Circularity of DCC materials – case study on three energy storage solutions

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Summary

Due to growing concerns about the environmental impacts of fossil fuels and the capacity and resilience of energy grids around the world, engineers and policymakers are increasingly turning their attention to energy storage solutions[1]. In turn, the huge demand for materials for such storage systems will require a considerable energy input in extraction, processing and materials formulation, and new and sustainable electrochemical systems need to be developed[2].

Current report is the result of the exploration work where the circularity and environmental potentials of biobased energy storage solutions were analysed in the form of iterative interviews with stakeholders along the energy storage and packaging value chains, complemented by literature research.

The work was performed within the scope of Digital Cellulose Center (DCC) research center[3] in the sub-project 1 “Circularity of DCC materials” of the Theme 1: Design for a circular bioeconomy.

Totally three systems were selected and analysed in the form of three respective case studies:

- Case study I: Biobased battery (Chemical energy storage system)
- Case study II: Biobased printed supercapacitor (Electrochemical energy storage system)
- Case study III: Intelligent packaging (Chemical or electrochemical energy storage for fiber-based packaging)

Each case study was put into the life cycle context where aspects such as legislation, circularity potential and potential environmental impact were discovered. The biobased battery for large-scale grid storage applications was classified as an industrial battery with collection rate requirement of 75% at end-of-life, of which 50% to be materially recycled. The biobased printed supercapacitor was classified as an electric and electronic equipment (EEE) with collection rate requirement of 65%, of which recovery and recycling / preparing for reuse targets vary between 55% - 85% depending on application. The material recycling target for the fiber-based intelligent packaging is 85% since being perceived as a paper-based packaging it would enter paper packaging recycling stream rather than entering the recycling stream of Waste electrical and electronic equipment (WEEE).

In next steps of this exploratory journey, the compositions of the respective energy storage solutions were identified, including biobased content and recycling potential on the short- and long-term, compared to their benchmark solutions where possible.

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[1] EESI, Factsheet Energy Storage, https://www.eesi.org/papers/view/energy-storage-2019, accessed at 2021-12-17

[2] Liu L. et al., Bio Based Batteries, https://www.researchgate.net/publication/349982765_Bio_Based_Batteries, accessed at 2021-12-17

[3] Research center Digital Cellulose Center, https://digitalcellulosecenter.se/, accessed at 2021-12-11

Today, the material recycling processes for batteries and WEEE are strongly economically driven: the material components that are considered as valuable by recyclers are mainly base metals (e.g., aluminium, steel) and to low extent critical raw materials (e.g., cobalt, nickel). The biobased energy storage solutions though do not contain any critical raw materials and use base metals to a less extent. This is a dilemma where the material value of the biobased, renewable materials (more sustainable materials by origin) is not favourable in the end-of-life processes of today and therefore will be lost (i.e., incinerated). A more balanced approach to such dilemma is urged in order to facilitate both economic and environmental incentives in the energy storage value cycles.

Current Battery and WEEE directives do not promote the recycling of materials that are critical or have a high environmental burden, which in practice results in loss of those materials, not least due to lack of economy in recycling processes. Moreover, the legislation needs to be adapted in order to meet innovative development in the area. It can be relevant to introduce a cross-sectoral category ‘Biobased energy storage solutions’ in the upcoming legislation with the aim to encourage use of more abundant, biobased materials and thus decouple energy storage applications from use of critical raw materials.

Key words: Energy storage, biobased battery, printed supercapacitor, intelligent packaging, circular economy, recycling, environmental assessment, hotspots, biobased electronics, R&D, cellulose, MET matrix, ecodesign.

Content

Preface

The current report is the result of the exploration work where the circularity and environmental aspects of biobased energy storage solutions were analysed. The work was conducted within the scope of the Digital Cellulose Center (DCC) research center[4] in the sub-project 1 "Circularity of DCC materials" of the Theme 1: Design for a circular bioeconomy.

To realize a true circular bioeconomy within the energy storage sector we need to:

1) find sustainable material sources, and

2) realise materials and methods for recycling, upcycling or decomposition.

One aim of the Theme 1 is to explore the modification and use of bio-based derivatives as functional materials for energy storage components. Another aim is to acknowledge the entire life cycle of digital cellulose products already from the beginning, which is being summarized in this report.

Can the materials be decomposed using existing recycling processes for batteries or electronics, paper or paper board, or will there be a need for new recycling routes? Are there innovative methods that can be used for decomposition or even upcycling?

The sub-project 1 "Circularity of DCC materials" would like to acknowledge participation and vigorous engagement of the following individuals and respective organizations:

- Peter Ringstad and Jakob Nilsson, Ligna Energy
- Karl Håkansson, RISE Bioeconomy & Health
- Anders Gustafsson and the team at Stena Recycling

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[4] Research center Digital Cellulose Center, https://digitalcellulosecenter.se/, accessed at 2021-12-11

Glossary

Battery or *accumulator* means any source of electrical energy generated by direct conversion of chemical energy and consisting of one or more primary battery cells (non-rechargeable) or consisting of one or more secondary battery cells (rechargeable)[5].

Battery pack means any set of batteries or accumulators that are connected together and/or encapsulated within an outer casing so as to form a complete unit that the end user is not intended to split up or open[5].

Button cell means any small round portable battery or accumulator whose diameter is greater than its height and which is used for special purposes such as hearing aids, watches, small portable equipment and back-up power[5].

CRM - Critical raw materials

DCC – research center Digital Cellulose Center, digitalcellulosecenter.se

EEE – Electric and Electronic Equipment

EMIM-ES – Ionic liquid (1-Ethyl-3-methylimidazolium ethyl sulfate)

EV – Electrical vehicles

Industrial battery or *accumulator* means any battery or accumulator designed for exclusively industrial or professional uses including batteries used in electric vehicle[5].

IL – Ionic liquid

GHG emissions – Greenhouse gas emissions

LCA – Life Cycle Assessment

LCO -Lithium cobalt oxide (LiCoO2)

LIBs - Lithium-ion batteries

LFP - Lithium iron phosphate, LiFePO4, battery cell

LMO - Lithium Manganese Oxide (LiMn2O4)

LNMO - Lithium Nickel Manganese Spinel (LiNi0.5Mn1.5O4)

NCA – Lithium Nickel Cobalt Aluminium Oxide (LiNiCoAlO2)

NMC - Lithium nickel manganese cobalt oxide battery cell

PEDOT:PSS - Conductive organic material (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate)

WEEE - Waste electrical and electronic equipment (also called e-waste)

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[5] DIRECTIVE 2006/66/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, accessed at 2021-12-11

1 Introduction

The production and use of energy account for more than 75% of the EU's greenhouse gas emissions. Decarbonising the EU's energy system is therefore critical to reach our 2030 climate objectives and the EU's long-term strategy of achieving carbon neutrality by 2050[6]. To this extent, a power sector must be developed that is based largely on renewable energy sources, complemented by the rapid phasing out of coal and by the decarbonising of natural gas[7].

Due to growing concerns about the environmental impacts of fossil fuels and the capacity and resilience of energy grids around the world, engineers and policymakers are increasingly turning their attention to energy storage solutions[1]. In turn, the huge demand for materials for such storage systems will require a considerable energy input in extraction, processing and materials formulation, and new and sustainable electrochemical systems need to be developed[2]. For electric vehicle batteries and energy storage, the EU would need up to 18 times more lithium and 5 times more cobalt in 2030, and almost 60 times more lithium and 15 times more cobalt in 2050, compared to the current supply to the whole EU economy. If not addressed, this increase in demand may lead to supply issues[8].

In Europe, over 1.9 million tonnes of waste batteries are generated annually, and the amount is expected to increase in the future. The collection and recycling rates, the profitability of recycling and impacts on the environment and health strongly depend on the battery type[9], ranging from 99% collection rate for automotive lead-acid batteries with lead recovery of 97% or more[25] to low collection (and negligible recycling) rates of lithium-ion batteries due to technologically challenging and costly recycling[25].

Waste electrical and electronic equipment (WEEE, also called e-waste) is one of the fastest growing waste streams in the EU, growing at 3 to 5 per cent per year. The overall amount of EEE placed on the market was 11.6 million tonnes in 2015. Currently in the EU, only one third of WEEE is being reported as separately collected and appropriately managed[49]. WEEE also includes a number of critical raw materials (CRMs) such as cobalt, lithium, natural graphite etc. Yet again, many critical metals or rare earth elements are not recycled, for example, because of low market prices that do not cover recycling costs, lack of recycling technologies at the commercial scale, or metallurgical limits to recovery processes[10].

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[6] European Commission, Energy and the Green Deal, https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/energy-and-green-deal_en, accessed at 2021-12-17.

[7] Polverini D. et al., Potential regulatory approaches on the environmental impactsof photovoltaics: Expected improvements and impacts ontechnological innovation, Wiley, 2020, accessed at 2021-12-17.

[8] European Commission, Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN, accessed at 2021-12-18.

[9] European Commission, Reducing loss of resources from waste management is key to strengthening the circular economy in Europe, https://www.eea.europa.eu/publications/reducing-loss-of-resources-from/reducing-loss-of-resources-from, accessed at 2021-12-18.

[10] Thiébaud, E., Hilty, L.M., Schluep, M., Böni, H.W., Faulstich, M., 2018. Where do our resources Go? Indium, neodymium, and gold flows connected to the use of electronic equipment in Switzerland. Sustain. 10.

Also, packaging materials innovation is happening at high pace in the efforts of phasing out single-use plastic, fossil-based and other non-circular packaging materials, while digitalisation expands packaging functionalities to e. g. traceability in value chains).

Intelligent packaging does not refer to a single technology, but to a variety of technologies that together are able to perform specific functions and thus inform the consumer about the product. In general, there are three types of intelligent packaging that are differentiated according to their main function: interactive packaging, sensors and indicators[11]. During the past few years, the topic of sustainability and circularity of packaging has gained an enormous attention from both politicians and the consumer side. With regard to intelligent packaging, its components can for instance have in some cases negative social environmental impact when its recovery is not ascertained[11], while the value added from the overall life cycle perspective can be substantial (e. g. monitoring environment conditions, traceability information).

Due to the abovementioned implications, storing electrical and chemical energy in more sustainable energy storage solutions is considered as promising options. However, these also need to be understood from a life cycle perspective and assessed in different applications due to variation in regulations, environmental profiles, end-of-life infrastructure, among other essential aspects.

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[11] ActinPack, Intelligent Packaging. Industry leaflet, http://www.actinpak.eu/wp-content/uploads/2018/10/Full_text_intelligent_download.pdf, accessed 2021-05-11.

2 Systems analysed and methods

2.1 Systems analysed – three case studies

Current report is the result of the exploration work where the circularity and environmental potentials of biobased energy storage solutions were analysed in the form of iterative interviews with stakeholders along the energy storage and packaging value chains, complemented by literature research. Totally three systems were selected and analysed in the form of three respective case studies:

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In particular, the case study I analysed one of the biobased battery concepts of Ligna Energy[12] in comparison to Li-ion batteries for use in large-scale grid applications:

	Case study I – New case	**Case study I - Current case *(benchmark object)***	**Comments**
Case study	Biobased battery	Li-ion battery (LFP typical)	Application areas: • Residential solar applications • Grid wind applications • Grid solar applications
Performance parameters	**Lifetime:** 5000 cycles (DOD 85%)	**Lifetime:** 3000 cycles (DOD 80%)	
	Cell-specific energy: 0.030 kWh/kg	**Cell-specific energy:** 0.150 kWh/kg	Comparison: the energy density of the biobased battery is 5 times lower than that of lithium-ion batteries (by mass).
	Specific power : 1.00 kW/kg	**Specific power:** 0.30 kW/kg	
	Cell cost efficiency: 150 $/kWh	**Cell cost efficiency:** 200 $/kWh	
	Cost efficiency: 0.04 $/kWh/cycle	**Cost efficiency:** 0.08 $/kWh/cycle	

This biobased energy storage solution is based on redox chemistry, being an electrochemical energy storage and thus categorized as a battery. This biobased energy solution belongs to chemical energy storage systems.

The case study II analysed a biobased printed supercapacitor developed at RISE Digital Systems[13] in comparison to Li-ion batteries for use in large-scale grid applications:

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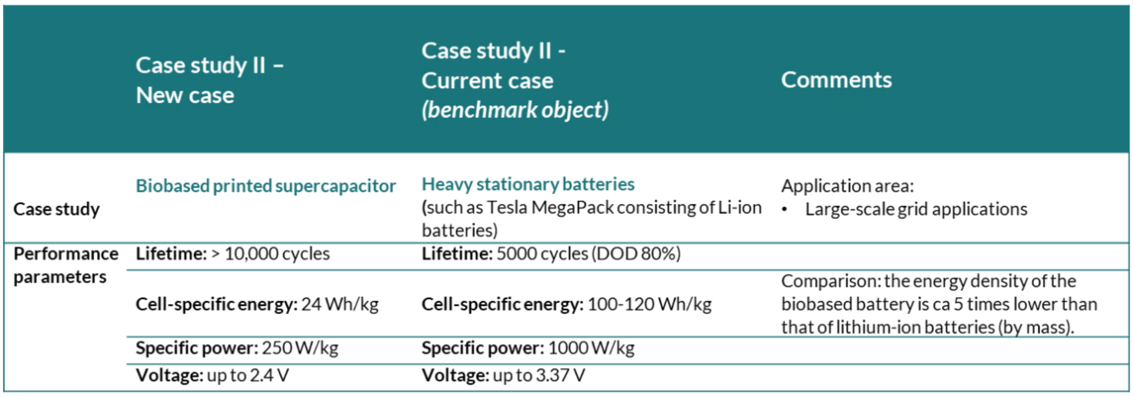
[12] Personal communication with Ligna Energy, https://lignaenergy.se/storage, December 2021.

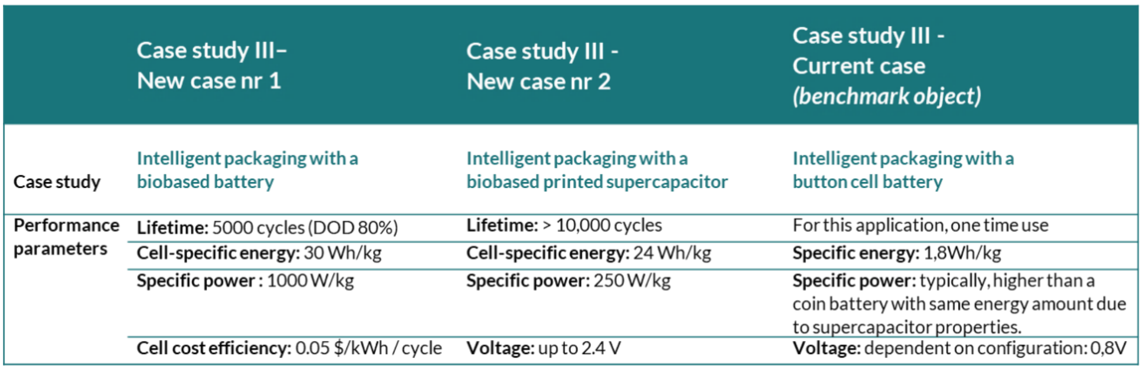
[13] Personal communication with RISE Digital Systems, November-December 2021.



	Case study II – New case	Case study II - Current case *(benchmark object)*	Comments
Case study	Biobased printed supercapacitor	Heavy stationary batteries (such as Tesla MegaPack consisting of Li-ion batteries)	Application area: • Large-scale grid applications
Performance parameters	**Lifetime:** > 10,000 cycles	**Lifetime:** 5000 cycles (DOD 80%)	
	Cell-specific energy: 24 Wh/kg	**Cell-specific energy:** 100-120 Wh/kg	Comparison: the energy density of the biobased battery is ca 5 times lower than that of lithium-ion batteries (by mass).
	Specific power: 250 W/kg	**Specific power:** 1000 W/kg	
	Voltage: up to 2.4 V	**Voltage:** up to 3.37 V	

This biobased energy storage solution belongs to the category of electrical energy storage systems.

The case study III analysed the biobased energy storage solutions from Case studies 1 and 2 in intelligent paper-based packaging applications, being compared to a button cell battery (also a lithium-ion battery). The biobased energy storage solutions in the new cases 1 and 2 were categorized as batteries and supercapacitors, respectively. The case represented an intelligent packaging with a cellulose fiber-based material substrate:



	Case study III– New case nr 1	Case study III - New case nr 2	Case study III - Current case *(benchmark object)*
Case study	Intelligent packaging with a biobased battery	Intelligent packaging with a biobased printed supercapacitor	Intelligent packaging with a button cell battery
Performance parameters	**Lifetime:** 5000 cycles (DOD 80%)	**Lifetime:** > 10,000 cycles	For this application, one time use
	Cell-specific energy: 30 Wh/kg	**Cell-specific energy:** 24 Wh/kg	**Specific energy:** 1,8Wh/kg
	Specific power : 1000 W/kg	**Specific power:** 250 W/kg	**Specific power:** typically, higher than a coin battery with same energy amount due to supercapacitor properties.
	Cell cost efficiency: 0.05 $/kWh / cycle	**Voltage:** up to 2.4 V	**Voltage:** dependent on configuration: 0,8V

Possible applications for the energy storage components in such intelligent packaging are: energy storage component providing energy for cold chain monitoring sensor (e.g. energy for a chip that measures temperature along a value chain); energy storage component providing energy for an anti-counterfeit protection component; and energy storage component providing energy for an anti-tampering protection component.

2.2 Methods

The character of this research is explorative. Several methods that support the assessment of potential environmental hot spots and benefits as well as assessment of circularity of materials and products were used along this explorational journey. Understanding of mandatory requirements was gained by performing an overview over relevant EU legislation for batteries, electronics and paper-based packaging.

In the context of circular economy, a circular business model mapping was performed, where the explorative case studies were discussed in terms of circularity potential on long- and short-term. The short-term time frame is defined as a 2-5 year perspective and therefore implies utilization of current waste management infrastructure as end-of-life routes. The long-term perspective covers the timeframe of 5-15 year from now and in this scenario the waste management methods are more abundant and economically efficient.

The case studies were also exposed to different categories of circular business models such as: circular supply chain, recovery & recycling, sharing platform, product as a service and product life extension, with their respective sub-models[14], see Figure 1. The latter in order to understand how the circularity potential can be maximized beyond the established waste management options, i.e., by inclusion of diverse recycling and reuse options along the value chains in the three case studies.

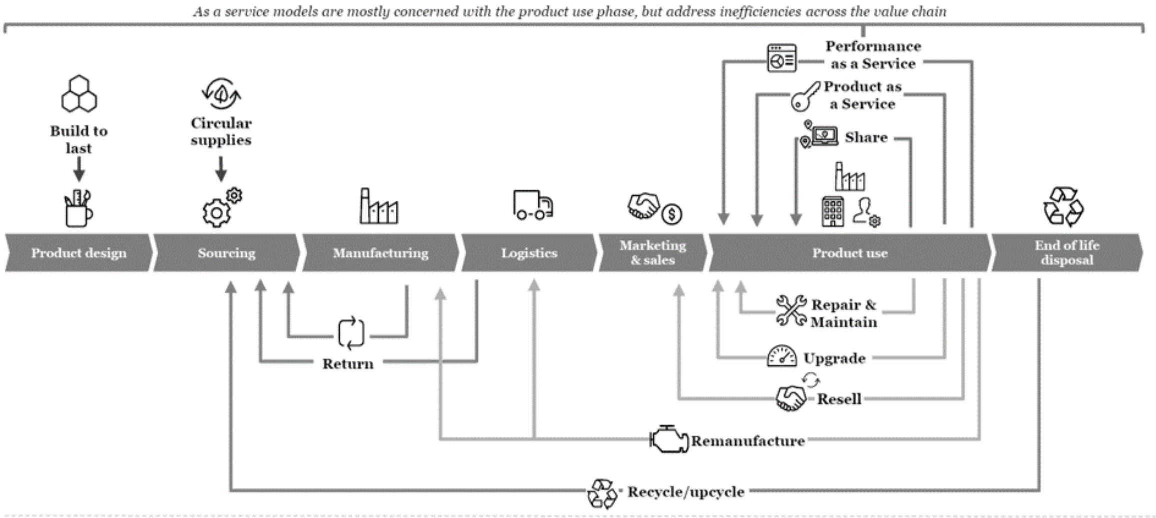


Figure 1 Circular business model specific sub-models modify different steps of the value chain to make it circular[14].

From the environmental perspective, the Materials and Energy use and Toxic emissions Matrix method, commonly referred to as the MET Matrix[15] was applied. This is a design tool that gives an overall insight into the environmental impact of a design during all of its life cycle stages (see Table 1).

The MET matrix was used as a tool for mapping the potential environmental aspects in the case studies (new cases and benchmark cases where possible), with aim to identify potential environmental advantages and hot spots already early in the R&D phase. The method is qualitative (descriptive) rather than quantitative and is suitable for assessment of systems that are in the development stage, lacking inventory data and other information to perform more detailed environmental analyses such as Life Cycle Assessment (LCA) or Eco-cost analyses.

The development of new products will inevitably have an impact on the environment and in order to minimise it, the ecodesign strategies can be followed[15]. Therefore, a complementary method, The Ecodesign Strategy Wheel (also called Life cycle design

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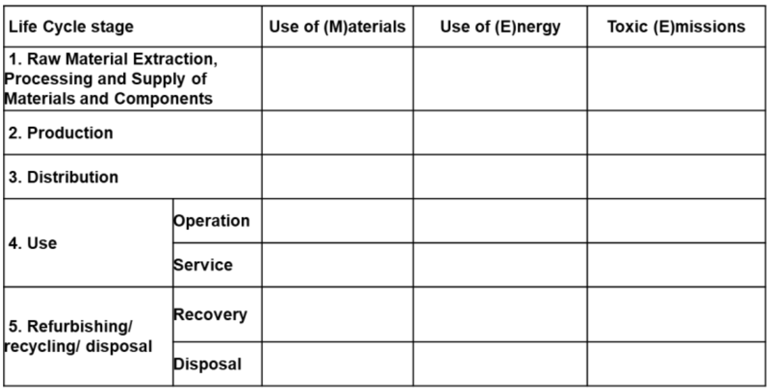
[14] SITRA Circular economy business models for the manufacturing industry (original source Accenture), https://teknologiateollisuus.fi/sites/default/files/inline-files/20180919_Circular%20Economy%20Playbook%20for%20Manufacturing_v1%200.pdf, accessed at 2021-12-17

[15] Delft University, Sustainable mechanical engineering guide, 2020.

Strategies), was applied in order to visualise and discuss the strategies that can be followed for Ecodesign of products. The method includes eight optimisation strategies and recommendations on reducing environmental impact in different phases of a product life cycle: Selection of low-impact materials, Reduction of materials usage, Optimisation of production techniques, Optimisation of distribution system, Reduction of impact during use, Optimisation of initial lifetime, Optimisation of end-of-life system and New concept development.

Table 1 The MET matrix framework.



Life Cycle stage		Use of (M)aterials	Use of (E)nergy	Toxic (E)missions
1. Raw Material Extraction, Processing and Supply of Materials and Components				
2. Production				
3. Distribution				
4. Use	Operation			
	Service			
5. Refurbishing/ recycling/ disposal	Recovery			
	Disposal			

The analysed aspects of environmental impact, circularity and legislation were afterwards summarized from a multi-criteria perspective. This is in order to serve as a systemic perspective input to researchers and industry in continuation of R&D of the biobased carbon solutions in the Digital Cellulose Center and beyond.

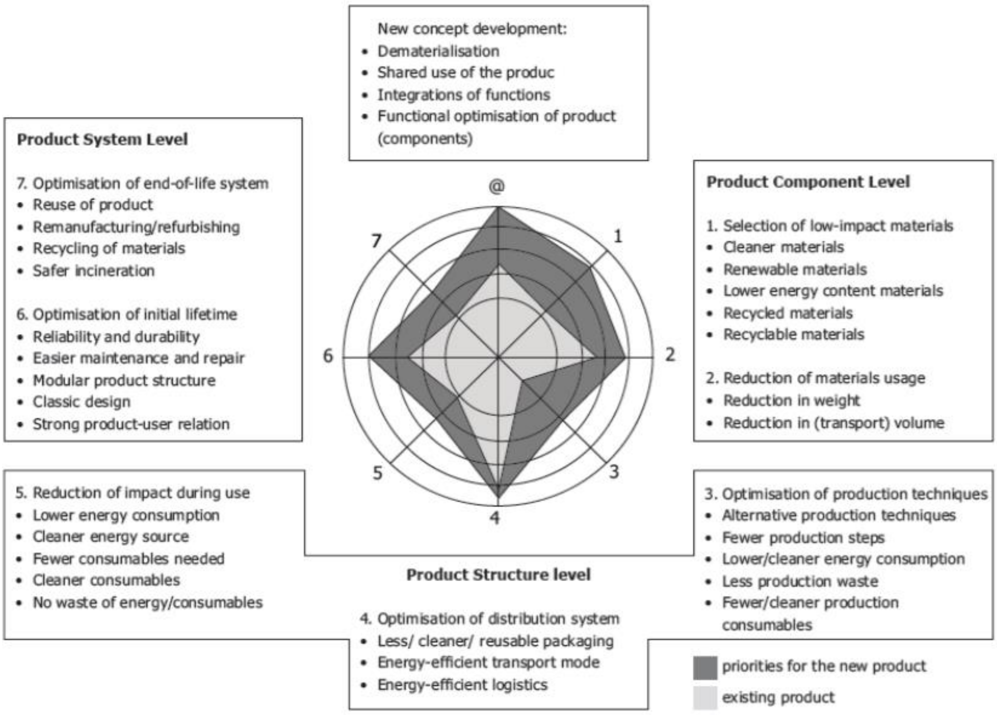


Figure 2 The Ecodesign strategy Wheel[16].

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[16] University of Delft, Faculteit Industrieel Ontwerpen, Delft Design Guide, 2010

3 Results and discussion

This chapter presents the results in terms of the legislative implications, overall environmental assessment and exploration of the circularity potential of the three case studies.

3.1 Legislation overview

In the European Union, Extended producer responsibility (EPR) is mandatory for battery waste[5], electric and electronic equipment waste (WEEE)[17] and packaging waste[38] among other certain waste streams, see Figure 3.

EPR can be defined as "an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle". EPR seeks to achieve a reduction in the environmental impact of products, throughout their lifespan, from production through end-of-life[18].

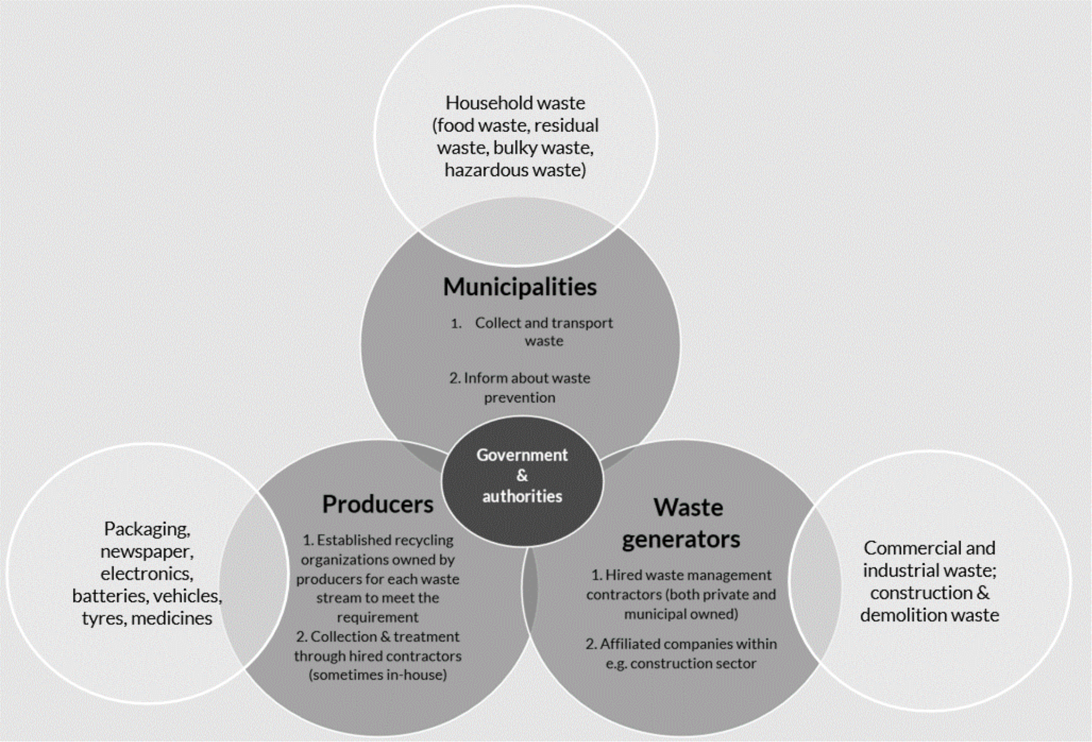

Figure 3 Legal and financial responsibilities in the Swedish waste management system. In the European Union, extended producer responsibility (EPR) is mandatory for packaging, newspaper, electric and electronic equipment (WEEE), batteries, vehicles (ELV), tires and medicines.

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[17] DIRECTIVE 2012/19/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 4 July 2012 on waste electrical and electronic equipment (WEEE), https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0019&from=EN, accessed at 2021-12-11

[18] OECD, Extended Producer Responsibility, https://www.oecd.org/env/tools-evaluation/extendedproducerresponsibility.htm, accessed at 2021-12-11

In turn, the EU legislation is implemented into the Swedish national legislation[19]. In Sweden there is a clear distribution of legal and financial responsibilities in the waste management system. From a legal point of view, there are three actors responsible for the management of the waste (municipalities, producers and waste generators):

- *For household waste* which includes the residual/mixed waste, sorted food waste and bulky waste etc. The municipality is responsible of managing the waste. This is done either by managing the waste by the municipality itself or procuring this service from waste management companies (which are privately or municipally owned).
- *For a number of waste flows* including battery waste and WEEE waste, the producers of these are legally responsible for collection and treatment of the generated waste, according to Polluter Pays Principle. To comply with set regulations manufacturing companies have established organizations like El-Kretsen[20] responsible for collection and management of the battery and EEE waste. Usually, the recycling organizations hire waste management companies for this, even though management of the waste in-house does occur (e g. sorting of plastic packaging).
- For other waste streams such as construction and demolition waste and industrial waste streams, the waste generator is responsible for the waste management. Most often, the generators hire waste management companies to comply with the set regulations.

3.1.1 The Battery Directive

The European Battery Directive[21] establishes rules on batteries and accumulators regarding the subject of:

- Hazardous substance limits
- Labeling
- Waste collection
- Treatment
- Recycling
- Disposal.

The Directive covers batteries and accumulators of all shapes, volumes, weights, material composition, and usage – excluding batteries for military and aerospace purposes.

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[19] Ordinance (2008:834) on producer responsibility for batteries, https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/ sfs-2008-834, accessed at 2021-12-11

[20] El-Kretsen, Collections statistics, https://kunskapsrummet.com/en/statistics/, accessed at 2021-12-11

[21] Compliance Gate, https://www.compliancegate.com/battery-directive-european-union/, accessed at 2021-12-11

Hence, the Battery Directive covers portables batteries, industrial and automobile batteries, and accumulators[21,22]:

- *Industrial batteries:* a battery exclusively for industrial or other professional use, alternatively in electrical vehicles.
- *Automotive batteries:* a battery to be used in a starting engine, lighting or ignition system of a vehicle and not being an industrial battery.
- *Portable batteries:* a sealed and easily portable battery that is not labeled as an automotive or industrial battery.

Of the batteries that are under the scope of the Battery Directive and are relevant for the current research study are lithium-ion and button-cell batteries, as benchmark objects in the three case studies.

The Battery Directive applies to most batteries placed on the EU market. However, some batteries are not covered by the Battery Directive, as they are covered by other directives or regulations due to their application. This is the case of *supercapacitors* that should be handled according to EU directive 2002/96/EC on waste electric and electronic equipment[23] when becoming waste.

The Directive restrains the content of certain substances such as mercury, cadmium, and their compounds in various types of batteries. Below follows an overview of restricted substances[5]:

- The batteries and accumulators that contain *more than 0.0005% by weight of mercury or mercury compounds* are prohibited to be placed in the EU market (with exemption for button cells with a mercury content of no more than 2 % by weight)
- Portable batteries and accumulators that contain *more than 0.002% by weight of cadmium or cadmium compounds* are prohibited to be marketed and distributed in the EU (with exemption for emergency and alarm systems, medical equipment and cordless power tools)
- Any battery that contains *more than 0.004% of lead* is not restricted but must include the symbol "Pb" on its labelling.

Further, the Battery Directive is implemented by each member state through its national legislative body and national battery law[19]. Therefore, there can be some slight variations on the battery requirements among each member state, mostly presented in the registration procedures and collection schemes[21].

In Sweden, section 7 of the Ordinance on producer responsibility for batteries'[19] objectives for *collection of batteries* are:

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[22] Swedish Environmental Protection Agency, Producer Responsibility for Batteries, https://www.naturvardsverket.se/en/guidance/extended-producer-responsibility-epr/producers-responsibility-for-batteries/, accessed at 2021-12-11

[23] Based on Jiang G., Pickering S. J., Recycling supercapacitors based on shredding and mild thermal treatment, https://www.researchgate.net/publication/283544798_Recycling_supercapacitors_based_on_shredding_and_mild_thermal_treatment, accessed at 2021-12-11

1. that 95 percent of the total number of sold *car and industrial batteries containing lead* is collected;

2. that 95 percent of the total number of sold *car and industrial batteries that do not contain lead are collected*, and

3. that 75 percent of the total number of batteries sold *other than those referred to in 1 and 2* be collected.

Section 8 of the Ordinance's objectives for *special disposal and recycling* are[19]:

1. in the case of *batteries containing mercury*, that 98% of the mercury content of the batteries is disposed of separately;

2. in the case of *lead-containing batteries*, that 65% of the average weight of the batteries is recovered with the highest possible recovery rate of the lead content;

3. in the case of *batteries containing nickel-cadmium*, that 75% of the average weight of the batteries is recovered with the highest possible recovery rate of the cadmium content, and

4. in the case of *batteries other than those referred to in 1-3*, that 50% of the average weight of the batteries is recovered.

It is also important to notice that Section 6 the Ordinance[19] aims to ensure that batteries are designed and manufactured in such a way that the *generation of waste is prevented* and, in the case of the waste that still arises, that producers shall provide systems for collecting the waste, that the batteries can be recycled and that the regulation's objectives for collection, especially disposal and recycling should be reached.

3.1.2 The Battery Directive revision

Since 2006, batteries and waste batteries have been regulated at EU level under the Batteries Directive (2006/66/EC), as summarized in the previous chapter.

In our fast-developing society, the demand for batteries is increasing rapidly and is set to increase 14-fold by 2030[24]. As a part of the Circular Economy Action Plan, in December 2020, the European Commission proposed to modernise the EU legislation on batteries in order to secure the sustainability and competitiveness of battery value chains, and thus replace the current Battery Directive. It would introduce *mandatory requirements on sustainability* for all batteries placed on the EU market[25], i.e., for industrial, automotive, electric vehicle and portable batteries. Requirements such as use

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[24] European Commission, Green Deal, Sustainable batteries for a circular and climate neutral economy, https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2312, accessed at 2021-12-11

[25] European Commission, New regulatory framework for batteries, Setting sustainability requirements, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689337/EPRS_BRI(2021)689337_EN.pdf, accessed at 2021-12-16

of responsibly sourced materials with restricted use of hazardous substances, minimum content of recycled materials, carbon footprint, performance and durability and labelling, as well as meeting collection and recycling targets, are proposed[24].

Some specific measures that are relevant for the current exploratory study are:

- From 1 July 2024, only rechargeable industrial and electric vehicles batteries for which a *carbon footprint declaration* has been established, can be placed on the market[24].
- A *recycled content declaration* requirement, which would apply from January 2027 to industrial batteries, EV batteries and automotive batteries containing cobalt, lead, lithium or nickel in active materials. Mandatory minimum levels of recycled content would be set for 2030 and 2035 (i.e. 12 % cobalt; 85 % lead, 4 % lithium and 4 % nickel as of 1 January 2030, increasing to 20 % cobalt, 10 % lithium and 12 % nickel from 1 January 2035, the share for lead being unchanged)[25].
- Minimum *electrochemical performance and durability* requirements for portable batteries of general use (applying from 1 January 2027), as well as for rechargeable industrial batteries (from 1 January 2026) [25].
- From January 2026, introduction of *Battery Passport* for increased transparency and traceability of large batteries throughout their life cycle (for EV and industrial rechargeable batteries with capacities larger than 2kWh). A Battery Passport resembles a digital ID that's unique to each battery and is relevant for the development of the secondary battery markets and for other traceability purposes.
- Due diligence obligations for economic operators as regards the sourcing of raw materials[25].
- Requirements relating to the operations of repurposing and remanufacturing for a second life of industrial and EV batteries[25]. Batteries have to be long-lasting and safe, and at the end of their life, they should be repurposed, remanufactured or recycled, feeding valuable materials back into the economy. The proposed regulation defines a framework that will facilitate the *repurposing of batteries* from electric vehicles so that they can have a second life, for example as stationary energy storage systems, or integration into electricity grids as energy resources[24].
- As regards recycling efficiencies, among others, new targets for lithium-based batteries (65 % by 2025, 70 % by 2030). The proposed regulation also envisages specific material recovery targets, namely 90 % for cobalt, copper, lead and nickel, and 35 % for lithium, to be achieved by the end of 2025. By 2030, the recovery levels should reach 95 % for cobalt, copper, lead and nickel, and 70 % for lithium[25].

As a whole, with this proposal, the Commission aims to boost the circular economy of the battery value chains and promote more efficient use of resources with the aim of minimising the environmental impact of batteries. The proposal is part of the European

Green Deal[26] and related initiatives, including the new circular economy action plan[27] and the new industrial strategy[28]. See Appendix I for the outline of the main requirements and timelines introduced for each battery category and within the three main areas of the proposal[29]:

- Sustainability and safety
- Labelling and information requirements
- End-of-life management

3.1.3 WEEE directive

The Directive on waste electrical and electronic equipment (WEEE) aims to prevent or reduce the negative environmental effects resulting from the generation and management of WEEE and from resource use[30]. This by reducing the amount of electrical and electronic waste going to landfill sites and improve recovery and recycling rates of these products. 'Electrical and electronic equipment' or 'EEE' means equipment which is[17]:

1. Designed for use with a voltage rating not exceeding 1 000 volts for alternating current and 1 500 volts for direct current
2. Dependent on electric currents or electromagnetic fields in order to work properly
3. Equipment for the generation of such currents, or
4. Equipment for the transfer of such currents, or
5. Equipment for the measurement of such currents.

The EEE excluded from the Directive are military and security, medical instruments, large scale stationary industrial tools and other special uses[17].

From 15 August 2018 onwards the scope of the Directive is widened to include all EEE. All EEE shall then be classified within 6 categories instead of the existing 10 categories such as: 1. Temperature exchange equipment; 2. Screens, monitors, and equipment containing screens having a surface greater than 100 cm^2; 3. Lamps; 4. Large equipment (any external dimension more than 50 cm); 5. Small equipment (no external dimension

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[26] European Commission, The European Green Deal, 2019, https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF, accessed at 2021-12-16

[27] European Commission, A new Circular Economy Action Plan For a cleaner and more competitive Europe, 2020, https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF, accessed at 2021-12-16

[28] European Commission, European industrial strategy, https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age/european-industrial-strategy_en, accessed at 2021-12-16.

[29] Minespider, Charging up for the new Battery Regulation Proposal, 2021, https://www.minespider.com/blog/charging-up-for-the-new-eu-battery-regulation-proposal, accessed at 2021-12-16

[30] European Commission, Frequently Asked Questions on Directive 2012/19/EU on Waste Electrical and Electronic Equipment(WEEE), https://ec.europa.eu/environment/pdf/waste/weee/faq.pdf, accessed at 2021-12-13

more than 50 cm); 6. Small IT and telecommunication equipment. Thus, the Directive covers all EEE used by consumers and EEE intended for professional use [30].

Examples of EEE that are covered by the Directive and might be relevant for the current research study are:

- Supercapacitors
- Radio Frequency Identification RFID tags (active and passive) meet the definition of EEE (Points 1-5 above)[30]
- Antennas and cables used for the transfer of electrical currents and electromagnetic fields meet the definition of EEE (see Points 1-5 above)[30]

From 2019, the minimum separate collection rate shall be 65 % calculated on the basis of the total weight of WEEE collected[31]. Recovery and recycling / preparing for reuse targets vary according to EEE type, being for instance 85% and 80% respectively for large equipment (any external dimension more than 50 cm) and 75% and 55% respectively for small equipment and small IT and telecommunication equipment (no external dimension more than 50 cm).

The overall amount of EEE placed on the market was 11.6 million tonnes in 2015. Currently in the EU, only one third of WEEE is being reported as separately collected and appropriately managed[49].

Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS)[32] is the EU Directive restricting the use of hazardous substances in electrical and electronic equipment (e. g. heavy metals like lead, mercury, cadmium etc) to protect the environment and public health. It is important to comply with RoHS for each component in EEE.

3.1.3.1 El-Kretsen – extended producer responsibility scheme for battery waste and WEEE in Sweden

El-Kretsen is the largest nation-wide collection and recycling system in Sweden and is divided into two categories: households and businesses[33]. The household collection is called “elretur” and is administered in co-operation with all of Swedens’ 290 municipalities. The collection from businesses is administered jointly with both municipalities and contracted transport carriers.

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[31] European Commission, Summary document of the Waste electrical and electronic equipment rates and targets, https://ec.europa.eu/eurostat/documents/342366/351758/Target-Rates-WEEE/b92a549c-7230-47ba-8525-b4eec7c78979, accessed at 2021-11-11.

[32] European Commission, DIRECTIVE 2011/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, 2011, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0065&from=EN, accessed at 2021-12-18.

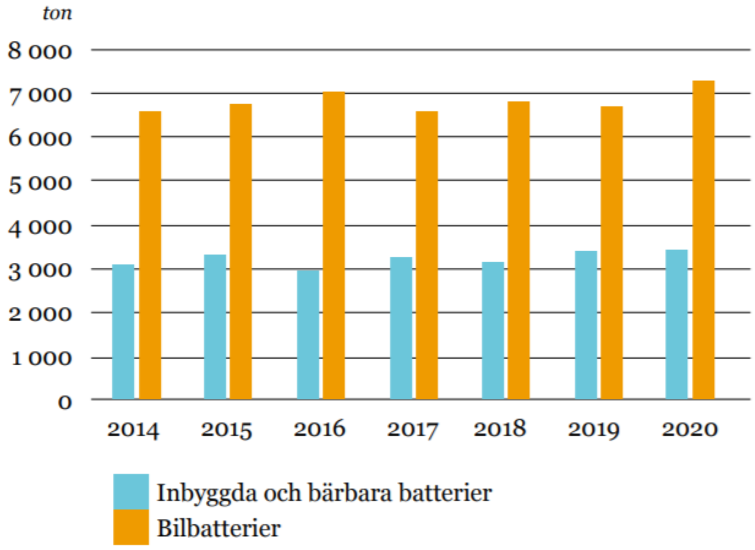
[33] El-Kretsen, Collections statistics, https://kunskapsrummet.com/en/statistics/, accessed at 2021-12-11

Table 2 The amounts collected and treated in Sweden that are reported by El-Kretsen to the Swedish Environmental Protection Agency in six separate categories[20].

Collected (weight in tonnes)	2019	2020
Small appliances	80 225	84 512
Refrigerators and freezers	24 662	28 120
White goods	35 805	36 017
Batteries	3 383	3 460
Fluorescent lamps **(compact and straight)**	1 878	1 813
LED and incandescent light bulbs	624	616
Other/professional electronics	1 030	1 183
Total	**147 627**	**155 721**

In Sweden in 2020, the total collection of electrical and electronic products and batteries amounted to 156 thousand tonnes which corresponds to approximately 15 kilograms per person and is an increase by 5.5 per cent since 2019 (as reported by the largest nation-wide collection scheme El-Kretsen), see Table 2.

Table 3 Amounts of collected batteries during 2014 – 2020 (blue columns – inbuilt and portable batteries; orange columns – automotive batteries)[34].



Batteries are sorted by chemical content before they are sent for recycling or disposal. In 2020, 3460 tons of batteries were collected and treated by El-Kretsen, whereas the

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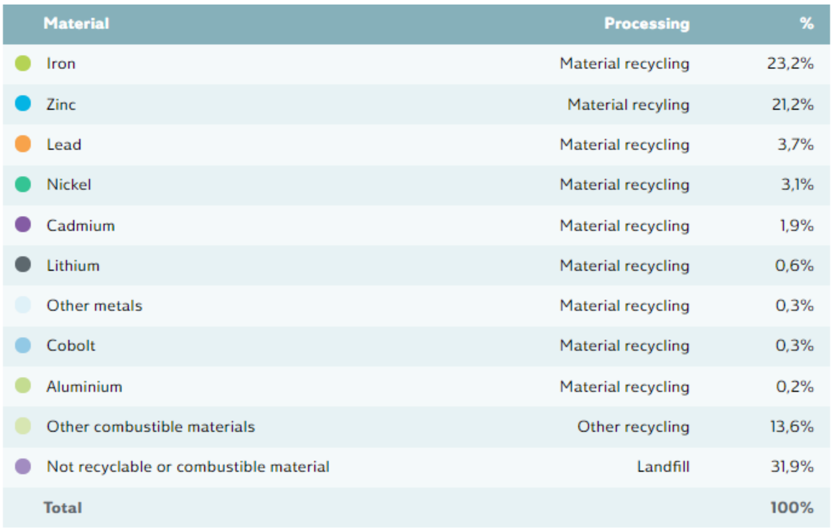
[34] Afvall Sverige, Svensk Avfallshantering 2020, https://www.avfallsverige.se/fileadmin/user_upload/4_kunskapsbank/Svensk_Avfallshantering_2020_publ2021_01.pdf, accessed at 2021-12-11

largest material fractions were 31,9% non-recyclable or combustible material, 23,3% iron and 21,2% zinc.

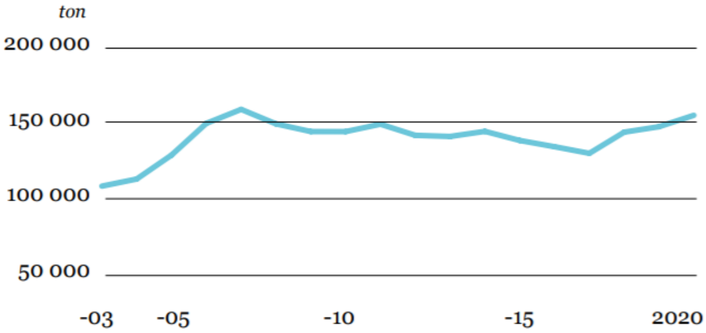
Table 4 Materials content in batteries and their respective end-of-life treatments[35].



	Material	Processing	%
●	Iron	Material recycling	23,2%
●	Zinc	Material recyling	21,2%
●	Lead	Material recycling	3,7%
●	Nickel	Material recycling	3,1%
●	Cadmium	Material recycling	1,9%
●	Lithium	Material recycling	0,6%
●	Other metals	Material recycling	0,3%
●	Cobolt	Material recycling	0,3%
●	Aluminium	Material recycling	0,2%
●	Other combustible materials	Other recycling	13,6%
●	Not recyclable or combustible material	Landfill	31,9%
	Total		**100%**

Other collection systems in Sweden are Recipo[36], BlybatteriRetur[37].

Table 5 Amounts of collected electric waste during 2003 – 2020[34].



Totally 155,840 tonnes of electrical waste excluding batteries were collected in Sweden in 2020. This is an increase of 6 percent, compared with 2019.

Under the Producer EPR scheme, all companies affiliated with the system in Sweden pay environmental fees in relation to the amount and type of batteries and EEE their operations generate (the fees are weight-based).

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[35] El-Kretsen, Sustainability Report, https://kunskapsrummet.com/en/sustainability-report-2020/, accessed at 2021-12-11

[36] https://recipo.com/, accessed at 2021-12-11

[37] https://blybatteriretur.se/, accessed at 2021-12-11

3.1.4 Packaging and packaging waste legislation

The EU has launched a number of laws in the new circular economy action plan[27] aiming at packaging and packaging waste. Among these, the most relevant is The European Parliament and Council Directive 94/62/EC on Packaging and Packaging Waste (PPWD)[38], which provides measures aimed at preventing the production of packaging waste and promoting reuse, recycling, and any other forms of material recovery. The EU Commission expects that these measures will lead to a reduction in the final disposal of packaging and, therefore, contribute to the transition towards a circular economy.

The requirements set by the *Directive 94/62/EC* apply to all packaging placed on the EU market. Some of these requirements focus on *packaging construction (design of packaging),* while others focus on *packaging collection and recycling*. The former ones are the so-called *Essential Requirements* and they include measures such as:

(i) weight and volume of the packaging must be kept to a minimum;
(ii) packaging should permit re-use or recycling/material recovery, and
(iii) the content of harmful and hazardous substance must be minimized.

For packaging producers in order to evaluate whether their packaging meets the criteria set in the *Essential Requirements* (packaging design requirements) of the PPWD directive, the standards EN 13427-13432[39] can be applied as guidance, see Figure 4. In particular, the packaging should be evaluated for prevention of packaging waste, for at least one of the recovery standards (material recovery, energy recovery and/or composting) and for the reuse standard, if the latter is applicable.

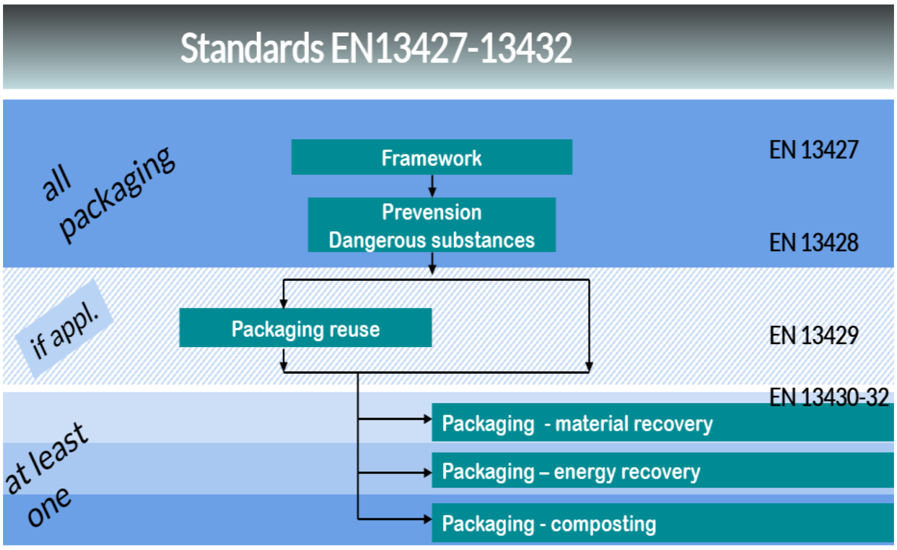

Figure 4. Requirements covered by the EN standards 13427-13432 on packaging and packaging waste.

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[38] European Parliament and Council Directive 64/62/EC of 20 December 1994 on packaging and packaging waste. Link: https://www.compostnetwork.info/wordpress/wp-content/uploads/CELEX_01994L0062-20180704_EN_TXT.pdf

[39] CEN-EN 13427- Packaging -Requirement for the use of European Standards in the field of packaging and packaging waste, 2004.

Regarding material renewability, the directive welcomes different incentives that promote waste hierarchy and minimization of environmental impacts of packaging and packaging waste from a life-cycle perspective. This considering, if appropriate, the benefits of using bio-based materials and materials suitable for multiple recycling.

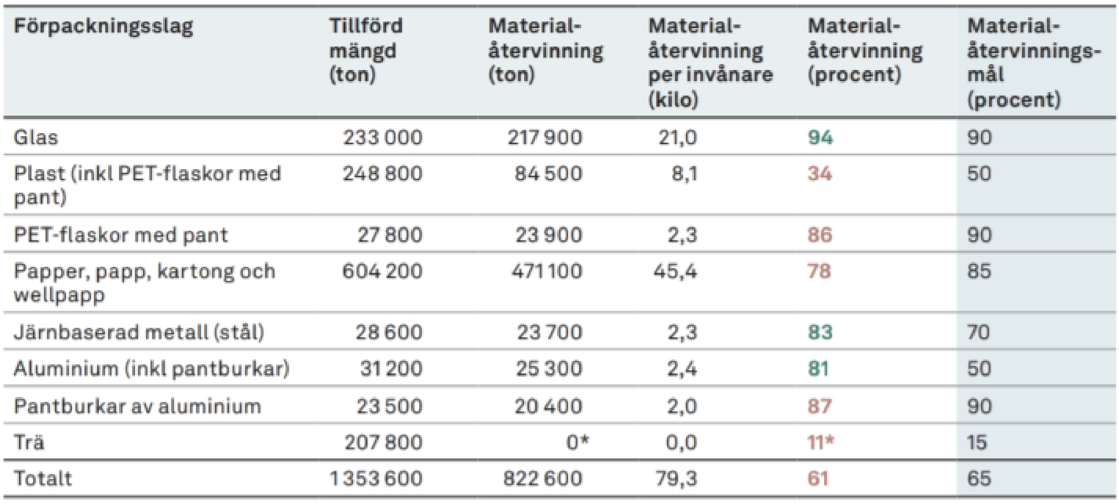
The EU legislation is implemented into the Swedish national legislation through *Regulation on producing responsibility for packaging*, Regulation (2018:1462)[40]. The regulation covers the design requirements of the packaging (*Essential requirements* in the EU Directive 94/62/EC) and the collection and recycling requirements (including recycling rates for packaging waste).

The essential requirements should be fulfilled, Individual responsibility of all companies that put packaging on the market. The Swedish Standards Institute (SIS) has issued the Swedish versions of the EU standards for evaluation of whether packaging meets the essential requirements:

- Prevention of waste (SS-EN 13428:2004)
- Re-use (SS-EN 13429:2004)
- Material recovery (SS-EN 13430:2004)
- Energy recovery (SS-EN 13431:2004)
- Composting and biodegradation (SS-EN 13432:2000)
- Instructions for applying the above standards (SS-EN 13427:2004)

The *overall* recycling rate of packaging, including different types of packaging materials (i.e., plastics, metal, paper, glass and wood) in Sweden is 61%, which is slightly lower than the current packaging recycling target set at 65 %[41].

Table 6 Packaging recycling rates and targets (from January 2021) in Sweden.



Förpackningsslag	Tillförd mängd (ton)	Material-återvinning (ton)	Material-återvinning per invånare (kilo)	Material-återvinning (procent)	Material-återvinnings-mål (procent)
Glas	233 000	217 900	21,0	94	90
Plast (inkl PET-flaskor med pant)	248 800	84 500	8,1	34	50
PET-flaskor med pant	27 800	23 900	2,3	86	90
Papper, papp, kartong och wellpapp	604 200	471 100	45,4	78	85
Järnbaserad metall (stål)	28 600	23 700	2,3	83	70
Aluminium (inkl pantburkar)	31 200	25 300	2,4	81	50
Pantburkar av aluminium	23 500	20 400	2,0	87	90
Trä	207 800	0*	0,0	11*	15
Totalt	1 353 600	822 600	79,3	61	65

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[40] Förordning (2018:1462) om producentansvar för förpackningar, 2018 (amended 2020), https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/forordning-20181462-om-producentansvar-for_sfs-2018-1462. Access: 25/10/2021.

[41] Naturvårdsverket, Sveriges återvinning av förpackningar och tidningar, 2021, https://www.naturvardsverket.se/contentassets/568ba7678ce94e25b99cfc1b02ad7e2a/forpackningsrapport_2020_211027.pdf, accessed at 2021-11-11.

A look at the recycling of packaging waste targets and rates in Sweden shows that the paper packaging waste recycling rate year 2020 was 78% (corresponding to 471 100 tonnes) and the new recycling target is set to 85%, see Table 6. The highest recycling rates are found for glass packaging (94%) followed by deposit aluminium cans (87%) and deposit PET bottles (86%).

The Packaging and Packaging Waste Directive is complemented with additional amendments and guidelines, including the guidance[42,43] on packaging composition in the context of verifying a packaging towards fulfilment of recycling targets. Here, if the packaging consisting of more than one material or composite packaging, with the proportion of such material being lower than 5% of the total packaging weight, that packaging material is considered insignificant and thus does not need to be separately accounted in the attainment of the recycling targets and vice versa (which influences obligations for calculation and reporting materials contained in a packaging).

3.1.4.1 FTI – extended producer responsibility scheme for packaging and packaging waste in Sweden

FTI (Förpacknings- och Tidningsinsamlingen)[44] is the main collection system in Sweden. It organises the collection system for household and non-household packaging waste. Both households and businesses are required to sort their packaging waste. The packaging waste can be disposed at packaging return points, drop-off sites/waste disposal rooms, and/or recycling stations.

All companies affiliated with the system in Sweden pay packaging fees in relation to the amount of packaging material their operations generate (the packaging fees are weight-based). Since 2019, the FTI has introduced an economic incentive in terms of differentiation of packaging fees (level 1 and level 2 fess) in order to encourage design for recycling or recyclability of packaging materials.

According to the incentive principles, the producers pay a lower fee for packaging material that is introduced on the Swedish market, if the packaging material is easily recyclable, and vice versa. Level 1 (the higher fee) comprises all paper packaging, including corrugated cardboard, with any form of:

- Plastic, wax or aluminum barrier
- Attached “windows" made of plastic
- Wet strength paper (paper that does not dissolve in water)
- Composite material consisting of a mixture of paper fiber and plastic.

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[42] European Commission, COMMISSION IMPLEMENTING DECISION (EU) 2019/665 of 17 April 2019 amending Decision 2005/270/EC establishing the formats relating to the database system pursuant to European Parliament and Council Directive 94/62/EC on packaging and packaging waste, see Article 6c(2), https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32005D0270&from=EN, accessed at 2021-12-20.

[43] European Commission, Guidance for the compilation and reporting of data on packaging and packaging waste according to Decision 2005/270/EC, https://ec.europa.eu/eurostat/documents/342366/351811/PPW+-+Guidance+for+the+compilation+and+reporting+of+data+on+packaging+and+packaging+waste.pdf/297d0cda-e5ff-41e5-855b-5d0abe425673?t=1621978014507, accessed at 2021-12-10.

[44] FTI, www.ftiab.se, accessed at 2021-11-15.

Level 2 (the lower fee) comprises all paper packaging, including corrugated cardboard, consisting solely of paper. The Level 1 fee for paper packaging is currently 35% higher, being charger per each kilogram of packaging material introduced on the Swedish market. Similar differentiated fees are also introduced for plastic packaging.

3.1.5 Discussion

It is the energy generation mechanisms as well as the application that define whether the product is a battery or EEE. In accordance with the Battery Directive, the biobased battery for large-scale grid storage applications in Case Study I can be classified as industrial battery with a requirement of 50% to be materially recycled. Therefore, it is advantageous if the biobased battery can be materially recycled partially or fully in order to contribute to the recycling target.

The biobased printed supercapacitor for large-scale grid storage applications in the Case Study II is an electrical energy storage solution, which can be classified as EEE. Different value chain actors though interpret supercapacitors as either a battery or an EEE. In the latter case, the recovery and recycling / preparing for reuse targets vary between 55%-85%.

The implementation of the current Battery directive and its impact on the environment as well as the functioning of the internal market was found to have a number of shortcomings related to its incapacity to incorporate technological novelties and new usages of batteries, the unsatisfactory collection of waste batteries and the insufficient recovery of materials[25].

For instance, the directive does not promote recycling of materials that are critical or have a high environmental burden[45], which in practice results in their loss due to lack of economy in recycling processes. In particular, lithium-based batteries fall within the scope of the directive but are not addressed specifically by its provisions, same is valid for critical raw materials such as cobalt, nickel etc. Another example of the inadequacy of the current directive was that there were no target rates for recycled content[46]. The same is valid for the WEEE Directive. Lacking specific requirements in end-of-life processes, the abovementioned directives (including the RoHS Directive) rather pose restriction on the limits of substances hazardous for health and environment in production processes of batteries and EEE.

The Case Study III iterates the usage of the abovementioned biobased battery or the biobased printed supercapacitor as energy storage components in intelligent packaging applications. The intelligent packaging will fall under the Battery or WEEE directives' producer responsibility schemes since it contains battery or supercapacitor components and will be classified respectively. However, in practice, the intelligent packaging will be perceived and sorted as paper packaging waste by consumers or businesses and thus enter paper recycling stream. The material recycling target for paper packaging is set to

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[45] Ellingsen, L. A-W. & Hung, C. R. 2018, Research for TRAN Committee – Resources, energy, and lifecycle greenhouse gas emission aspects of electric vehicles, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels

[46] European Commission, Batteries Directive briefing, https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/654184/EPRS_BRI(2020)654184_EN.pdf, accessed at 2021-12-18.

85%. Such packaging will be subjected to a higher national packaging fee when introduced on the Swedish market since the packaging material will not be classified as packaging consisting solely of paper. Moreover, the 5% limit of containment of more than one material in the packaging (i.e., energy storage component in case study III) or composite packaging is important to be aware of when verifying and reporting the overall packaging recyclability rate. It should also be noted that if such intelligent packaging is intended for food contact, the legislation on food contact materials should apply additionally.

According to the Swedish case study on differentiated producer responsibility fees for EEE, it was doubtful that implementation of such fees in Sweden or any other relatively small markets will lead to changes in product design. The main reason is that the electrical and electronic sector often operates globally, thus reducing the incentives to modify the product design for a single market[47].

To summarize, in the legislation overview it was observed that the biobased energy storage solutions can become attractive alternatives to the traditional ones, not least due to shifting the European legislative focus to stronger environmental perspective (e.g., through carbon footprint declarations) and awareness of raw materials supply risks etc, as discussed in the Battery revision proposal. It is important that the energy storage solutions are sustainable along their entire life cycle.

The measures that the Commission proposes will facilitate achieving climate neutrality by 2050[24].

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[47] Fråne A., IVL, Re:Source, Differentiated producer responsibility fees – case study for electrical and electronic equipment, 2018, http://databas.resource-sip.se/storage/kJvesezCt4RQNzZuiNGRmx7dbNZskGaYmOBRLv1v.pdf, accessed at 2021-11-11.

3.2 Circularity potential

The circular economy action plan identified batteries among resource-intensive sectors with high potential for circularity to be addressed as a matter of priority[25]. Therefore, it is crucially important to consider the whole life cycle perspective already in the development stages of the novel biobased battery and, also biobased printed supercapacitor solutions.

In the current chapter, exploration of the circularity potential of the biobased solutions on the short- and long term is analysed. The short-term time frame is defined as a 2-5 years perspective and therefore implies utilization of current waste management infrastructure as end-of-life routes. The long-term perspective covers the timeframe of 5-15 year from now and in this scenario the waste management methods are assumed to be more abundant and economically viable.

The chapter starts with a brief overview of lithium-ion battery recycling, i.e., recycling of the benchmark solutions.

3.2.1 Lithium-ion battery recycling

In the EU there are around 10 industrial recycling facilities for lithium-ion batteries (LIBs) with a total processing capacity of 38,000 tonnes per year[48]. Li-ion cells and modules are currently recycled in existing industrial facilities using a combination of different operations such as mechanical, pyrometallurgical and hydrometallurgical treatments[49].

The *pyrometallurgical* method (thermal processes) comes with one main advantage: simplicity of the process. Any battery cell just needs to be filled into a large shaft furnace. However, plastics, separator, electrolyte and all other volatile components cannot be recycled and both the quality and quantity of the few regained metals are low[50]. The current industrial processes utilizing pyrometallurgy are focused on recovering metals like cobalt, nickel and copper. Graphite and lithium are usually not recovered but lithium ends up in slag after the pyrometallurgical treatment.

Hydrometallurgy, i.e., leaching, solution purification and metal recovery, demands prior physical separation and sorting processes of the battery components, since the efficiency and selectivity of leaching and subsequent solvent extraction decreases with an increasing spectrum of components[50]. When using hydrometallurgical recycling, lithium can also be recovered. To date it has not been considered economically feasible, though. Recycling efficiencies for LIBs and their materials *are estimated* at about 95 per cent for

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[48] Alves Dias, P., et al., 2018, Cobalt: demand-supply balances in the transition to electric mobility, EUR 29381 EN, Publications Office of the European Union, Luxembourg, JRC112285.

[49] European Environmental Agency, ETC Report: Are we losing resources when managing Europe´s waste?, https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/are-we-losing-resources-when-managing-europes-waste-1, accessed at 2021-12-18.

[50] Wolf A. et al., Centrifugation based separation of lithium iron phosphate (LFP) and carbon black for lithium-ion battery recycling, Chemical Engineering and Processing - Process intensification, https://www.sciencedirect.com/science/article/pii/S0255270121000143, accessed at 2021-11-11.

cobalt (Co) and nickel (Ni), 80 per cent for copper (Cu) and 50 per cent for aluminium (Al), depending on the specific process. Graphite is not recovered. The battery management system also contains valuable materials (such as tin, silver, and gold) relevant for recycling[51].

Similar to hydrometallurgy, *direct recycling* comes with a high complexity in terms of process engineering, including many different physical separation and sorting techniques. However, most of the battery components can be recycled[50].

The chemical composition and design of a battery depend on the manufacturer, which causes challenges for recycling as different chemistries (LMO, LNO, LCO, NCA, NMC, LFP etc) of lithium-ion batteries are currently not indicated on the battery packs. International standards for battery markings including the chemistry would reduce economic and material losses as well as ensure safe handling of batteries during the recycling process[52].

In the case of EV lithium-ion battery packs, the housing of the battery pack and modules corresponds to almost half of the total mass of the battery system and the amount of Co can be as low as 3 to 5 per cent of the total mass. In the directive on waste batteries, the minimum recycling efficiency that must be achieved is set by average weight, and for ‘other battery’ category the required efficiency is 50 per cent.

While closing the material loops as much as possible would help reduce raw material supply risks, within the EU, the volume of recovered metals that are used in battery manufacturing is currently low. Only 22 % of cobalt, 8 % of manganese, 16 % of nickel and 12 % of aluminium used within the EU is actually recycled.

Today, almost no lithium is recovered in the EU because it is deemed not cost-effective compared with primary supplies (i.e., virgin lithium). Recycling is geared towards recovering cobalt, nickel and copper, considered more economically valuable[25].

3.2.2 Case Study I – Biobased battery

The analysis of the circularity potential was initiated by mapping the components of the biobased battery. It is the choice of battery materials together with how the battery is constructed that to a high extent pre-define circularity capabilities already in the beginning of life cycle.

The Ligna Energy battery concept is a roll-to-roll manufacturing set-up that uses a combination of water-based electrolyte, metal collectors, binders and organic polymers with carbon, cellulose and lignin from the forest, with the total weight of 200 grams per battery cell[12], see Figure 5.

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[51] Stahl et al., 2018, Study in support of evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators -Final Report, Rotterdam, 8 October 2018

[52] Tecchio, P., Ardente, F., Marwede, M., Christian, C., Dimitrova, G. and Mathieux, F., 2018, Analysis of material efficiency aspects of personal computers product group, EUR 28394 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-64943-1.

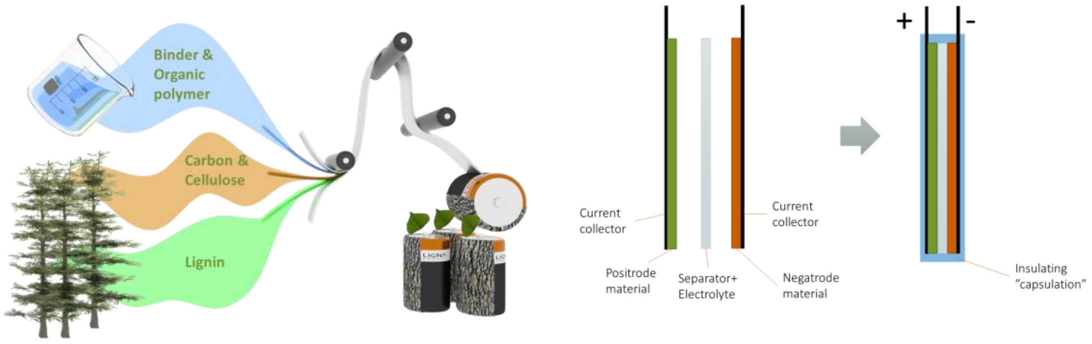

Figure 5 Visionary and schematic diagrams of the Linga Energy biobased battery cell.

The raw materials used in the production of the biobased batteries are presented in Table 7:

Table 7 Raw material composition of the Ligna Energy biobased battery concept.

Positrode:	**39%**
• Lignin 50%	
• Carbon Black 45%, Forest based or Petroleum-based	
• Binder 5%, Cellulose based (CMC)	
Negatrode:	**17%**
• Organic Polymer 50% (1/3 biobased)	
• Carbon Black 45%, Forest based or Petroleum-based	
• Binder 5%, Cellulose based (CMC)	
Collectors:	**14%**
• Aluminum	
Electrolyte:	**10%**
• Water	
• Non fluorinated salts	
• Anti freezing agent (e.g glycerol)	
Separator:	**2%**
• Cellulose or Petroleum-based	
Insulating capsulation:	**18%**
• Cellulose based or same as Li-ion (stainless steel)	

The biobased content of the battery was calculated based on the weight of different components, being 61,3%-79,3% depending on the choice of insulating capsulation material.

Circularity potential on the short-term

The next step in the circularity potential analysis was to map possible recovery routes for the biobased battery in the current end-of-life infrastructure. Totally, two routes were identified as technically and economically viable: material recycling and incineration with energy recovery. In particular, the recycling of collector material (aluminium) and insulating capsulation materials (stainless steel or possibly cellulose) is viable today when the battery at its end-of-life is collected as a battery waste. At a battery and WEEE recycling facility the battery will be shredded into small pieces and the metals will be separated out for further recycling. Rest of the battery components have no material value for recyclers today and will be sent to incineration with energy recovery, see Table 8.

As discussed earlier in the report, according to the Battery Directive, the biobased battery in Case Study I can be classified as an industrial battery with material recycling target of 50% (see Chapter 3.1.5). Therefore, it is advantageous if the battery can be materially recycled partially or fully in order to contribute to the recycling target. The current recycling potential of the biobased battery considering economic viability of recycling processes**Error! Bookmark not defined.**,[53] is estimated to 14%-32% (recovery of aluminium and a lso stainless steel, if the encapsulation chosen is metal-based).

Table 8 Summary of the recovery routes and value of the Case Study I Biobased battery in today's end-of-life infrastructure.

Case study I	**Biobased battery**
Recovery routes	**Scenario 1:** Separation of certain components for material recycling and incineration with energy recovery of the rest of components as non-hazardous material. **Scenario 2:** Incineration with energy recovery of the whole battery as non-hazardous material.
Recovery of which components?	**Scenario 1:** Material recycling of base metals (stainless steel and aluminum) and eventually cellulose after separation from electrode materials. **Scenario 2:** Incineration with energy recovery in terms of electricity and heat.
Recovery incentives	Contributing to EU and national material recycling targets economic incentives for material recovery of base metals, energy value recovery.

When incinerated, the biobased materials containing carbon will release biogenic carbon dioxide emissions, being a part of the renewable carbon cycle between the biosphere and the atmosphere. The biobased battery contains lignocellulosic components, which may cause SO_x emissions and therefore need to be controlled at incineration plants in order not to affect both health and the environment (e.g., formation of small particles in the atmosphere, acid rains, decrease growth of trees and plants). No chlorine-containing organic materials are present in the battery and therefore no chlorine-based emissions will occur at incineration process.

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[53] Personal communication with Stena Recycling, April-September 2020.

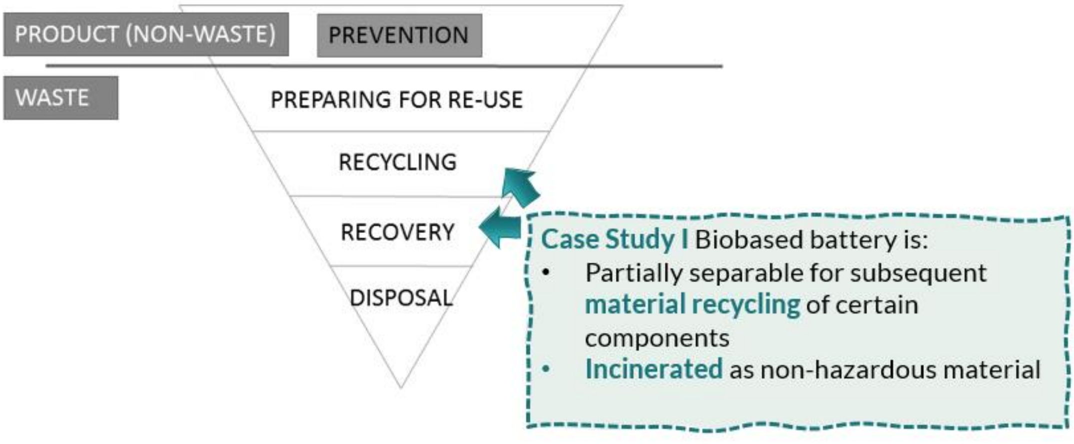

Figure 6 Mapping of Case Study I Biobased battery on the EU Waste Hierarchy, from a short-term perspective.

The results above were also mapped in the context of the EU Waste Hierarchy that defines a 'hierarchy' in waste management in EU, see Figure 6. According to the Hierarchy principles, waste prevention and re-use are the most preferred options, followed by recycling (including composting), then energy recovery, while waste disposal through landfills should be the very last resort.

An additional end-of-life scenario discussed was the scenario where the carbon is classified as recycling is smelting[53]. Smelting, a process by which metals obtained, either as the element or as a simple compound, from its ore by heating beyond the melting point, ordinarily in the presence of oxidizing agents, such as air, or reducing agents, such as coke[54]. The partial combustion of the carbon source produces carbon monoxide which acts as a reducing agent. Here, the biobased carbon in the biobased battery may act as an alternative biobased reduction agent in reduction smelting facilities.

Circularity potential on the long-term

Circularity potential of the biobased battery was further iterated beyond the current end-of-life options. The discussion resulted in increased material recycling degree from 32% to 57% due to additional recovery of carbon black. Furthermore, material recycling of the cellulose-containing components could also be attractive if larger volumes of such waste stream would occur at battery and electronics recycling facilities[27]. The materials such as paper, metals and glass are widely recycled today in other applications such as packaging.

Different recycling methods are being researched nowadays. For instance, the materials can be shredded followed by mild thermal treatment in order to recover electrode materials, solvents and aluminium[55] or carbon black recovered by centrifugation[50], these

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[54] Britannica, Smelting, https://www.britannica.com/technology/smelting, accessed at 2021-12-16.

[55] Jiang G., Pickering S. J., Recycling supercapacitors based on shredding and mild thermal treatment, Waste Management, https://www.sciencedirect.com/science/article/pii/S0956053X15301768, accessed at 2021-11-11.

instead of thermal processes that are commercially practiced nowadays, removing all organic matter.

Based on the discussions above, the maximum possible recycling degree of 80% was estimated. In this scenario, the components of the whole battery could be recycled apart from the lignin-based components due to too low material value for recyclers.

Organizing take-back systems with reuse / repurposing options for the biobased batteries was not relevant in this case study since the batteries are supposed to serve their total lifetime in the same application that is heavy stationary batteries prior removal for end-of-life management.

Case study I conclusions

Today, the battery material recycling processes are strongly economically driven: the material components that are considered as valuable by recyclers are mainly base metals and to some degree critical raw materials. The biobased battery though does not contain any critical raw materials and uses base metals to less extent. Instead, it contains electrolyte solution that is dispersed in biobased carbon electrodes.

This can be interpreted as a dilemma since the material value in the end-of-life processes is sought from critical, non-renewable raw materials (e.g. cobalt, nickel and base metals like aluminium and steel), which have to be present in batteries in order to incentivize recycling and thus to reaching national and EU recycling targets. *The material value* of the biobased, renewable materials (more sustainable materials by origin) is considered low and therefore will be lost (i.e., incinerated). This decreases the overall battery material recycling potential as of today.

More balanced approach to this dilemma is urged in order to facilitate economic and environmental incentives in the battery value cycles. Both legislation needs to be adapted towards encouraging more sustainable-by-origin energy storage as well as alternative recycling procedures must be developed to biobased carbon components instead of incinerating these. Regarding legislation adaptation needs and in order to meet innovative development in the area, it can be relevant to introduce a cross-sectoral category ‘Biobased energy storage solutions’ in the upcoming legislation with aim to encourage use of more abundant, biobased materials rather than critical raw materials.

The circularity potential of the biobased battery varied between 32% to 80% depending on the timeframe of the analysis.

3.2.3 Case Study II – Biobased printed supercapacitor

The analysis of the circularity potential was started by mapping the components of the biobased printed supercapacitor, see Figure 7.

This energy storage solution is manufactured using screen printing technology, with the total weight of 10 grams per supercapacitor cell [13]. Printed electronics is one avenue of producing energy storage devices via potentially high-throughput procedures at the same time achieving customizable designs at low costs[56].

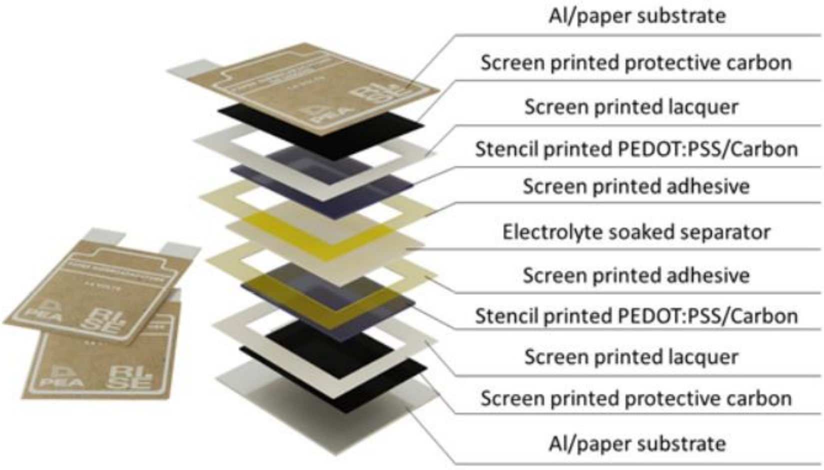

Figure 7 Schematic diagram of the RISE printed supercapacitor cell.

The biobased content of the supercapacitor was calculated based on the weight of different components, being 55,4%, see Table 9.

Table 9 Raw material composition of the RISE printed supercapacitor[13].

Electrolyte:	**37.75%**
• Ionic liquid (EMIM-ES)	29.1%
• Hydroxyethyl cellulose (HEC) as binder	2.36%
• Separator	6.3%
Adhesive (screen printed adhesive):	**0.31%**
Dielectric (screen printed lacquer):	**0.31%**
Electrodes:	**4.15%**
• Conductive polymer (PEDOT:PSS)	0.17%
• Carbon (activated carbon from coconut shell)	1.47%
• Cellulose binder (carboxymethylated pulp)	2.52%
Collector:	**10.28%**
• Screen printed carbon (petroleum based)	0.64%
• Aluminum (attached to the packaging material)	9.65%
Packaging material:	**47.82%**
• Paper mixed with small amount of plastic	

Circularity potential on the short-term

The next step in the circularity potential analysis was to identify possible recovery routes

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[56] Brooke R., Edberg J. et al., Supercapacitors on demand: all-printed energy storage devices with adaptable design, IOP Publishing, http://liu.diva-portal.org/smash/get/diva2:1416463/FULLTEXT01.pdf accessed at2021-11-11.

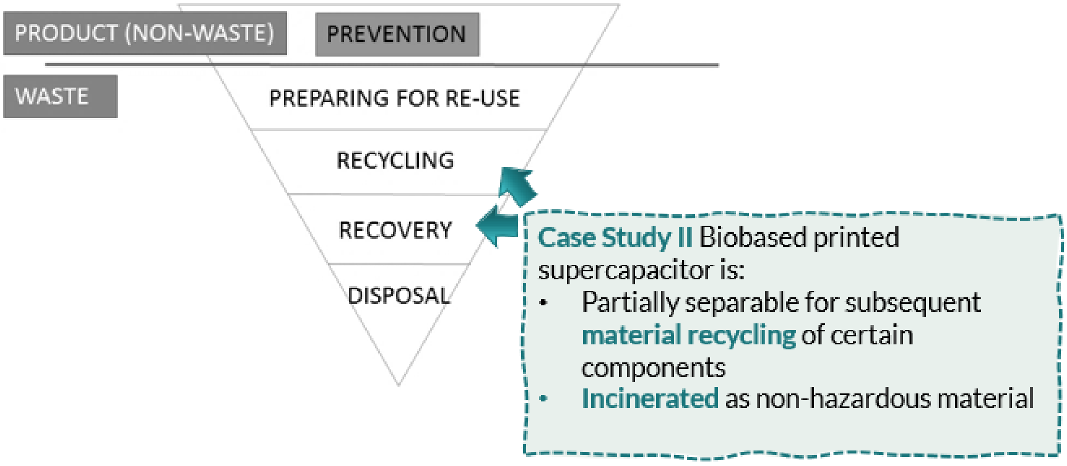
for the printed supercapacitor in the current end-of-life infrastructure. Similarly to Case Study I, two routes were identified as technically and economically viable: material recycling and incineration with energy recovery. The component that will be materially recovered is aluminium in collector and possibly packaging material when the discarded supercapacitor will be collected as WEEE at its end-of-life. At a battery and WEEE recycling facility it will be shredded into small pieces and aluminium will be separated out for further recycling. Rest of the components have no material value for recyclers today and will be sent to incineration with energy recovery, see Table 10.

Table 10 Summary of the recovery routes and value of the Case Study II Biobased printed supercapacitor in today's end-of-life infrastructure.

Case study II	Biobased printed supercapacitor
Recovery routes	**Scenario 1:** Separation of certain components for material recycling and incineration with energy recovery of the rest of components as non-hazardous material. **Scenario 2:** Incineration with energy recovery of the whole printed supercapacitor as non-hazardous material.
Recovery of which components?	**Scenario 1:** Material recycling of base metal (aluminum) and possibly cellulose after separation from electrode materials. **Scenario 2:** Incineration with energy recovery in terms of electricity and heat.
Recovery incentives	Contributing to EU and national material recycling targets, economic incentives for material recovery of base metals, energy value recovery.

As discussed earlier in the report, the printed supercapacitor for large-scale grid storage applications in the Case Study II is an electrical energy storage solution, which can be classified as EEE. Different value chain actors though interpret supercapacitors as either a battery or an EEE. In the latter case, the collection rate of 65% is the target, and recovery and recycling / preparing for reuse targets ranging from 55% to 85%. Therefore, it is beneficial if the supercapacitor can be materially recycled partially or fully in order to contribute to the recovery and recycling targets. The current recycling potential of the biobased supercapacitor considering economic viability of recycling processes is estimated to 9,7%-52,4% (recovery of aluminium and possibly cellulose fraction in the packaging material).

When incinerated, the biobased materials containing carbon will release biogenic carbon dioxide emissions, being a part of the renewable carbon cycle between the biosphere and the atmosphere. The supercapacitor contains rather expensive ionic liquid components, which may cause SO_x emissions and thus need to be controlled at incineration plants in order not to affect both health and the environment (e.g. formation of small particles in the atmosphere, acid rains, decrease growth of trees and plants). No chlorine-containing organic materials are present in the battery and therefore no chlorine emissions will occur at incineration process.



Case Study II Biobased printed supercapacitor is:

- Partially separable for subsequent **material recycling** of certain components
- **Incinerated** as non-hazardous material

Figure 8 Mapping of Case Study II Biobased printed supercapacitor on the EU Waste Hierarchy, from a short-term perspective.

Mapping of the supercapacitor in the context of the EU Waste Hierarchy showed similar results as in Case Study I, see Figure 8.

Circularity potential on the long-term

The circularity potential of the printed supercapacitor was further iterated beyond the current end-of-life options. Recyclers see the potential in recycling of ionic liquid due to their high economic value[53]. Ionic liquids (ILs) are a family of nonconventional molten salts that offer many advantages, such as negligible vapor pressures, negligible flammability, wide liquidus ranges, good thermal stability, and much synthesis flexibility[57]. Ionic liquids are used as organic solvents in recovery of critical metals like lithium, nickel, cobalt and can also be recovered for example from Li-ion battery electrolyte[58]. Ionic liquid recovery efforts would promptly increase the recycling potential of the printed supercapacitor to 81,6%.

Case study II conclusions

Today, the supercapacitor material recycling processes are also strongly economically driven as in the Case Study I. The components that are considered valuable for recycling are the base metal aluminium and possibly cellulose fibres in the packaging material.

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[57] Wang T. et al., Direct Recycling of Spent NCM Cathodes through Ionothermal Lithiation, https://onlinelibrary.wiley.com/doi/10.1002/aenm.202001204, Advance Energy Materials, accessed at 2021-11-11.

[58] Wang T. et al., Direct Recycling of Spent NCM Cathodes through Ionothermal Lithiation, https://onlinelibrary.wiley.com/doi/10.1002/aenm.202001204, Advance Energy Materials, accessed at 2021-11-11.

Further recycling of ionic liquid from the electrolyte solution would increase recyclability of these energy storage cells to a considerably higher extent.

As in Case Study I, the composition of the printed supercapacitor is a complex, multi-layer structure of cathode, anode, separator, electrolyte and other layers that are tightly stacked together, being not designed for easy disassembly. The screen-printed adhesives and laquers could probably be separated by a solvent. Large battery packs may contain a high number of cells reducing the recycling process efficiency further.

Also, in this case study, *the material value* of the biobased, renewable materials (more sustainable materials by origin) is considered low at end-of-life and therefore will be lost (i.e., no economic incitament in material value to recover, being incinerated instead), thus decreasing the overall battery material recycling potential today. The circularity potential of the biobased battery varied between 9,7% and 81,6% depending on the timeframe of the analysis.

3.2.4 Case Study III – Intelligent packaging

Current case study investigated paper-based intelligent packaging applications, iterating on usage of the biobased battery or the biobased printed supercapacitor as energy storage components for cold chain monitoring sensor, anti-counterfeit or anti-tampering protection solutions for products such as medicines, food, premium class products etc.

The paper-based material was assumed to be in the range from a single product packaging (primary packaging) to a packaging that protects a number of single products (secondary packaging) or transport packaging (tertiary packaging) that contains a number of products packed into secondary packaging on a pallet, see Figure 9. The energy storage module will be either attached to the packaging by applying glue or by printing on it.

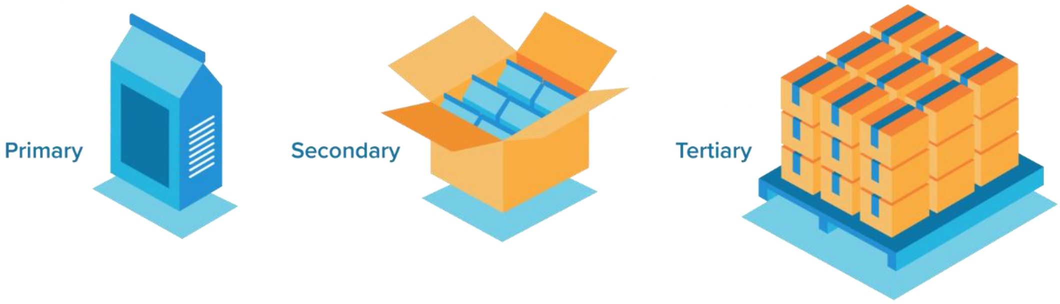

Figure 9 Example of packaging in a packaging system[59].

When introducing the packaging on the Swedish market, it will probably be subjected to the higher packaging fee per each kilogram of material since the packaging material will

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[59] CRB, Food packaging process: balancing innovation with marketplace dynamics, https://www.crbgroup.com/insights/food-beverage/food-packaging-process, accessed at 2021-12-18.

not be classified as packaging consisting solely of paper but rather as packaging containing an additional material apart paper.

Circularity potential in the short-term

Regardless the packaging type described in Figure 9, the paper-based packaging will be sorted and recycled as paper packaging waste in Sweden, with the recycling target of 85%.

At a recovered paper mill where intelligent packaging waste will serve as raw material for new paper-based products, the packaging will be shredded into smaller pieces and afterwards mixed with water in a paper re-slushing process where the paper will be disintegrated back into paper fibres and also separated from other materials like plastic, aluminium foil and eventually other materials. In the paper recycling process, it is paper fibres that are recycled, while other materials are considered as rejects and thus will be incinerated for energy recovery on-site or externally. In particular, the following will occur:

- The biobased battery in intelligent packaging will be separated from the packaging fibres and sorted out as reject for subsequent incineration with energy recovery.
- The printed supercapacitor component in intelligent packaging will be separated from the packaging fibres. However, since the printed supercapacitor component contains a large fraction of (plastic-laminated) paper, this paper may also be re-slushed into paper fibres, thus contributing to the overall recycling of the intelligent packaging.

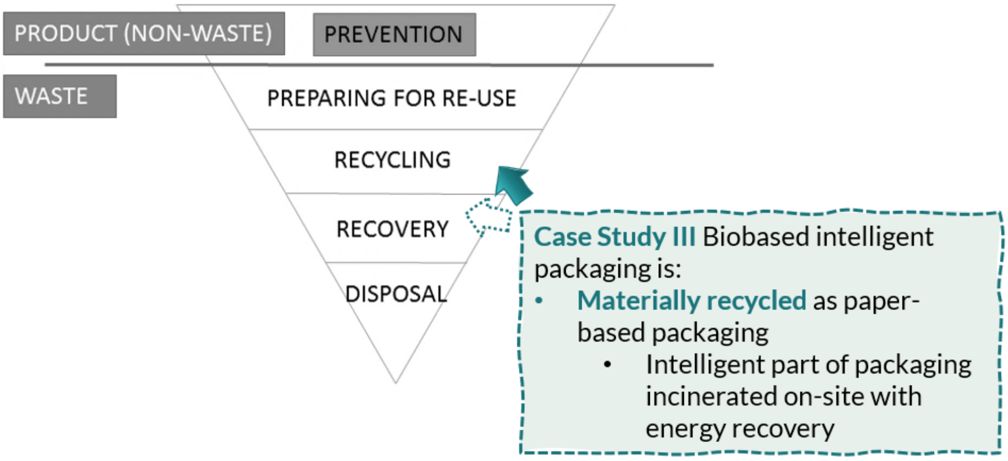
Table 11 Summary of the recovery routes and value of the Case Study III Biobased intelligent packaging in today's end-of-life infrastructure.

Case study III	**Intelligent packaging**
Recovery routes	Recycled as paper packaging (paper, carton, corrugated board etc.). Non-hazardous and possibly suitable for food-contact.
Recovery of which components?	Paper fibers materially recycled. Intelligent part of the packaging separated at a recovered paper mill for incineration with energy recovery on-site or externally.
Recovery incentives	Contributing to EU and national material recycling targets, economic incentives for material recovery of paper fibers, energy value recovery from the intelligent part of the packaging.

A simple exercise below showed that the energy storage components of this kind would be more relevant for packaging of larger volumes such as for example heavy-duty transportation packaging. The discussion[60] was related to the regulation on the packaging consisting of more than one material or composite packaging in the context of verifying a packaging towards fulfilment of recycling targets, as stated in the Guidelines[43]. If the proportion of materials in packaging other that the main packaging material is lower than 5% of the total packaging weight, the packaging material is considered insignificant and thus does not need to be accounted in the attainment of the recycling targets.

In the exercise, a liquid packaging board as the primary packaging material for juice was assumed, with the juice packaging weight of 22,8 – 30,08 grams/packaging unit. Considering the weight of the biobased printed supercapacitor being 10 grams, its weight will constitute 25% - 30,5% of the total weight of intelligent packaging, thus exceeding the threshold value of 5% as discussed above.

The current recycling potential of such intelligent packaging will be 56,1% - 57,2% (i.e., paper fiber material fraction in the packaging substrate). Furthermore, taking into account the paper fiber fraction in the biobased printed supercapacitor, the recycling potential is increased to 66,8% - 70,2%. In case of using the biobased battery as energy storage component in intelligent packaging, its weight will exceed the fiber-based material weight. As a whole, the overall intelligent packaging recyclability will depend on the packaging unit size.



Case Study III Biobased intelligent packaging is:

- **Materially recycled** as paper-based packaging
    - Intelligent part of packaging incinerated on-site with energy recovery

Figure 10 Mapping of Case Study III Biobased intelligent packaging on the EU Waste Hierarchy, from a short-term perspective.

Mapping of Case Study III on the EU Waste Hierarchy is shown in Figure 10.

Circularity potential in the long-term

The discussions on maximizing the circularity potential of the intelligent packaging included redesigning of how the energy storage modules can be attached or de-attached from the fiber-based packaging prior sorting and recycling, and possibly reused.

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[60] Personal communication with a fiber-based packaging material producer, 2021-12-18.

Case study III conclusions

In the current paper packaging recycling stream, the paper packaging substrate will be recycled back into paper fibers and the energy storage components will be handled as rejects that will have energy value recovered rather than the material value. The benefits of introducing such energy storage component on packaging are instead sought in the increase of the overall value chain efficiency for example in terms of reduced food waste (and thus also packaging waste) along a value chain due to temperature control sensor etc. rather than in end-of-life processes particularly.

3.3 Environmental potential

Batteries contain a wide variety of materials, such as base metals, critical raw materials and chemicals, which can raise issues in terms of resource availability, toxicity, safety, production and recycling or disposal impacts[25]. According to World Economic Forum and Global Battery Alliance calculations[61], the most greenhouse gas (GHG) emission-intense steps in the battery value chain are the manufacturing of active materials and other components, and the manufacturing of cells. The carbon footprint of batteries very much depends on the energy source used in manufacturing.

This chapter presents the results from MET matrix analysis of the potential environmental hot spots and benefits performed in the three exploratory case studies and to a possible extent for their respective benchmark objects such as lithium-ion batteries.

3.3.1 Li-ion batteries

The analysis of the overall environmental aspects by applying the MET matrix method is summarized for the Lithium-ion batteries in Table 12.

In terms of the environmental aspects (mainly based on available carbon footprint analyses), the major environmental hot spots in the lithium-ion battery production system are[62,63]:

- Electricity consumption in cell manufacturing (fossil-based electricity)
- Cathode production (utilization of rare metals), followed by anode, electrolyte (and the pack), all are often made of virgin materials.

Production of lithium-ion batteries, or at least the cells they contain, generally takes place in Asian countries, with an energy mix relying on more polluting sources. One research[64] shows, for instance, that NMC (Nickel-manganese-cobalt oxide-based cathodes) lithium-ion cells for electric vehicles manufactured in South Korea with an electricity mix

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[61] Global Battery Alliance and World Economic Forum, A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation, 2019, https://www3.weforum.org/docs/WEF_A_Vision_for_a_Sustainable_Battery_Value_Chain_in_2030_Report.pdf, accessed at 2021/12/17.

[62] Romare M., Dahllöf L., The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries, A Study with Focus on Current Technology and Batteries for light-duty vehicles, https://www.ivl.se/download/18.34244ba71728fcb3f3fa2f/1591705755278/C243.pdf 2017, accessed at 2020-10-12.

[63] Melin H. E., State-of-the-art in reuse and recycling of lithium-ion batteries – A research review, http://www.energimyndigheten.se/globalassets/forskning--innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf, accessed at 2021-11-12.

[64] Ager-Wick Ellingsen L. et al, Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack, Journal of industrial ecology, February 2014.

Table 12 MET matrix of lithium-ion batteries (summarized based on literature used in the current chapter).

Life Cycle stage		Use of Materials	Use of Energy	Toxic Emissions
1. Raw Material Extraction, Processing and Supply of Materials and Components		-**Complex chemistries with** different mixtures of raw materials (other than lithium components vary, and batteries chemistry is constantly shifting). **Average weight (%) of total battery pack:** **-the active material in the cathode (Li, Co, Ni, Mn), 20%** **-the active material in the anode (graphite), 10%** -separator 1-3% **-aluminium substrate (cathode), 2-3%** **-copper substrate (anode), 8-13%** -electrolyte, 9-12% -battery management system (electronics), 3% -cooling, 4% **-packaging (steel, recycled or virgin aluminium, plastic), 30%**	-Manufacturing of active materials and their components is intense in terms of energy consumption -Energy sources have large impact (fossil-based electricity mix at production location)	**Toxic emissions from extraction of critical raw materials:** -water pollution and depletion at extraction -toxic chemicals in processing -soil harm and air contamination
2. Production		-Trend: larger battery packs with higher number of cells for increased energy storage capacity -Difficult processes with components tightly wound or stacked together – not designed for disassembly. -Packing efficiency for increased energy storage capacity -**Battery** cathode production has the largest impact	**-Electricity consumption** in cell manufacturing **stands for 45-60% of GHG emissions** due to choice of energy sources (fossil-based electricity mix at production location, mostly in Asian counties; location selection is driven by labour cost)	
3. Distribution				
4. Use	**Operation**	-Lifetime 5-10 years -Specific energy 120-240 Wh/kg -Specific power 1000 – 3000 W/kg -Trend: larger battery pack – means higher emissions earlier in life cycle -Possible reuse in less demanding applications	-electricity use	
	Service			
5. Refurbishing/ recycling/ disposal	**Recovery**	**-Virgin materials are cheaper than recycled.** Economic incentives for recycling of Co, Ni, Cu, Al. -Almost no lithium recovery in EU due to low cost-efficiency. -Pyro- or hydrometallurgy (recovery of mainly Co, Ni, Cu, Fe or Cu, Al, Co, Li2CO3). **-Pyrometallurgy:** lithium in furnace,	-High energy use in pyrometallurgy -Hammer mill and Li-brine in hydrometallurgy	-Safety issues in dismantling process **-toxic, highly reactive, and flammable** lithium
	Disposal	Pyrometallurgy slag is possible to use as cement filler or landfill.		

dominated by coal, nuclear and gas, have a global warming potential that is 60 % higher than if they were manufactured using electricity based on hydroelectric power.

There are also low recycling incentives due to high focus on economy of recycling processes. There is seldom aclosed-loop recycling (due to quality loss and all processing to be re-done in case of reuse in batteries). Also, toxicity of materials is a challenge along the life cycle.

As a whole, it can be stated that economic value in the lithium-ion battery systems is not aligned with environmental values, i.e., toxic emissions, greenhouse gas (GHG) emissions, energy consumption (fossil-based energy sources), and material shortage issues.

3.3.2 Case Study I – Biobased battery

The MET matrix of the biobased battery was explored through a number of interviews with Ligna Energy[12] and the report authors, with the aim to map the potential environmental benefits and hotspots along the whole life cycle. See the results in Table 13. The discussions were facilitated by using the Ecodesign Strategy Wheel method in order to understand the environmental benefits and hotspots of the biobased battery in a deeper context.

Thus, most of environmental benefits of the battery are found in the beginning of the life cycle where abundant, organic and non-hazardous raw materials are selected for the biobased battery production. There is also a clear advantage over using locally produced raw materials such as for example lignin and also local battery production, which requires less energy and uses less greenhouse gas-intensive energy sources.

Modular pack design of the battery allows for service and replacement of the battery components when necessary to ensure the long life of the overall battery solution. Standardized pack designs are not only enabling efficient production processes and support an efficient use but may also enable efficient material recycling in the end-of-life, once there are standardized labelling, designs, and dismantling procedures in place.

While the size of batteries is not a critical parameter in the stationary battery applications, it should be noted that the energy density of the biobased batteries is however five times lower than that lithium-ion batteries can provide, which will require larger volumes of the biobased batteries, if used in applications with the same specific energy requirements as lithium batteries. This implies utilization of higher amount of raw materials per equivalent energy quantity provided, while raw materials used are not critical or hazardous raw materials.

Among end-of-life options material recycling of base metal components is possible in the current recycling infrastructure, while the rest of the components will be incinerated with energy recovery. Alternatively, the whole battery will be incinerated as non-hazardous material. Since the battery is classified as a battery according to the Battery Directive, the collection target is 75%, of which at least 50% must be recycled.

3.3.3 Case Study II – Biobased printed supercapacitor

The MET matrix of the biobased printed supercapacitor was explored through a number of interviews with the report authors, with the aim to map the potential environmental benefits and hotspots along the whole life cycle. See results in *Table 14*.

In similarity to Case Study I:

- Many environmental benefits of the supercapacitor are found in the beginning of the life cycle where abundant, organic and non-hazardous raw materials are selected for the production.
- Utilization of the locally produced raw materials in different components as well as use of local energy from renewable sources in production reduces the carbon nt of the energy storage solution.
- The design of the supercapacitor is also modular.
- The cell-specific energy is five times lower than that of the lithium-ion batteries can provide, which will require larger volumes of the printed supercapacitors per equivalent energy quantity provided.
- At end-of-life, material recycling of the base metal aluminium (and possibly of paper in insulating capsulation) is economically viable in the current recycling infrastructure, while the rest of the components will be incinerated with energy recovery. Alternatively, the whole supercapacitor will be incinerated as non-hazardous material.

The case unique additional environmental aspects are water-based electrolyte solution and very low energy consumption in production processes.

Also, since the supercapacitor is classified as EEE according to the WEEE Directive the recycling target for collection is 65%, while recovery and recycling / preparing for reuse targets ranging from 55% to 85% depending on application.

3.3.4 Case Study III – Intelligent packaging

Current case study investigated cellulose fiber-based intelligent packaging applications, iterating on usage of the biobased battery or the biobased printed supercapacitor as energy storage components for cold chain monitoring sensor, anti-counterfeit or anti-tampering protection solutions for products such as medicines, food, premium class products etc.

The potential environmental benefits and hotspots along the whole life cycle were explored for the fiber-based intelligent packaging. The MET matrices of the stand-alone biobased battery and the printed supercapacitor are presented separately in the previous chapters.

In comparison to the button-cell battery's' cell-specific energy, the biobased energy storage solutions intended for intelligent packaging application has ca 13-17 times higher energy density, see Chapter 2.1.

The benefits of introducing such energy storage component on packaging are instead sought in the increase of the overall value chain efficiency for example in terms of reduced food waste (and thus also packaging waste) along a value chain due to temperature control sensor etc. rather than in end-of-life processes particularly.

Table 13 MET matrix of Ligna Energy biobased battery.

Life Cycle stage		**Use of Materials**	**Use of Energy**	**Toxic Emissions**
1. Raw Material Extraction, Processing and Supply of Materials and Components		-Use of abundant organic, non-hazardous raw materials, incl. in active components. Lignin is a by-product in pulp production that is incinerated for energy recovery. -Locally supplied materials -No use of critical raw materials -Biobased battery content is 61,3%-79,3% depending on the choice of insulating capsulation material -Materials choice in battery pre-determines balance in between end-of-life routes of material recycling and incineration. -For weight (%) composition of the battery cell, see Table 7.	-Lower energy consumption in raw material extraction.	No known toxic emissions.
2. Production		-Trend: larger battery packs for increased energy storage capacity -The cell, pack and rack principle is modular	-Lower electricity use in cell manufacturing -Local electricity mix at production location (Sweden, EU)	
3. Distribution		-Reduced transportation due to local supply of raw materials.		
4. Use	**Operation**	-Same type of battery management system as for Li-ion battery -Lifetime 10 years -Larger battery volume in use if compared to Li-ion (ca 5 times) – critical parameters are energy, power density and battery internal efficiency.	-Initial target is 80% charge/discharge efficiency (90% in Li-ion batteries).	-No emission from batteries -Depends on source of energy
	Service	-Modular structure enables service and replacement of subsystem levels, if necessary.		
5. Refurbishing/ recycling/ disposal	**Recovery**	-Economic incentives for material recycling of base metals (aluminium and steel) and possibly material recycling of cellulose in insulating capsulation. -Material recycling potential is 14-32% in current recycling infrastructure and up to 80% on the longer term, considering material value. -Incineration with energy recovery.	-Electricity and heat co-generation in the incineration scenario. -Carbon and lignin generate biogenic emissions in incineration. Potential source of SOx emissions in incineration of lignocellulosic battery components. -No chlorine emissions in incineration.	-No known toxic emissions
	Disposal	No disposal but material or energy recovery.		

Table 14 MET matrix of the RISE biobased printed supercapacitor.

Life Cycle stage		**Use of Materials**	**Use of Energy**	**Toxic Emissions**
1. Raw Material Extraction, Processing and Supply of Materials and Components		-100% organic materials and partially biobased (biobased content. -55,4%), incl. biobased electrode carbon locally produced from hard- or softwood in the future. -No utilization of critical raw materials. - Water-based electrolyte -For weight (%) composition of the printed supercapacitor cell, see Table 9.	-Lower energy use in raw materials extraction. -Local raw materials production (Sweden, EU).	No known toxic emissions.
2. Production		-Trend: larger battery packs for increased energy storage capacity -Modular product structure with interconnected supercapacitor cells -Scalable production processes	-Very low energy use: electricity for printing machines and drying process. -Low temperature processes. -Local production.	-Carbon printing ink contains organic solvents and in drying process will emit volatile organic compounds. -Water-based or nanocellulose-based printing ink in the future.
3. Distribution				
4. Use	**Operation**	-Larger battery volume compared to Li-ion (ca 5 times) due to lower cell-specific energy. Size is though not a priority parameter in the industrial large-scale applications (fields, roofs of the factories). -Self-discharge max 25% in 24 hours.	-Lower electricity use in cell manufacturing -Local electricity mix at production location (Sweden, EU)	
	Service			
5. Refurbishing/ recycling/ disposal	**Recovery**	-Economic incentives for material recycling of the base metal in the collector (aluminium) and possibly material recycling of cellulose in insulating capsulation. -Material recycling potential is 9,7% - 52,4% in current recycling infrastructure (aluminium and possibly paper) and up to 81,6% on the longer term (inc. also l ionic liquids). -Incineration of the rest of the product alternatively the whole product.	-Electricity and heat co-generation in the incineration scenario. -Biobased carbon generates biogenic emissions in incineration. Potential source of SOx emissions in incineration of the ionic liquid component. -No chlorine emissions in incineration.	-No known toxic emissions.
	Disposal	No disposal.		

4 Conclusions

Current report is the result of the exploration work where circularity and potential environmental hotspots of biobased and organic energy storage solutions were analysed. The analysis was based on iterative interviews with stakeholders along the energy storage and packaging value chains, complemented by literature research. The work was performed within the scope of the Digital Cellulose Center (DCC) research center[65] in the sub-project 1 "Circularity of DCC materials" within the Theme 1: Design for a circular bioeconomy.

The following three case studies were selected:

- Case study I: Biobased battery for large-scale energy storage applications (Chemical energy storage system)
- Case study II: Biobased printed supercapacitor for large-scale energy storage applications (Electrochemical energy storage system)
- Case study III: Intelligent packaging (Chemical or electrochemical energy storage for fiber-based packaging)

Each case study was put into the life cycle context where aspects such as legislation, circularity potential and potential environmental impact were discussed. It is the energy generation mechanisms as well as the application that define whether the product is a battery or EEE.

In accordance with the Battery Directive, the biobased battery in Case Study I can be classified as industrial battery with a requirement of 50% to be materially recycled. The biobased printed supercapacitor in the Case Study II is an electrical energy storage solution, which can be classified as EEE. Different value chain actors though interpret supercapacitors as either a battery or an EEE. In the latter case, the recovery and recycling / preparing for reuse targets vary between 55%-85%. The material recycling target for the fiber-based intelligent packaging is 85% since in practice it would enter packaging paper recycling stream rather that a waste of electric and electronic equipment (WEEE recycling stream). Hence, it is advantageous if the energy storage solutions can be materially recycled partially or fully in order to contribute to the recycling targets. Below is the summary of the analysed circularity potentials and biobased contents in the respective case studies:

Parameters	**Case study I**	**Case study II**	**Case study III**
Biobased content	61,3% - 79,3%	55,4%	70% - 74,1%*
Circularity potential on short-term	14 - 32%	9,7% - 52,4%	51,6% - 57,2%*
Circularity potential on long-term	57% - 80%	81,6%	66,8% - 70,2%*

**The results will vary on the packaging weight. The calculation above is based on the juice packaging example for the demonstration purposes only.*

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[65] Research center Digital Cellulose Center, https://digitalcellulosecenter.se/, accessed at 2021-12-11

Current legislation in terms of the Battery and WEEE directives does not address specifically the recycling of materials that are critical or have a high environmental burden, which in turn are sustainable incentives for designing future energy storage solutions. As of today, the material recycling processes for batteries and WEEE are solely economically driven: the material components that are considered as valuable by recyclers are mainly base metals and to some extent critical raw materials (e.g., cobalt, nickel and base metals like aluminium and steel).

The analysed biobased energy storage solutions though do not contain any critical raw materials and uses base metals to less extent. This is the dilemma where the material value of the biobased, renewable materials (more sustainable materials by origin) is considered low and therefore will be lost (i.e., incinerated). A more balanced approach to this dilemma is urged in order to facilitate both economic and environmental incentives in the energy storage value cycles. In particular, the legislation needs to be adapted in order to meet innovative development in the area. It can be relevant to introduce a cross-sectoral category ‘Biobased energy storage solutions’ in the upcoming legislation with aim to encourage the use of more abundant, biobased materials rather than critical raw materials and thus decouple energy storage applications from use of critical raw materials.

From the environmental perspective, in the benchmarked traditional energy storage solutions, the materials shortage issues and manufacturing of active materials and cells with respective emissions are the identified hotspots (the latter depending on energy sources used in the respective manufacturing processes).

Many environmental benefits of the biobased energy storage solutions are found in the beginning of the life cycle where abundant, organic and non-hazardous raw materials are selected for the production. Also, utilization of the locally produced raw materials in different components as well as use of local energy from renewable sources in production reduces the carbon footprint. The cell-specific energy is though lower than that of the lithium-ion batteries can provide, which may require larger volumes of raw materials per equivalent energy quantity provided.

It is important that the energy storage solutions are sustainable along their entire life cycle, with economic and environmental values aligned.

5 Recommendations

This exploratory research elaborated broadly on the life cycle perspective of the three case studies of biobased energy storage solutions, including their different end-of-life scenarios and environmental aspects. It is recommended that:

- The three case studies are further investigated in more details regarding practical recyclability and other circularity options, including recycling tests that could give more insights on optimisation possibilities.
- The three case studies are developed into full Life Cycle Assessment (LCA) analyses with the aim to quantify their environmental impacts. The LCA studies can serve as support in the decision-making in the R&D of biobased energy storage solutions.
- Create sustainability and circularity guidelines for the design of electronic devices from a life cycle perspective, based on the material and production concepts developed within the Digital Cellulose Center.
- Inform the parties responsible for upcoming recycling directives to also include new innovative energy storage solutions and guidelines on how to set up new incentives that can drive towards more sustainable energy storage solutions in the future.

6 Appendix

Appendix I Summary of main New EU Battery Regulation requirements[29].

Table 15 Summary of main New EU Battery Regulation requirements[29].

EU Battery Regulation Requirements

REQUIREMENTS	**Battery type**				**Period**							
Sustainability and safety	Portable	Automotive	Industrial	EV battery	2022	2023	2024	2025	2026	2027	2030	2035
Carbon footprint declaration	✗	✗	✓*	✓			01 JUL					
Carbon footprint performance class	✗	✗	✓*	✓					01 JAN			
Carbon footprint threshold	✗	✗	✓*	✓						01 JUL		
Recycled content for batteries containing Li, Ni, Co or Pb in active materials	✗	✓	✓	✓						01 JAN		
Minimum recycled content rates (12% Co; 85% Pb; 4% Li; 4% Ni)	✗	✓	✓	✓							01 JAN	
Minimum recycled content rates (20% Co; 85% Pb; 10% Li; 12% Ni)	✗	✓	✓	✓								01 JAN
Performance and durability requirements for portable batteries	✓	✗	✗	✗					01 JAN			
Electrochemical performance and durability parameters**	✗	✗	✓*	✓	*** requirement applicable 12 months after regulation comes into force.*							
Supply chain Due Diligence**	✗	✗	✓*	✓	*** requirement applicable 12 months after regulation comes into force.*							
Labelling and information requirements	Portable	Automotive	Industrial	EV battery	2022	2023	2024	2025	2026	2027	2030	2035
Manufacturer's name, registered trade name or trademark (part of the Label and QR code)	✓	✓	✓	✓						01 JAN		
Battery type, batch or serial number of the battery (unequivocal identification) (part of the Label and QR code)	✓	✓	✓	✓						01 JAN		
Battery model identifier (part of the Label and QR code)	✓	✓	✓	✓						01 JAN		
Date of manufacture (part of the Label and QR code)	✓	✓	✓	✓						01 JAN		
Date of placing on market (part of the Label and QR code)	✓	✓	✓	✓						01 JAN		
Chemistry (part of the Label and QR code)	✓	✓	✓	✓						01 JAN		
Hazardous substances other than mercury, cadmium or lead (part of the Label and QR code)	✓	✓	✓	✓						01 JAN		
Critical raw material contained in the battery (part of the Label and QR code)	✓	✓	✓	✓						01 JAN		
Information on capacity (part of the Label and QR code)	✓	✓	✗	✗						01 JAN		
Information on minimum average duration when used in specific applications (part of the Label and QR code)	✓	✗	✗	✗						01 JAN		
Separate collection symbol (part of the Label - 01 July 2023 and QR code - 01 Jan 2023)	✓	✓	✓	✓		01 JAN						
Chemical symbol Cd (for >0.002%) or Pb (>0.004) (part of the Label - 01 July 2023 and QR code - 01 Jan 2023)	✓	✓	✓	✓		01 JAN						
Supply chain Due Diligence report** (QR code)	✗	✗	✓*	✓	*** requirement applicable 12 months after regulation comes into force.*							
EU declaration of conformity (QR code)	✓	✓	✓	✓		01 JAN						
End-of-life information (QR code)	✓	✓	✓	✓		01 JUL						
Electronic Exchange System	✗	✗	✓*	✓					01 JAN			
Battery passport	✗	✗	✓*	✓					01 JAN			
End-of-life management	Portable	Automotive	Industrial	EV battery	2022	2023	2024	2025	2026	2027	2030	2035
Collection rates of waste portable batteries (45% by Dec2023, 65% by Dec 2025; 70% by Dec 2030)	✓	✗	✗	✗		31 DEC		31 DEC			31 DEC	

** industrial rechargeable batteries with internal storage and capacity above 2KWh*

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