspects regarding energy consumption, safety risk, products, cost etc. are evaluated and listed in Table 2.

Table 2 qualitative comparison of different routes

Route	Energy consumption	Waste treatment cost	Recycled products	Recovery rate	Safety	Cost	Economic index
1	0	++	Steel, Cu, Co, Ni	--	--	++	0
2	+	0	Cu, Co, Ni	0	0	+	+
3	+	0	Cu, Co, Ni	0	0	+	+
4	-	0	Steel, Cu, Co, Ni	0	0	+	++

Every recycling process step consumes energy. In above mentioned processes, the energy consumption in pyrometallurgy and hydrometallurgy steps is much higher than that in pretreatment. However, the pretreatment step can not only deactivate lithium-ion batteries but also separate several components. As a result, fewer components need be treated in pyro/hydrometallurgy. Route 4, which separates most of components before pyrometallurgy, has the lowest energy consumption. Route 2 and 3, which remove fewer components than route 1 and 4 before pyrometallurgy, consume more energy. Regarding waste treatment cost, only route 1 deactivates batteries by mechanical pretreatment while other routes applies thermal pretreatment. The electrolyte in lithium-ion battery is toxic and flammable. The treatment of electrolyte by thermal pretreatment can be done by either oxidization or evaporation and then subsequent collected by condensation. After thermal pretreatment, it can be sure that the material is organic free. While during mechanical pretreatment, electrolyte cannot be removed completely at room temperature. Therefore, electrolyte need to be also treated after the mechanical pretreatment until the pyrometallurgy step, e.g., during transportation, storage. Therefore, the waste treatment cost of route 1 is much higher than others. As seen in Table 2, all four routes recover precious metals like cobalt, nickel, and copper. However, the recovery rate of route 1 is low since mechanical pretreatment is unable to crack PVDF binder between cathode aluminum foils [7]. The economic index is mainly a sum of cost and recovery rate as seen in Table 2.

The most cost-efficient way to separate steel casing, copper and aluminum from end-of-life lithium-ion batteries is mechanical separation (route 1 and 4). However, route 1 has more safety risk than route 4 due to not well treated electrolyte. Like RECUPYL and Retriev's processes, mechanical pretreatment for route 1 can only be carried out under certain conditions. Off-gas need to be well treated since the electrolyte is volatile and flammable at ambient condition. Therefore, the cost of mechanical pretreatment in route 1 is more expensive than route 4 regarding off-gas treatment. Mechanical pretreatment in route 4 is a much safer process than route 1 since the end-of-life lithium-ion batteries are deactivated in thermal pretreatment before mechanical pretreatment.

Route 2 and 3 do not separate steel casing, copper, and aluminum before pyrometallurgy process where the batteries are melted. As a result, a significant amount of steel (mainly iron, chromium and nickel) and aluminum remain in the alloy. These elements, especially iron and aluminum, are considered as impurities or undesired elements for the subsequent hydrometallurgy process. The aim of the hydrometallurgy process is to refine mainly copper, nickel and cobalt. The presence of those undesired elements results in higher operation and waste treatment cost. The purpose of thermal pretreatment process in route 2 is to deactivate the end-of-life batteries and remove impurities e.g., plastic and organic components. Compare to route 3, route 2 has lower transportation and storage cost between thermal pretreatment and pyrometallurgy process.

The (PH)EV market is estimated to experience a huge boom in coming years. This triggers the booming of traction battery market as well. As a result, secured raw material supply becomes critical for EU. The existing recycling processes in different companies are dedicated to recovering precious metals such as cobalt and nickel. None of them has the intention to recover lithium from lithium-ion batteries since nowadays lithium is inexpensive and recovering lithium from slag is technical costly compared to refining lithium from raw lithium salt. However, due to criticality of lithium supplement outside of EU, it is believed that lithium recovery from lithium ion battery need to be realized by the recycling industry.

3.2 Calculation tool for EV battery recycling

The proposed processes in Table 2 have multiple indicators regarding off-gas, cost, energy, recovery rate etc. Each process has its own advantages as well as disadvantages at certain aspect. In order to quantitatively evaluate those processes objectively, the following investigation focuses only on the recyclability of materials with optimum conditions. ACC has carried out an investigation on the recyclability for every possible element in lithium-ion battery in each possible compound at each recycling process step for 4 processes in Table 2. The result of this investigation is a database containing distribution indicators of different elements in each process step in each recycling process. In order to better disseminate the database and result, ACC has developed a C++ program to demonstrate material flow in different recycling processes. The iModBatt battery was selected as input material.

The software allows the user to define the input material for recycling as Figure 5 shows. During the project, 5 different type of cells were investigated with respect to their electro-chemical properties for the battery pack. In the recycling investigation, detailed composition of different elements in those cells were studied and were all listed here. At the module level, 98 cells were integrated into one module with additional components like cables, PCBs, housing etc. developed by TYVA. Then, at pack level, 26 modules were integrated to form a battery pack for the Renault ZOE vehicle and 13 modules were designed for the e.Go vehicle. All materials with different configurations were summarized into this software and can be set as input material for recycling simulation.

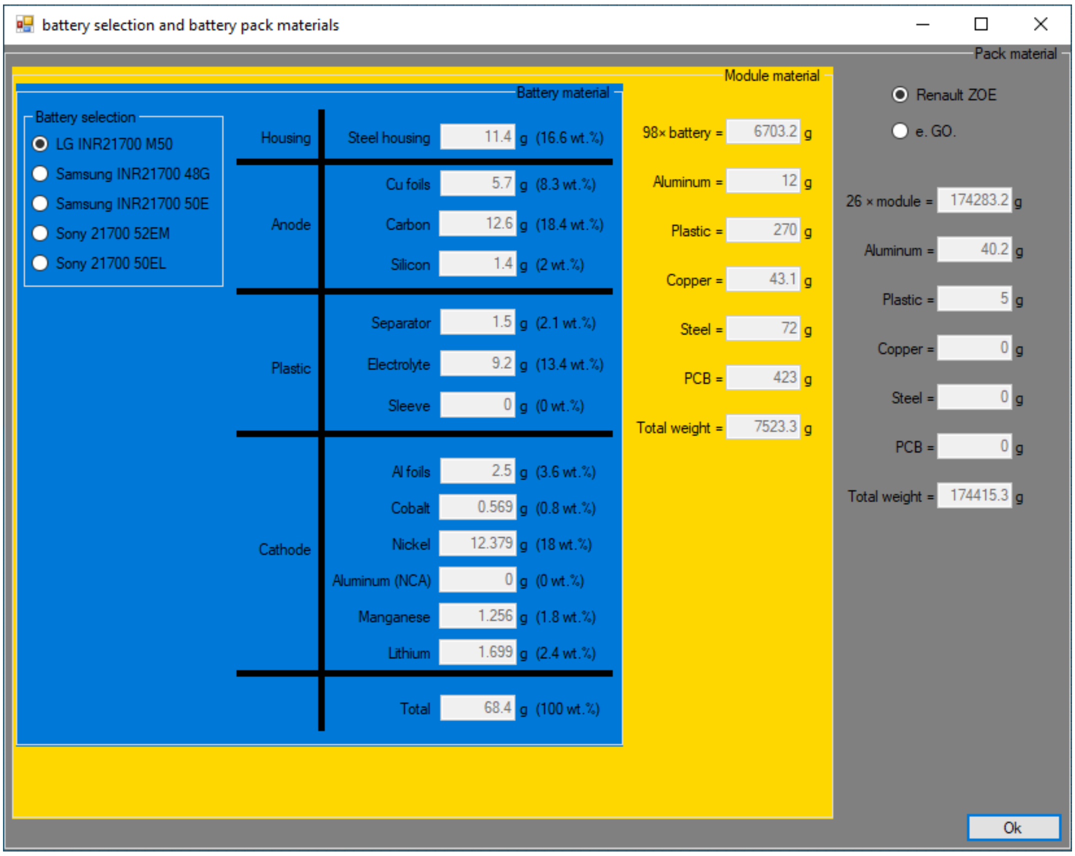


Figure 5 input material definition for recycling calculation

After defining the input material, users can select the recycling process from the 4 possible routes in Figure 4. The selection of recycling process is shown in Figure 6. For an electric vehicle battery pack, before recycling treatment, dismantling plays an important role. In this software, it is possible to select dismantling until module level, cell level or do not dismantle. After that, the software can show the result of the selected recycling process as included in Figure 7 and Figure 8.

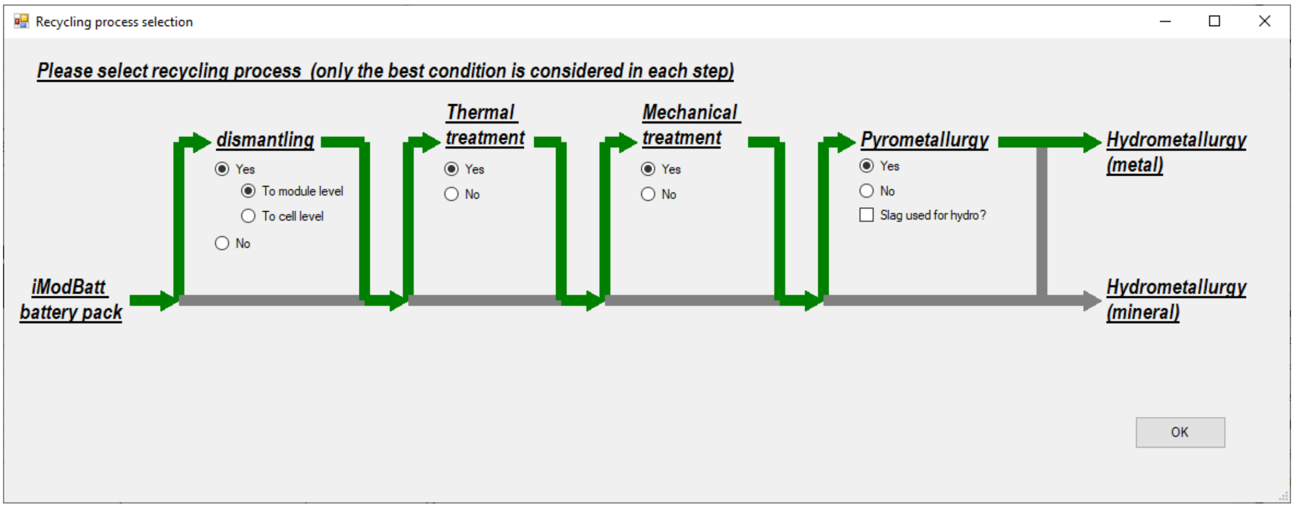
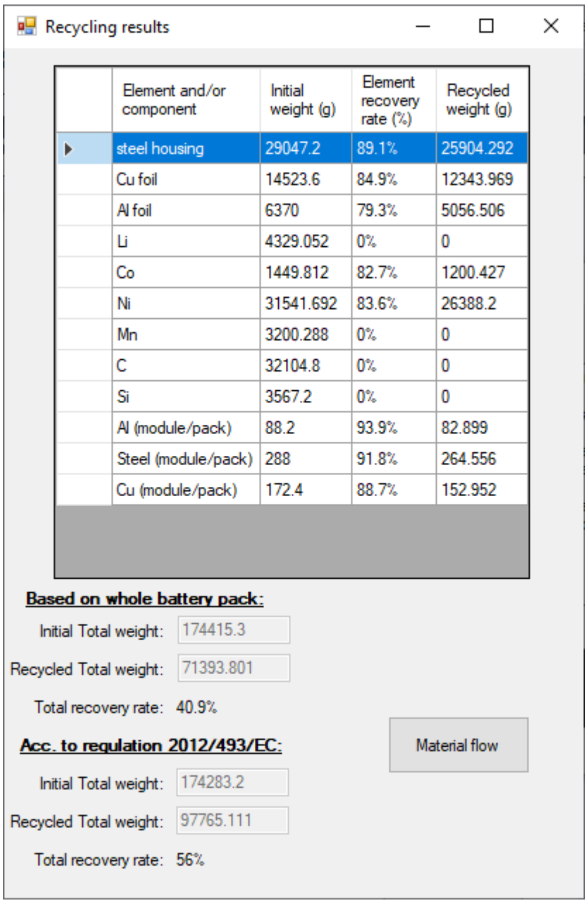


Figure 6 selection of recycling process for recycling calculation

The recycling result in Figure 7 summarizes all available elements in the selected input battery pack and their overall recovery rate over the selected recycling process. Then, the recycled total weight was calculated by adding recycled weight of all these elements. The total recovery rate is also weight basis calculation which is same to the calculation method in battery directive 2006/66/EC. Recovery rate based on battery pack and according to EU regulation 493/2012 are provided. The regulation 492/2012 defines that recovery rate only calculates the cells in a battery pack. Here, the software provides also the whole battery pack as input material for recovery rate calculation.



Element and/or component	Initial weight (g)	Element recovery rate (%)	Recycled weight (g)
steel housing	29047.2	89.1%	25904.292
Cu foil	14523.6	84.9%	12343.969
Al foil	6370	79.3%	5056.506
Li	4329.052	0%	0
Co	1449.812	82.7%	1200.427
Ni	31541.692	83.6%	26388.2
Mn	3200.288	0%	0
C	32104.8	0%	0
Si	3567.2	0%	0
Al (module/pack)	88.2	93.9%	82.899
Steel (module/pack)	288	91.8%	264.556
Cu (module/pack)	172.4	88.7%	152.952

Figure 7 recycling result of selected recycling process

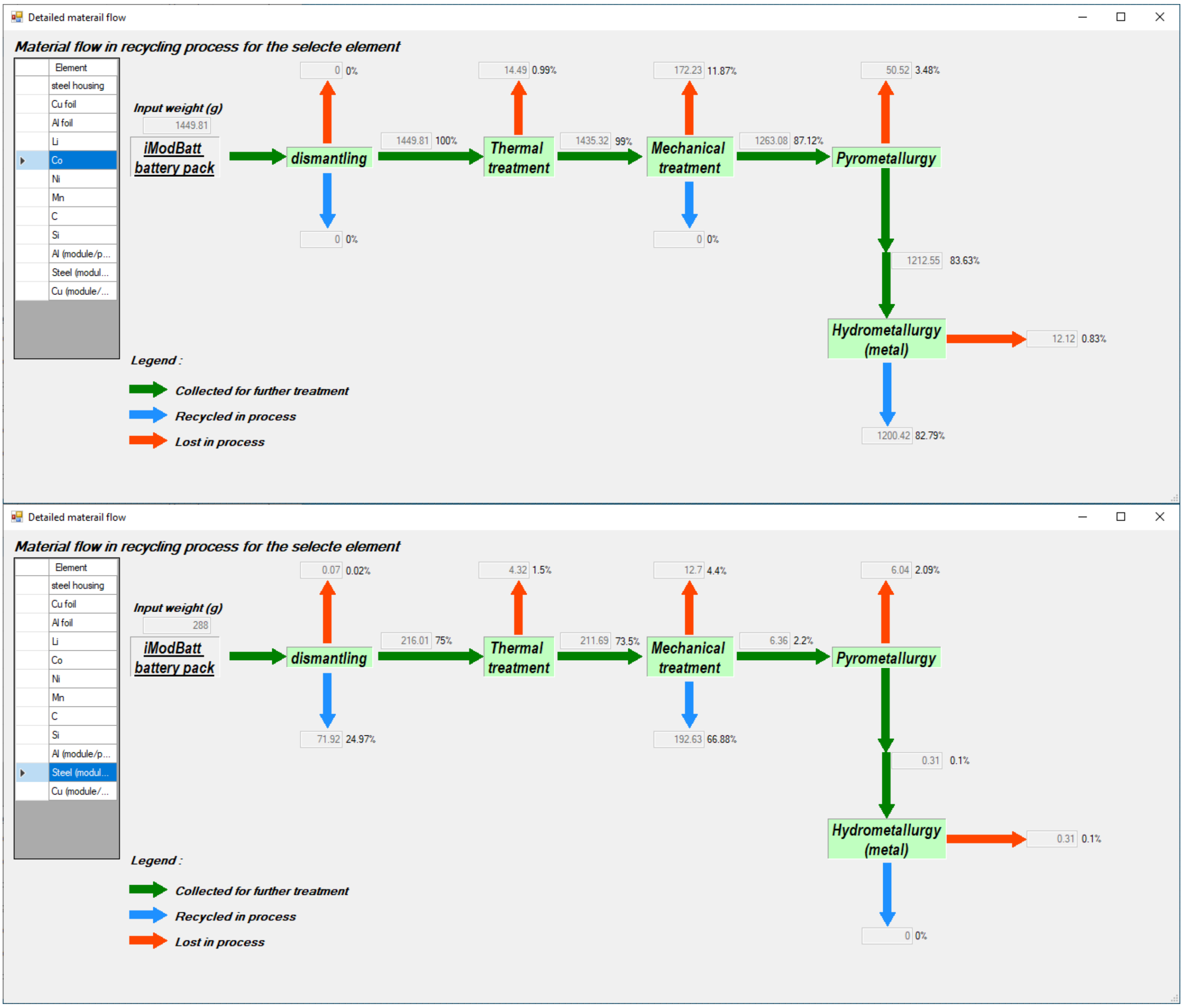
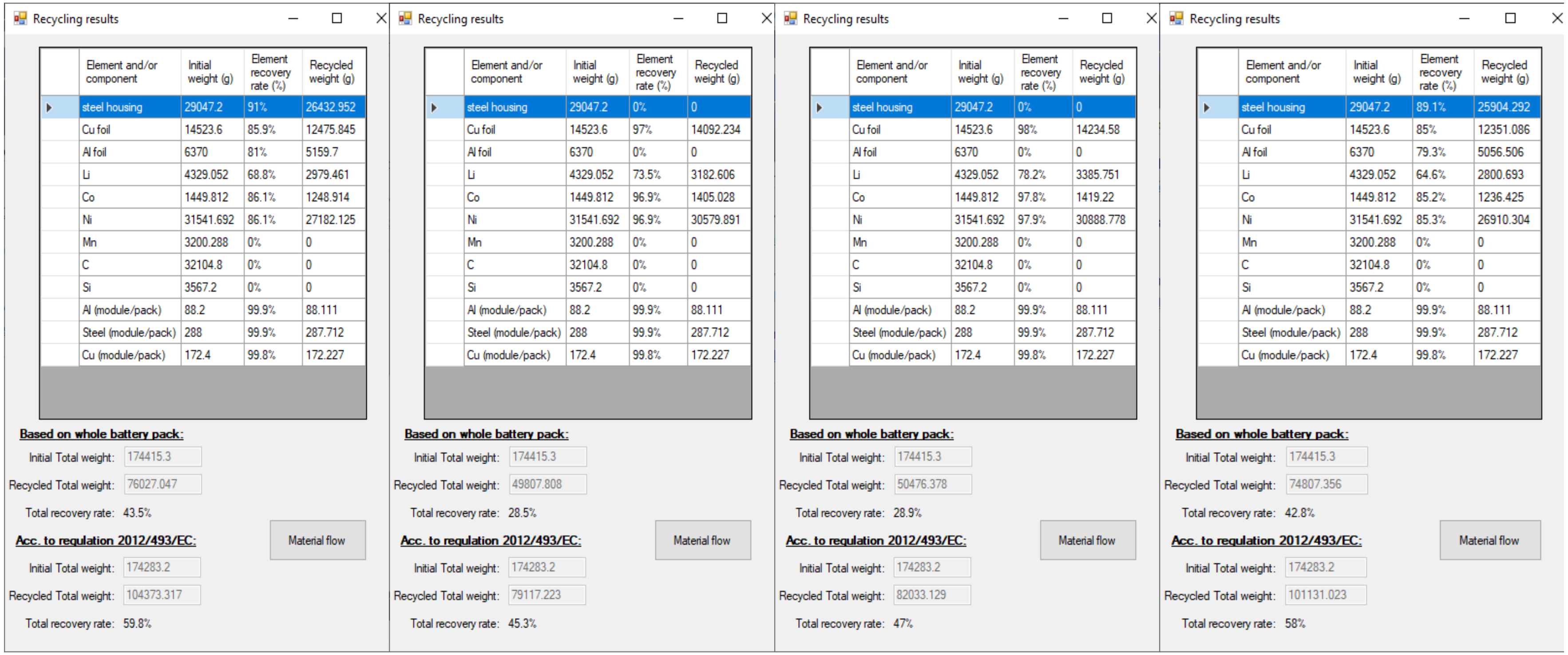


Figure 8 detailed material flow of cobalt and steel (module/pack) in selected recycling process

Figure 8 shows the detailed cobalt and steel (module/pack) flow in the selected recycling process. It is found that for cobalt, ca. 83 wt.% can be recycled in the eventual hydrometallurgy step by the selected recycling process. The main losses are in mechanical treatment (ca. 12 wt.%) and pyrometallurgy (ca. 4 wt.%). The losses in hydrometallurgy and thermal treatment is minor and no losses are founded in dismantling step. This result indicates that for cobalt the improvement should be focused on mechanical treatment and pyrometallurgy. On the other hand, for the steel from module and pack, the recovery rate depends mostly on the dismantling step, as Figure 8 shows, only ca. 25 wt.% are recycled in dismantling step. Because the rest 75 wt.% steels is in module, those steels need to be treated by thermal treatment and eventually be recycled in mechanical treatment. Although ca. 92 wt.% of the steel can be recycled eventually in this recycling process, but the efficiency of the steel recycling is low. Therefore, it is recommended to dismantle the battery pack as much as possible.

4 Application of smart software for different recycling process

In the frame of iModBatt project, this software was also used to simulate the proposed recycling processes in Figure 4 for Renault ZOE iModBatt battery pack. The results are shown in **¡Error! No se encuentra el origen de la referencia.**. Here the dismantling for all processes has been set to cell level. The recycling rate of metals from modules and packs are all nearly 100% for all processes. Apart from that, the material recycling rate depends on the selected recycling processes.



Process 1 — Recycling results

Element and/or component	Initial weight (g)	Element recovery rate (%)	Recycled weight (g)
steel housing	29047.2	91%	26432.952
Cu foil	14523.6	85.9%	12475.845
Al foil	6370	81%	5159.7
Li	4329.052	68.8%	2979.461
Co	1449.812	86.1%	1248.914
Ni	31541.692	86.1%	27182.125
Mn	3200.288	0%	0
C	32104.8	0%	0
Si	3567.2	0%	0
Al (module/pack)	88.2	99.9%	88.111
Steel (module/pack)	288	99.9%	287.712
Cu (module/pack)	172.4	99.8%	172.227

Based on whole battery pack:
Initial Total weight: 174415.3
Recycled Total weight: 76027.047
Total recovery rate: 43.5%

Acc. to regulation 2012/493/EC:
Initial Total weight: 174283.2
Recycled Total weight: 104373.317
Total recovery rate: 59.8%

Material flow

Process 2 — Recycling results

Element and/or component	Initial weight (g)	Element recovery rate (%)	Recycled weight (g)
steel housing	29047.2	0%	0
Cu foil	14523.6	97%	14092.234
Al foil	6370	0%	0
Li	4329.052	73.5%	3182.606
Co	1449.812	96.9%	1405.028
Ni	31541.692	96.9%	30579.891
Mn	3200.288	0%	0
C	32104.8	0%	0
Si	3567.2	0%	0
Al (module/pack)	88.2	99.9%	88.111
Steel (module/pack)	288	99.9%	287.712
Cu (module/pack)	172.4	99.8%	172.227

Based on whole battery pack:
Initial Total weight: 174415.3
Recycled Total weight: 49807.808
Total recovery rate: 28.5%

Acc. to regulation 2012/493/EC:
Initial Total weight: 174283.2
Recycled Total weight: 79117.223
Total recovery rate: 45.3%

Material flow

Process 3 — Recycling results

Element and/or component	Initial weight (g)	Element recovery rate (%)	Recycled weight (g)
steel housing	29047.2	0%	0
Cu foil	14523.6	98%	14234.58
Al foil	6370	0%	0
Li	4329.052	78.2%	3385.751
Co	1449.812	97.8%	1419.22
Ni	31541.692	97.9%	30888.778
Mn	3200.288	0%	0
C	32104.8	0%	0
Si	3567.2	0%	0
Al (module/pack)	88.2	99.9%	88.111
Steel (module/pack)	288	99.9%	287.712
Cu (module/pack)	172.4	99.8%	172.227

Based on whole battery pack:
Initial Total weight: 174415.3
Recycled Total weight: 50476.378
Total recovery rate: 28.9%

Acc. to regulation 2012/493/EC:
Initial Total weight: 174283.2
Recycled Total weight: 82033.129
Total recovery rate: 47%

Material flow

Process 4 — Recycling results

Element and/or component	Initial weight (g)	Element recovery rate (%)	Recycled weight (g)
steel housing	29047.2	89.1%	25904.292
Cu foil	14523.6	85%	12351.086
Al foil	6370	79.3%	5056.506
Li	4329.052	64.6%	2800.693
Co	1449.812	85.2%	1236.425
Ni	31541.692	85.3%	26910.304
Mn	3200.288	0%	0
C	32104.8	0%	0
Si	3567.2	0%	0
Al (module/pack)	88.2	99.9%	88.111
Steel (module/pack)	288	99.9%	287.712
Cu (module/pack)	172.4	99.8%	172.227

Based on whole battery pack:
Initial Total weight: 174415.3
Recycled Total weight: 74807.356
Total recovery rate: 42.8%

Acc. to regulation 2012/493/EC:
Initial Total weight: 174283.2
Recycled Total weight: 101131.023
Total recovery rate: 58%

Material flow

Process 1 Process 2 Process 3 Process 4

Figure 9 recycling result of the 4 proposed processes

The results generally show which element can be recycled by the best-case scenario. It can be seen that the recycling rate of the main recycling targets, specifically cobalt, nickel and copper, are all above 85%. The main difference is on other elements and components.

Process 2 and 3 has less process steps compared to process 1 and 4. The mechanical treatment allows the process to recycle steel housing and aluminum foil before pyrometallurgy. Therefore, the overall recycling efficiency of process 1 and 4 is higher than process 2 and 3. On the other hand, because of shorter process steps, process 2 and 3 are more dedicated for recycling of cobalt, nickel and copper. The specific recycling efficiency of those elements in process 2 and 3 is higher than process 1 and 4. In general, the difference regarding recycling efficiency between process 2 and 3 is minor. Process 3 has fewer steps than process 2, resulting in fewer losses. The main difference between process 2 and 3 is on storage and logistic side which is not indicated in recycling efficiency calculation. The difference regarding recycling efficiency between process 1 and 4 is also minor. Since adding a thermal treatment before mechanical treatment does not change the targets significantly. Only organics and plastics are intended to be removed by thermal treatment; only limited amount of recycling target was considered as lost in dust fraction by thermal treatment. The difference regarding recycling efficiency from process 1 and 4 is also minor. Process 1, which has fewer steps, has higher recycling efficiency compared to process 4. However, the main difference between process 1 and process 4 is that the mechanical treatment in process 1 is more complex regarding off-gas treatment and atmosphere control, which is also not indicated in recycling rate in this software.

To conclude, the software provides preliminary simulation to all industrial available recycling technologies and the results show that all processes are suitable for recycling target metals like cobalt, nickel and copper. The main differences between those processes are mainly on other aspects like energy consumption, transportation, storage, safety management etc. which was not included in the software simulation.

5 Conclusions

Currently, due to limited processing material, lithium-ion battery recycling industry is still preliminary. Most end-of-life lithium-ion batteries come from 3C application and powder tools. End-of-life lithium-ion battery from electric vehicle application is still limited. It is foreseen that in the coming years, due to massively traction batteries being put on market, the recycling industry is experiencing a huge technology innovation and market booming. Therefore, a comprehensive investigation of the recycling industry is essential. A comparison between different recycling technologies and processes is important.

In this deliverable, different recycling processes all over the world are summarized and classified into 4 different routes. Recycling processes are evaluated qualitatively with respect to their energy consumption, waste treatment, safety risk, costs etc. The 4 routes are then evaluated quantitatively regarding their elements recovery rate. The data are summarized into a smart calculation tool, a C++ software, which shows the detailed material flow in the 4 recycling routes. The calculation tool shows clearly that material is recycled or lost in specific recycling steps. The calculation tool helps the EU and the public to understand the lithium-ion recycling industry better.

6 Reference

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