D1.4 State-of-the-art analysis of technologies, circular business models and ecodesign practices for plastic waste, end-of-life electric vehicle batteries and bio-based side and waste streams

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Acronyms and abbreviations

Acronym	Full name
ABS	Acrylonitrile butadiene styrene
AD	Anaerobic digestion
AI	Artificial intelligence
B2B	Business to business
B2C	Business to customer
BAT	Best Available Techniques
BMS	Battery management system
BSFT	Black Soldier Fly Treatment
BSWS	Bio-based side and waste streams
CCS/CCU	Carbon capture and storage/utilization
CDW	Construction and demolition waste
CE	Circular Economy
CEAP	Circular Economy Action Plan
CMD	Catalytic microwave depolymerisation
CO	Carbon monoxide
CO_2	Carbon dioxide
D	Deliverable report
DRS	Deposit return system
DV-IC	Differential voltage and incremental capacity
ECM	Equivalent circuit model
EIS	Electrochemical impedance spectroscopy
ELV	End of life vehicle
EMS	Energy management system
EOL	End-of-life
EPR	Extended producer responsibility
EPS	Expanded polystyrene
ESS	Energy storage system
EV	Electric vehicle
EVBs	Electric vehicle batteries
EVOH	Ethylene-vinyl alcohol
GDP	Gross domestic product
GHG	Greenhouse gas
GHS	Globally harmonized system
H_2	Hydrogen
HDPE	High density polyethylene

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HIPS	High impact polystyrene
HTC	Hydrothermal carbonization
IoT	Internet of Things
LBG	Liquefied biogas
LCA	Life cycle assessment
LDPE	Low density polyethylene
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
LUKE	Natural Resources Institute Finland
MDO	Machine direction orientation
MFI	Melt flow index
MTK	The Central Union of Agricultural Producers and Forest Owners
N_2	Nitrogen
NCA	Nickel cobalt aluminum oxide
NIR	Near infrared
NMC	Nickel manganese cobalt oxide
OEM	Original equipment manufacturer
PA	Polyamides
PAYT	Pay-As-You-Throw
PC	Polycarbonate
PCR	Post Consumer Recycled Material
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	Polylactic acid
PP	Polypropylene
PPWD	Packaging and packaging waste directive
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
RES	Renewable energy sources
RFID	Radio-frequency identification
rHDPE	Recycled polypropylene
rPP	Recycled high density polyethylene
RUL	Remaining useful life
SINTEF	SINTEF AS / SINTEF Energy
SLB	Second-life battery
SOC	State of charge
SOH	State of health
VAREX	Value retention extruder

VFAs	Volatile fatty acids
VTT	VTT Technical Research Centre of Finland Ltd
WEEE	Waste from electronics and electrical equipment
WP	Work package
XCT	X-ray computed tomography

Executive Summary

This deliverable outlines the state-of-the-art technologies, circular business models as well as ecodesign and good practices related to each of the targeted project value chains. Main focus in the plastic waste section is on recycling, in the end-of-life electric vehicle (EV) batteries on repurposing and in the bio-based side and waste streams on the production of biogas as well as circular nutrients and fertilizers.

Regarding the plastics value chain, the main discussed technologies are collection, sorting, purification, mechanical recycling, solvent-based chemical recycling, pyrolysis and gasification. The circular business models related to the value chain are currently focused on mechanical recycling rather than other circular strategies. This is also mostly due to legislative actions. However, other circular strategies, such as reuse of packaging, are emerging and will be further supported by upcoming legislation. For the EV batteries, different types of electric vehicle batteries, the repurposing process, and second life storage application examples are presented. Whereas, for the bio-based side and waste streams that are used for biogas and circular nutrients production, an analysis of collection and sorting is presented. In addition, examples of different aspects on valorisation are discussed. These include biological conversion, composting, anaerobic digestion, biogas upgrading, black soldier fly treatment, thermal-chemical conversion, pyrolysis and hydrothermal carbonisation.

As the new proposal for Ecodesign Regulation framework will expand from the energy-focused approach to a broader approach, the new requirements will impact all of the above-mentioned value chains. The new framework will include, for example, the following elements: product durability, reusability, upgradability and reparability, possibility of maintenance and refurbishment, presence of substances of concern that inhibit circularity, energy and resource efficiency of recycled content, possibility of remanufacturing and recycling possibility of recovery of materials, environmental impacts - carbon and environmental footprints, information requirements including Digital Product Passport, and expected generation of waste materials. The implementation of circular strategies will be more straightforward, when more information is communicated about material history.

It should be noted that different ecodesign practices for designing materials and products are established and implemented in various ways. Also, mainstream circular business models are typically supported by legislation. For example, mechanical recycling of plastics is predominant, while for the end-of-life batteries it is recycling over repurposing. In the case of packaging, the focus of ecodesign is mostly in packaging design driven by legislation. This can mean, for example, that there are different mandates that pertain certain recyclate-content in new products or demand recyclability of the product. Regarding the repurposing end-of-life EV batteries, the upcoming ecodesign directive will be important. Critical aspects that ensure suitability of the battery for next lifecycle are, for example, design for disassembly and modularity and getting information on the battery's state and condition via digital battery passport. Whereas the bio-based side and waste streams are often processed in a cascading manner utilising by-fractions and side streams. This significantly improves resource efficiency.

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Part I: Introduction to TREASoURcE and setting the scene

1. Introduction to TREASoURcE and setting the scene for three different value chains

This report is part of Work Package 1 Circular Economy framework analysis and actions to enhance circular economy. This report provides an overview of state-of-the-art technologies and good practices for circular strategies in the targeted value chains, practices and framework for eco-design and circular business models. The overall aim is to support further development and implementation of the project's key value chain demonstrations, but in a broader sense, support transition to circularity of the targeted value chains.

The main focus in the plastic waste section is on recycling, in the end-of-life electric vehicle (EV) batteries on repurposing and in the bio-based side and waste streams on the production of biogas and circular nutrients and fertilizers. As there are several topics that have been covered, a lot of content has been generated. Due to this, this deliverable is outlined in five different sections that can be read individually to support those who seek information on the specific value chains, but also a more thorough overview can be gained using the whole report. The last chapter, Part V, discusses cross-cutting issues and presents conclusions drawn on actions that can be used to push the transition to circular economy forward.

1.2. TREASoURcE and targeted key value chains

TREASoURcE aims to initiate systemic change by developing systemic circular economy solutions in cities and regions for currently underutilised or unused plastic waste, end-of-life electric vehicle batteries and bio-based waste and side streams. Implementing these solutions together with companies, societies (including citizens, consumers, communities and regional actors) and experts in the field is expected to significantly increase product and material circulation in the Nordic and Baltic Sea Regions.

Climate change, environmental degradation and loss of biodiversity are major global threats that require urgent collaborative actions across industry, sectors, cities and regions, communities, and citizens. Half of total greenhouse gas emissions and more than 90 % of biodiversity losses come from resource extraction and processing. Global consumption of materials, especially biomass, fossil fuels, metals and minerals are expected to double by 2060 and annual waste generation is estimated to increase by 70 % by 2050. TREASoURcE activities aim to create added value products from currently non-circulated plastic waste to support the market development of recycled plastics and to capture the value lost today by utilising mechanical and thermochemical recycling. TREASoURcE will also evaluate the potential for use of 2nd life electric vehicle batteries as energy storage systems and demonstrate their functionality and sustainability in three demo cases as energy storage for solar power. In addition, TREASoURcE will demonstrate efficient formation of local value chains that utilize local resources for biogasification and recovered fertilizers instead of being unutilized or transported elsewhere.

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TREASoURcE brings together a wide range of stakeholders, including businesses, decision makers, consumers and local communities, to innovate collaboratively and cross-sectorally in order to overcome the challenges related to geography or formation of value chains. The combination of the cities and regions will enable large reach and bigger impact and boost the replicability and scalability potential of the circular economy solutions. The systemic circular economy solutions support the regions in introducing circular economy practices to their citizens and businesses to help decouple from fossil virgin resources and excess raw material consumption, increase resilience (self-sufficiency, value chain security, environment, and nature), decrease greenhouse gas emissions, and contribute to climate neutral economies.

Plastics are used in a multitude of applications, thus, also our focus in the project is on different application areas: agricultural plastics, post-consumer packaging waste recycling rejects and industrial plastic waste streams, such as the battery recycling industry. The EU's Strategy for Plastics in the Circular Economy aims to address the increasing consumption of plastics and tackle plastic pollution by supporting the uptake of recycled plastics and contributing towards more sustainable plastics. Actions towards the goal, such as mandatory recycled contents and plastic waste reduction measures for key products, like packaging, construction materials and vehicles will be set. In TREASoURcE, we are also focusing on improving the circularity of current post-consumer packaging waste rejects, which are one of the most challenging packaging types to recycle. Packaging is also listed as one of the key value chains in the Circular Economy Action Plan (CEAP). Packaging materials are used in an ever-growing manner and the amount of raw material needed is increasing. Currently most packaging is single-use, which means that the amount of packaging waste is also increasing. In 2017, 173 kg of packaging waste was generated per inhabitant in the EU. European Union aims to make all packaging either reusable or recyclable by 2030 and reduce (over)packaging and packaging waste. This includes setting waste prevention measures, as well as consider reducing the complexity of packaging materials, such as multilayer solutions. (European Comission, 2022)

Batteries and vehicles are EU's one key value chain listed in the Circular Economy Action Plan. It is seen that sustainable batteries and vehicles support the mobility of the future. A new Batteries Regulation was introduced enhance sustainability of the emerging battery value chain for electro-mobility and boost circular potential of all batteries. However, it focuses mainly on mandatory recycled contents and measures to improve collection and recycling rates as the main circular strategy for recovering valuable and critical materials. (European Comission, 2022)

The TREASoURcE project focuses on the increasing the circularity of bio-based side and waste streams for biogas and fertilizers. Also, food, water and nutrients are listed in the CEAP as key value chains. Circular economy is seen to have a significant role in reducing negative environmental impacts of resource extractions and use, while contributing towards restoring biodiversity and natural capital. The Bioeconomy Strategy and Action Plan and Integrated Nutrient Management Plan are critical EU-level plans from the Commission to ensure sustainable application of nutrients and stimulating markets for recovered nutrients. (European Comission, 2022)

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1.2. Circular strategies and sustainable circular design

Most material use is based on linear approach where resources are extracted, made into products, which are used only once and then discarded. Materials circulate to some extend back to the economy via end-of-life management, but majority of the potential is lost due to incineration, landfilling, exporting, dumping and littering. Furthermore, material consumption rates are still increasing even though we are facing issues with material sufficiency. It is estimated that if we continue like this on global level, we would need three planet Earths to match our consumption. Global consumption of materials - like biomass, fossil fuels, metals and minerals - is expected to double by 2040 and the annual waste generation is estimated to increase by 70% by 2050. (European Commission, 2020)

The increased consumption and material use, as well as improper circulation of valuable resources links to several environmental and societal issues. For example, half of total greenhouse gas emissions and more than 90% of biodiversity loss and water stress comes from resource extraction and processing. (European Commission, 2020)

European Union's (EU) Circular Economy Action Plan (CEAP) is seen as a key to ensuring that circular economy can be scaled up, that circular economy truly contributes to EU's climate neutrality target by 2050, and that economic growth is decoupled from resource use. The plan ensures long-term competitiveness and security of value chains and materials, as well as a just transition to circular economy. Transition to sustainable circular economy is also part of the new EU industrial strategy and hence, businesses are expected to work together to create a framework for sustainable products that could produce new opportunities within the EU and globally. It is estimated that transitioning to circular economy has the potential to increase EU GDP by an additional 0.5% by 2030 creating 700 000 new jobs. It is also estimated that European manufacturing businesses on average spend 40% on materials; therefore, circular European material loops can increase the profitability and level of security by protecting businesses from resource price fluctuations and lack of resources. (European Commission, 2020)

A critical part of the Circular Economy Action plan is to support the designing of sustainable products as 80% of products' environmental impacts are determined already at the design phase. For example, characteristic features of products that are designed for linear economy are short product life span, product reuse is challenging or impossible, not feasible to repair or recycle, and many are products made for single use only. These aspects should be taken into consideration when designing for circular economy. (European Commission, 2020)

Circularity is driven forward as an integral part of a wider transformation of industry towards climate-neutrality and long-term competitiveness and seen as an important part to integrate into production processes. Significant material savings can be created throughout value chains and production processes. Key aspects for greater industry are for example integration of circular economy practices in Best Available Techniques (BAT) reference documents, facilitating industrial symbiosis, circular bioeconomy, digitalisation for tracking, tracing and mapping of resources, and green technologies through the EU Environmental Technology Verification scheme. (European Comission, 2022)

Circularity is a broad topic and entails several different circular strategies. Potting et al. (2017) have introduced a 9R framework in which ten circular strategies are placed in a hierarchy where they are arranged from high circularity (low R-number) to low circularity (high R-number) (Potting, Hekkert, Worrell, & Hanemaaijer, 2017). Despite ranking the lowest, most circular policies and targets currently focus on R8-R9 strategies, whilst biggest single impact could be created for example through making a product redundant in the first place (refuse).

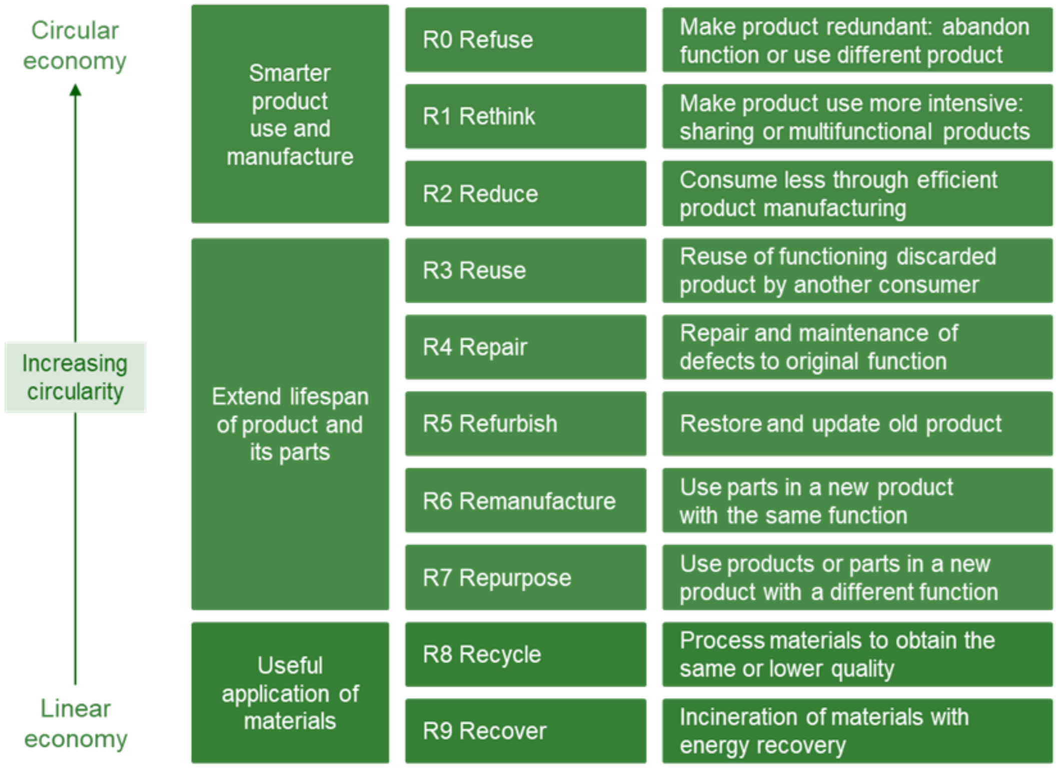

Figure 1. 9R circularity framework developed by (Potting, Hekkert, Worrell, & Hanemaaijer, 2017)

When aiming for higher circularity levels, the circularity of the whole value chain and its life stages need to be considered through design starting from the material selection through to the end of product life cycle. There are different types of design principles that have been adapted – ranging from ecodesign, circular product design, design for sustainability and so on. Design is in everything and is the basis for how materials, products and services are created, used and managed. A key aim of ecodesign is to reduce to a minimum the overall environmental impact and it should be viewed as a forever evolving concept and an approach to sustainability. (EcoDesign Circle, 2023; SVID, 2018)

The EcoDesign Circle project has created an ecodesign guide, where 8 different interconnected levels are identified: design; materials and parts; manufacturing; product; distribution; sales & marketing; use; end-of-life (infinity recycling). For example, in the end-of-life section tips are shared for design for disassembly and reassembly, design for collection and take-back programmes, full-circle supply chain and upcycling. (EcoDesign Circle, 2023; SVID, 2018)

Figure 2. Ecodesign approach and guide developed by the EcoDesign Circle project (EcoDesign Circle, 2023; SVID, 2018)

Ecodesign is also driven by legislation in the EU. The Ecodesign Directive 2009/125/EC has focused on energy-related products and their energy consumption. In 2021 alone, the impact of the current ecodesign legislation measures, covering 31 product groups, saved EUR 120 billion in energy expenditure for EU consumers and led to a 10% lower annual energy consumption of the products. A new Ecodesign for Sustainable Products Regulation was published in March 2022 to build on the existing Directive. The new Regulation will be the cornerstone for European Commission's ambition to have more environmentally sustainable and circular products on the markets. It is expected that by 2030, the new sustainable products framework can lead to 132 million tonne of primary energy savings, which corresponds roughly to 150 billion cubic meters of natural gas, almost equivalent to EU's import of Russian gas. (Directorate-General for Environment, 2022)

The new framework is very broad and sets a wide range of requirements, which include the following (Directorate-General for Environment, 2022):

- product durability, reusability, upgradability and reparability
- possibility of maintenance and refurbishment
- presence of substances of concern that inhibit circularity
- energy and resource efficiency
- recycled content
- possibility of remanufacturing and recycling
- possibility of recovery of materials
- environmental impacts - carbon and environmental footprints
- information requirements, including a Digital Product Passport
- expected generation of waste materials

Part II: Circular plastics value chain

2. Circular plastics value chains

Ultimately achieving circularity for plastics is a complex topic. Today, there are thousands of different types of plastics. There are numerous applications for plastics of which packaging is the main application in Europe (40,5 %) alongside buildings and construction (20,4 %), automotive sector (8,8 %), waste from electronics and electrical equipment (WEEE) (6,2 %), household, leisure and sports (4,3 %), agriculture (3,2 %). (Plastics Europe, 2021) There are many different types of applications that have plastics in them, hence there is no single collection or recycling strategy let alone a single circular business model that could address and resolve circularity problem of plastics. Challenges across the plastic value chain have been identified, which depicts the scale and complexity of the value chain. These challenges are, for example, issues related to feedstock acquisition and its quality; sorting, identification and recycling technologies; recycled plastic and its uptake, as well as regulatory environment. (Myrä, 2023)

2.1. Circular business models

Circular business models, CBMs, in the circular plastics economy have been focusing on recycling, which is a widespread strategy that does not require a shift in the core business model. Regulative recycling targets and the use of recyclates is driven by national and EU level legislation. Lately, also other business models having circularity in their core are emerging, such as designing out unnecessary plastic-based products like packaging, or reusing plastic packaging or repairing equipment and replacing broken plastic components. Use-cases often deal with creating value from waste and substituting fossil polymers with bioplastics (Dijkstra, Beukering, & Brouwer, 2020). Also, efforts towards using recycled plastics in added value products are seen. For example, in the EU PRIMUS project there are automotive and electrical equipment demonstrations, and Electrolux and recycler Coolrec have created a recyclate-based refrigerator as a joined undertaking, which won the first place of Plastics Recycling Awards Europe 2023 in the category of Automotive, Electrical & Electronic Product.

Sustainable actions targeting higher circularity have been prompted by several external and internal factors, including regulatory or industry pressure, organizational commitment, competition and collaboration. The main opportunities for circular plastic include competitive advantage and improving resource use efficiency. Reported barriers, on the other hand, involve high investment and transition costs required of new innovations, especially new technologies or system shifts such as implementing take-back systems. Furthermore, new ways of delivering products or services can require different behaviors or relationships from customers, both in B2B and B2C context.

Circular business model practices are next presented for packaging and agricultural plastics, which together make up the major part of plastic waste generated in the TREASoURcE regions, but also represent quite a high area where collection and recycling is insufficient.

Household and packaging plastics

Plastic packaging waste is the major contributor to the municipal plastic waste fraction. Against this background, EU's Directive on Packaging and Packaging Waste is going through a revision, which largely drives new business innovations in the market. These regulations relate to banning certain single use products and the mandatory inclusion rates of recycled plastics as well as mandatory shares of reusable packaging.

Figure 3 gives an overview of sustainability-oriented packaging improvements, which reflects the new business models generated around circular plastic packaging.

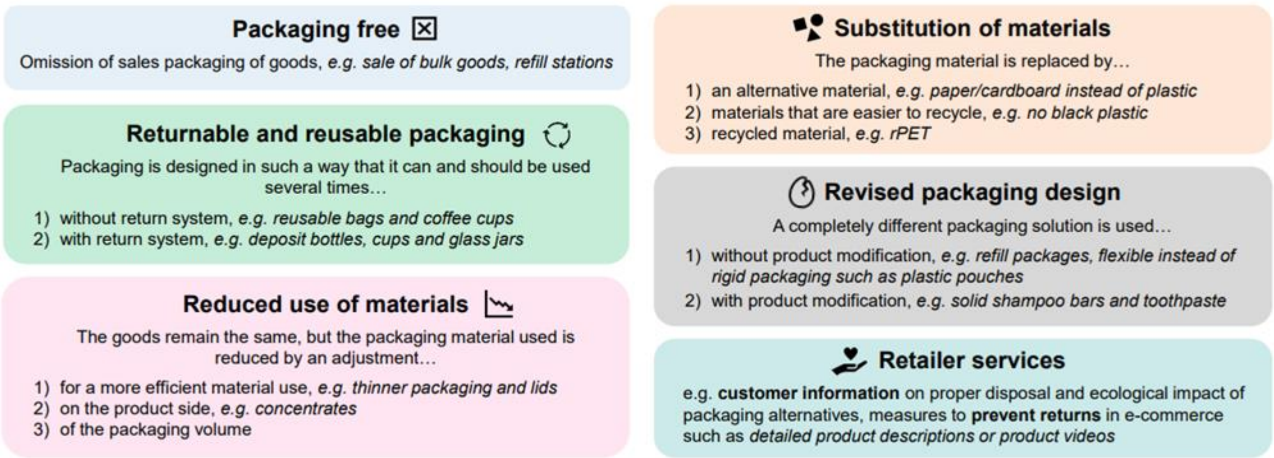

Figure 3. Sustainability-oriented packaging improvements (SOPI taxonomy) (Schmidt, 2020)

Good example: Kamupak - Digital deposit system for reusable products

Kamupak introduces themselves as "a circular economy service for products and materials that can be reused". The idea of Kamupak is to reduce waste caused by single-use packaging by offering reusable packaging for takeaway food, named KamuDishes. The company has chosen to focus on take away packaging as this sector is responsible for 50% of all single-use packaging waste globally. Currently KamuDishes are used in approximately 50 restaurants, cafes and supermarkets selling takeaway food around Finland and the network is to be expanded to other Nordic countries. The solution works so that the consumer orders takeaway in reusable KamuDish(es), pays a deposit of 3€, returns the dish to a Kamu location after use and chooses either to exchange the dish for a fresh one, get the deposit back or receive a digital KamuCredit in the Kamupak app. The consumers can use the KamuCredits for a new KamuDish later. When a KamuDish has reached the end of its life cycle, it is returned to the manufacturer to be recycled as raw material. The company has calculated that one KamuDish is used on average 100 times. One KamuDish, which has been used 100 times, can reduce CO_2 emissions up to 72-95 % compared to 100 pieces of single-use polyethylene terephthalate (PET) plastic trays. (Sitra, 2021; Kamupak, n.d.)

Error! Reference source not found. depicts the circular economy business model of Kamupak using a framework for sustainable circular business model innovation by (Antikainen & Valkokari, 2016)

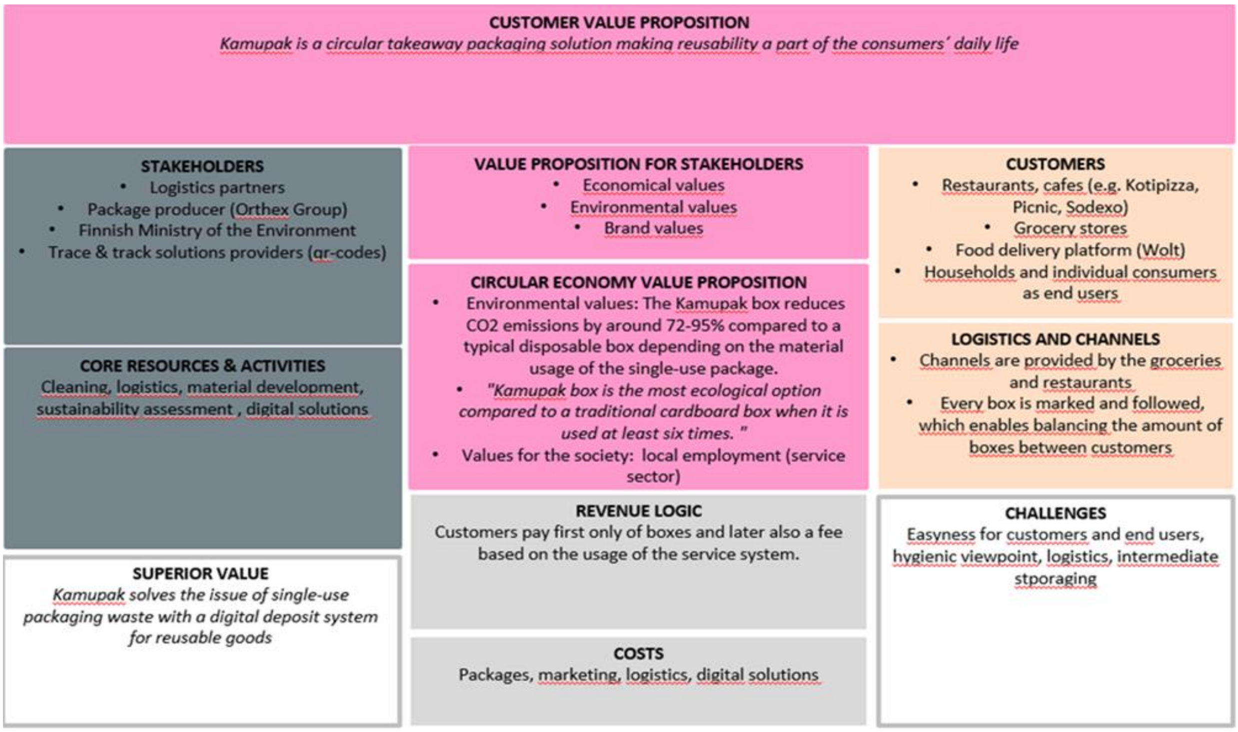

Figure 4. Kamupak´s circular economy business model depicted through a framework for sustainable circular business model innovation (Antikainen & Valkokari, 2016)

Good example: Trioworld

Trioworld is a leading producer of polyethylene films and multinational company originated from Sweden. They have several sustainable and recyclable solutions for plastic packages. Loop is their label for polyethylene (PE) film that contains up to 80% PCR (Post Consumer Recycled Material). By using PCR they reduce waste, lower the carbon footprint, close the material loop and drive circularity of plastics. Typical Loop products are shrink and stretch films as well as carrier bags. The company also provides services for horticulture and the industry, such as 1) TrioSmart, an environmental-friendly horticultural solution made of high recycled plastics content that includes a circular collection service meaning that the product is taken back to the Trioworld factory after use for recycling. 2) Concept of Trioloop Truecycle which works so that a company collects the waste generated in their operations and recycles it in a Trioworld plant or a Trioworld partner's recycling plant, depending on the location. The Trioworld plant or its partners will produce a new product of the recycled material and then give the waste generating company the opportunity to sell it again in their store. (Trioworld, 2023)

Agricultural plastics

Agriculture plastic circulation differentiates between countries. In Finland, a fifth of agricultural plastics are recycled as raw material whereas the majority goes to energy use or final disposal. For example, fertilizer sacks have been recycled since the 1970s - and the non-profit 4H associations still collect them (4H, 2023). According to surveys and interviews conducted in national and EU Horizon projects (ÄLYMUOVI, 2022) (Dahlbo, 2022) (Hytönen;Räsänen;& Pesonen, 2023), farmers are interested in plastic recycling. However, recycling is reduced because of lack of information, for example, the instructions for agriculture plastic recycling may not be readily available. Moreover, low quality (dirt, mixed polymer types) of the feedstock is conceived as a general problem regarding the utilization of collected plastics.

Good example: Rani Plast

Rani Plast is a Finnish multinational plastic company working with responsible values. Rani Plast produces industrial and agricultural packaging films. They are implementing several ways to improve sustainability in their actions and the innovation of new ways is at the focus of their business. One of their approaches is to combine fossil-based plastic raw materials with recycled and renewable plastic materials derived from pines, sugar cane or biodiesel-based waste products. Through mixing these raw materials they can optimize the carbon footprint and the mechanical properties of the film. Currently they are using downgauging to produce a multilayer film. They are also using MDO (machine direction orientation) technology to achieve thinner, stiffer and stronger films. Stronger films enable the compression of insulation material, which results in more economical transportation of goods. MDO-films can also be used to manufacture food packaging made of monolaminates, that consists of polyethylene film substrates only, which are then easy to recycle. In addition, they are continuously developing more sustainable inking methods (Rani Plast, 2023).

Good example: Platsretur - collection of agricultural plastics in Norway

In Norway, the collection of agricultural plastic is organized locally by farmers, in collaboration with local collectors. All collectors who have a business agreement with Plastretur regarding agricultural plastic are obliged to accept ready-sorted agricultural plastic free of charge. Today, it is possible to deliver the plastic packaging to around 100 collectors. In some places, local collectors have established collection of plastic packaging from the farmer, but these are local initiatives where the collector often takes payment (Norge, Grønt Punkt, 2023)

Good example: Svensk Ensilageplast Retur - Recycling management of agricultural plastic products in Sweden

Svensk Ensilageplast Retur in Sweden is a non-profit trade association for manufacturers, importers and retailers of silage films, plastic bags, cultivation foils and the like. This association works through its material company to create an environmentally friendly and flexible recycling solution for farmers, growers, and horse owners. Operations are managed by the nonprofit extended producer responsibility (EPR) company Svensk Ensilageplast Retur AB. They charge a fee to finance the whole recycling management of the agricultural plastic products which corresponds to the real costs and the level of service. Since the fee is paid directly at the time of purchase, the company needs only to leave the plastic at the collection point. The company that uses agricultural plastics does not need to pay separately for the further processing of them after use, as it has already been paid at the time of purchasing the product. (Svepretur, 2023). In Finland, for example, there is no such arrangement, and the removal of agricultural plastics can cost thousands of euros as a one-time payment (Älymuovi, 2023).

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Good example: RecyQuest - Recycling agricultural plastics in France

RecyQuest, a green economy start-up based in Argentan, France, specializes in the recycling of contaminated filamentary thermoplastics, including nets for round bales and twines. These single-use products are commonly utilized by farmers for storing fodder or straw after harvest. RecyQuest owns a patented process which effectively regenerates high density polyethylene (HDPE) from agricultural nets and polypropylene (PP) from agricultural twine. This innovative method eliminates the need for water or chemical products through the dry cleaning process, resulting in lower energy consumption. The recycled materials, Polypropylene (rPP) and High Density Polyethylene (rHDPE), are available in chipboard or high-quality granule forms that closely resemble virgin raw materials. (RecyQuest, n.d.)

Considering the global nature of agricultural plastic flows, cooperation is needed throughout the entire chain, from the manufacturer to the user and the recycler. Information is needed, among other things, on how sorting at sort can increase the processing rate of plastic waste and reduce costs. To build a connection, we need broader responsibility both nationally, EU and worldwide, without forgetting the actions of the individual actors.

Good example: Cirplus – marketplace for recyclates and plastic waste feedstock

Cirplus is a start-up company that provides a marketplace for recyclates and plastic waste feedstocks. The company is located in Germany, but it aims to work globally. The marketplace is meant for business to business and organizations can buy and sell recycled plastics though it. To be able to do transactions users have to sign in the system. Currently the marketplace does not take any charge of using the service, but the plan is to introduce business model based on interactions with the platform. In addition to marketplace, the company offers consultancy services. (Cirplus, n.d.) The marketplace is an example of business model that support plastic recycling and usage of side streams by connecting the suppliers and consumers in easy and efficient way.

2.2. State-of-the-art of the technologies used across plastics value chains

Technologies related to plastic waste recycling can be divided into sorting, pre-treatment, mechanical recycling, and chemical recycling, including thermochemical and solvent-based recycling. Depending on the types of applications plastic is used in as well as in which sector it is used, the collection systems vary. This affects the feedstock and its composition, collection, and quality. This in turn affects the suitability of the type of recycling procedures.

2.2.1. Collection

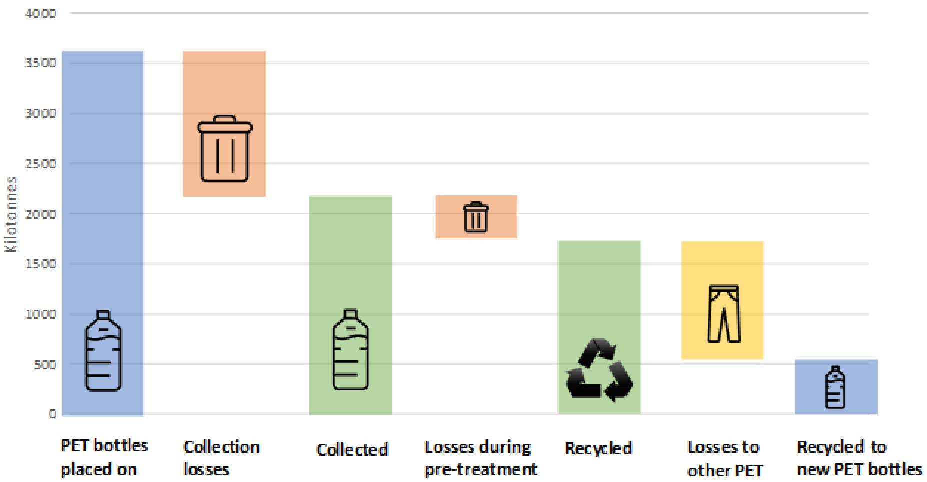
For circular economy, optimizing waste collection is a fundamental first step towards effective recycling. When plastic waste is collected and separated correctly, its recycling is also efficient and the recyclate quality and quantity are higher. Widespread and proper waste collection influences the quality of the waste streams directly and ensures their suitability for efficient downstream pre-treatment, sorting, and recycling and recovery operations. A harmonized process for waste collection and separation would be ideal, and it should be implemented across the value chain from waste collection and management companies to municipal and commercial operations. The EU's Waste Framework Directive sets out the basic requirements and concepts for waste management, including two important elements that affect the plastic waste collection (Plastics Europe, 2023):

- 'Polluter pays principle'
- Extended Producer Responsibility (EPR)

EPR is an environmental policy approach making producers responsible of product's end-of-life management (Kosior & Mitchell, 2020). As EPR shifts the cost of waste management from local governments to the producing industry, it creates incentive for easier recyclability of products. By making the industry take back their products that have reached end-of-life state encourages them to design them for recyclability or reusability. This in turn minimizes the production costs for the industry by encouraging the reuse of recovered material in new products. (Crescenzi & Kosior, 2020) A successful example of EPR scheme is the deposit return system (DRS) for plastic bottles. It works by including monetary value on a bottle, which customer pays when buying a beverage. The money is then returned to the customer when the empty bottle is returned to the local retailer.

Good example: Efficient collection PET bottle to bottle

PET bottle recycling system is the most developed of every PET product. Average collection rate of PET bottles in European countries which have implemented the deposit return system (DRS) is estimated at 96% and for those who do not have the DRS at only 48%, making the average collection rate of around 60% (Eunomia, 2022). Remaining 40% of PET bottles placed on the market are falling out of circulation and ending up in landfills, incineration, or in the environment (Figure 5).



Typically rec ... l losses also happen duri ... ing in a form of lost caps, ... e losses are estimated tc ... n the market end up in re ... h as trays or textiles and ... 22)

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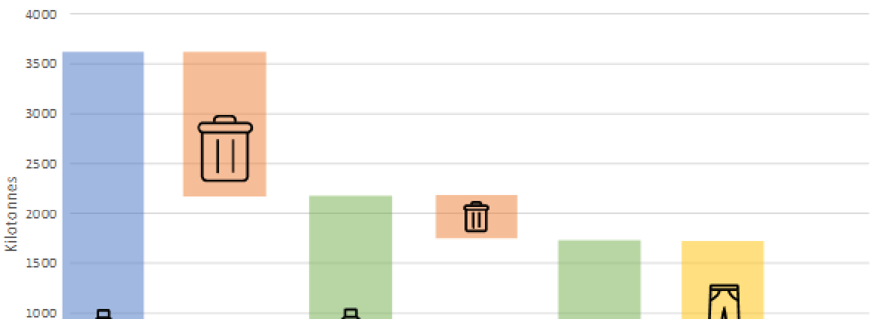

High success and positive impact of the DRS on PET bottle collection will likely attract the rest of the European countries to implement the system. Increased adoption of the DRS scheme will improve the quality of collected bottles and reduce contamination and material losses caused by separately collected bottle streams. (Eunomia and Zero Waste Europe, 2022)

Post-consumer plastic waste consists of everyday plastic products. The products are mainly plastic bottles and packaging. This waste stream can include all kinds of plastics but mainly PE, PP and PET. Post-consumer plastic waste stream often contains foreign materials and contaminants such as additives, paper, glass, and even hazardous substances due to improper sorting by consumers or businesses. Therefore, post-consumer plastic waste stream is very heterogenous, even though it often is collected separately. (Lange, 2021)

Collection of post-consumer plastic waste is typically done in the EU by curb side pickup or with permanent drop-off collection points, deposit-return points, or special collections. Plastic waste can be included in single-stream recycling where multiple types of recyclable materials such as plastic, glass, paper, and aluminium are placed in a single bag or container. This mixed collection method has lower collection costs, but major drawbacks are lower quality recycled material due to contamination and higher sorting costs. Another way is separate collection. When all recyclable materials are collected separately, the waste stream that ends up at the recyclers is more homogenous. The more homogenous stream is the easier it is to sort, and it is less contaminated from other material, and thus better-quality material is produced through recycling. (BCC Publishing, 2022)

Waste coming from electrical and electronic equipment (WEEE) is growing rapidly. In 2019 globally generated e-waste was estimated to be 53,6 Mt and expected to grow to 74,7 Mt by the year 2030. Whereas e-waste generated in the EU in 2019 was 12 Mt. In the EU, e-waste management infrastructure is considered well-developed covering collection, recovery of recyclable components and residual disposal in environmentally sound manner. However, only 5,1 Mt of e-waste was documented to be collected and properly recycled in EU. (Forti, Baldé, Kuehr, & Bel, 2020)

The WEEE is complicated waste stream due to wide range of different equipment and appliances as well as composition such as ferrous metals, non-ferrous metals, plastics, glass, and hazardous substances. Plastics' share in WEEE is estimated to be 10-51 % and mainly consisting of acrylonitrile butadiene styrene (ABS), high impact polystyrene (HIPS), polycarbonate (PC) and PP (Weißenbacher, et al., 2015). As a result of the complex waste stream, identification and plastic separation is an expensive, time-consuming, and complicated process, and therefore a large share of plastics remain unrecycled. Generally, in Europe WEEE-streams are collected and treated separately from other streams thus avoiding mixing into other streams. However, as WEEE-streams contain valuable metals the traditional recycling processes are optimized for metal recovery and not for plastic recycling which results in high incineration rate of the plastic residue. (Kaartinen, et al., 2020)

Similarly, to WEEE-stream, end of life vehicle (ELV) waste stream has a composition containing various materials and hazardous substances but mainly ferrous metals, non-ferrous metals, and plastics. For the same reason, as in the case of WEEE, the treatment of ELV is optimized for valuable metal recovery. The share of plastics in the waste varies depending on the model of the vehicle but generally is 13-21 %. (Kaartinen, et al., 2020)

Construction and demolition waste (CDW) comes from construction, renovation and demolition of buildings and infrastructure. The waste stream is complex, containing various materials such as plastic, concrete, bricks, gypsum, wood, glass etc. including hazardous substances. Collection of CDW is reported to vary within countries in the EU. This makes treatment of CDW hard as there is no harmony across EU countries in definition of CDW, collection or on-site separation. (Kaartinen, et al., 2020)

It is estimated that one fifth of all plastics are used in construction. Typical uses of plastics are insulation materials, moisture, and damp proofing materials. Mainly PVC is used accounting for 50-55% of polymers used in building. PS is also a typical polymer present in building with a share of around 14-19%. Other polymers are also present but typically in amount of less than 10%. (Häkkinen, Kuittinen, & Vares, 2019)

2.2.2. Sorting

A wide range of technologies are currently used for waste pre-treatment and sorting. These range from manual dismantling and picking to automated processes. The sorting is typically done based on size, shape, density, color, or chemical composition and is usually done in a sequence of sorting steps (Lange, 2021). Some of the widely used sorting methods are waste screening, air separation, ballistic separation, magnetic separation, eddy current separation, sensor-based sorting and to some extend manual sorting (Kol, et al., 2021). However, recently emerging technologies such as watermark and bar-coding are being investigated to enhance the sorting efficiency of plastics (AIM, 2022).

Sorting by size is typically done manually or with sieves. There are various methods for plastic separation from other material such as metal and glass. Common methods are the use of gravity in air flow or density-based separation in water. Additionally, metals can also be separated efficiently with magnetic separation. Optical sorting with equipment such as near infrared (NIR) detectors is commonly done to identify and sort the plastic accordingly in sorting units. (Lange, 2021)

HolyGrail 2.0 – good example for sorting

HolyGrail 2.0 is a digital watermark initiative driven by AIM – European Brands Association and powered by the Alliance to End Plastic Waste. The objective of this pilot project is to prove technical and economic viability of digital watermarks to enhance sorting of packaging waste on a large scale. (AIM, n.d.)

Digital watermarks contain codes that are invisible for the naked eye. They are small barcodes placed on the surface of the plastic product containing information about the plastic. The idea is to use high resolution cameras on the sorting line that will detect and decode the barcodes on the objects and sort them according to the information received from the watermark (e.g., polymer type, food vs non-food usage, manufacturer etc.) Additionally, to sorting and recycling, markings can have benefits for various sectors in plastics lifecycle, where product data can be utilized. (AIM, n.d.)

The results achieved were highly promising in terms of detection (99 %), ejection (95 w- %) and purity (95 w-%). Approximately 125 000 pieces of packaging from 260 stock keeping units were processed. Industrial tests are set to begin in 2022. (AIM, 2022)

2.2.3. Purification

Generally cleaning of plastic waste is necessary for mechanical recycling but also highly beneficial for chemical recycling. Often contaminants and dirt can hamper the reprocessing. Hence even well sorted plastic is often not suitable for reprocessing without washing. Cleaning is typically done by water and could be assisted by caustic agents or detergents. Washing unit is often integrated after size reduction into sink-float sorting step. Purification step is relatively expensive, requiring washing and drying equipment as well as wastewater treatment unit. Moreover, even with the most efficient washing for example odorous components are not removed entirely even by caustic wash and nonpolar components require additional detergent or organic solvent to be removed more efficiently, which requires effective wastewater treatment unit. (Lange, 2021)

2.2.4. Mechanical recycling

Mechanical recycling is currently by far the most used recycling process for plastics. In 2020 out of all collected post-consumer plastic waste around 35 % was sent to recycling of which only 0,2 % was recycled chemically and the rest mechanically (Plastics Europe, 2021). Mechanical recycling is a mature technology and widely used for processing single-polymer plastic waste, such as polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP) and polystyrene (PS), but also mixed plastic waste streams can be treated mechanically in some cases (Hahladakis;Lacovidou;& Gerassimidou, 2020).

A general method for mechanical recycling is an extrusion process. An extrusion process is relatively inexpensive, simple and able to provide continuous output (Dynisco, 2021). Thermoplastics are fed into extruder through hopper where high temperature softens the plastic waste. The temperature is specified according to the plastic type (Schyns & Shaver, 2021). Volatile substances such as some of the monomers and solvents are removed through suctioning system (Feil & Pretz, 2020). During melting the plastic waste is also homogenised and compressed by the rotating screw (Feil & Pretz, 2020). The rotating screw conveys the melt forward and through a filter to remove any solid impurities (Feil & Pretz, 2020). In some cases, post-extrusion forming can take place for shaping the product and fixing the product by cooling the recycled plastic (Dynisco, 2021).

Mechanical recycled plastic can replace virgin plastics in the production of the same, similar, or completely different product. Recycling can be categorized into two categories based on the properties of recycled plastic, known as closed-loop and open-loop. (Hahladakis;Lacovidou;& Gerassimidou, 2020)

Closed-loop recycling or upcycling is more desired of the two. In closed-loop recycling the properties of the recycled plastic remain similar as of the virgin material. Therefore, recycled plastic can be reprocessed into same original products and thus, reduce dependence on the virgin plastics. One of the most successful and widely implemented closed-loop recycling of plastic is PET bottle to bottle recycling. (Hahladakis;Lacovidou;& Gerassimidou, 2020)

On the other hand, open-loop recycling also known as downcycling or cascading the properties of the recycled plastic are downgraded to a lower quality, which makes it not suitable in production of same products (Hahladakis;Lacovidou;& Gerassimidou, 2020). Generally, plastics can undergo mechanical treatment only a few times before it loses too much of its quality for closed-loop applications. The degradation of plastic in mechanical recycling is inevitable. Degradation is caused by the heat and shear stress targeted on polymers in the extruder (Schyns & Shaver, 2021). These factors induce chain scission, branching or crosslinking of the polymer and can cause reduction in the polymer chain length lowering its mechanical properties and processability (Schyns & Shaver, 2021). Various additional factors, such as additives and processing of mixed plastic can accelerate this issue. However, even that open-loop recycling is less desirable of the two, it still should be considered as a viable solution for material recovery (Hahladakis;Lacovidou;& Gerassimidou, 2020).

Good example: VAREX advanced mechanical recycling

Value Retention Extruder (VAREX) extrusion line is an advanced mechanical recycling technology developed by VTT. With this innovative tandem extrusion line, the properties of mechanically recycled plastics can be upgraded to reach ideally virgin-like properties by using in-line measurement of melt rheological properties (e.g., shear and extensional viscosity). (Rytöluoto & Pelto, 2022)

Filtrated melt is fed through melt flow index (MFI) measurement unit and data is transferred to the second extrusion which is a twin-screw extruder. These extruders are constantly communicating with adaptive controller, sending process values from the extrusion line, and receiving new feeder set points if feedstock quality is changing. Several feeders can be connected to the twin-screw extruder, depending on a case-by-case basis. The feeders can be used to feed virgin polymers, additives, stabilizers, compatibilizers etc., and added to the melt according to the set points received through the extruders. In the outlet before processed plastic is collected there is in-line elongational rheometer, which measures shear and extensional viscosities of the final output material. This viscosity data is then utilized in controlling of material feeding and extrusion process. At the end stabilized recycled plastic with upgraded rheological properties is collected. The full system is described in **Error! Reference source not found.**. (Rytöluoto & Pelto, 2022)

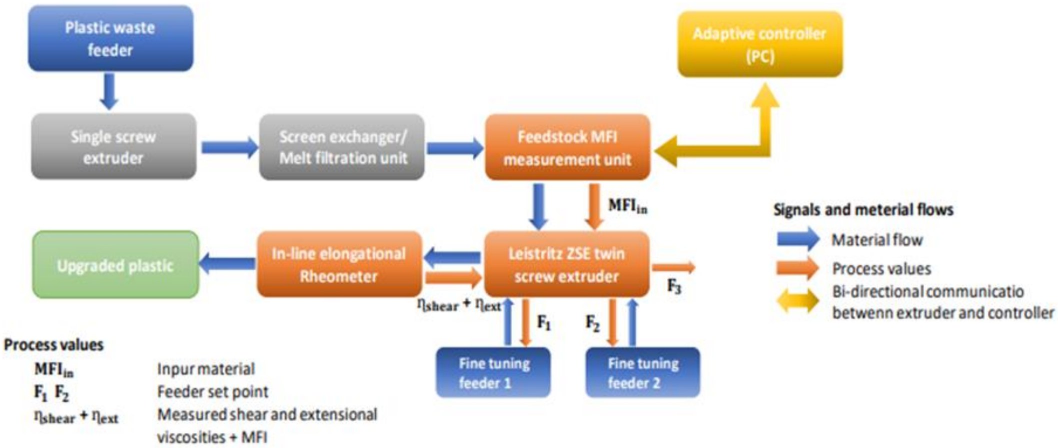

Figure 7. VAREX mechanical recycling line with adaptive in-line rheology control. Own illustration, modified from (Rytöluoto & Pelto, 2022)

The advantages of the VAREX extrusion line are in-line measurement and collection of rheological data of the recycled polymers, compounds, and blends. Said data can be directly presented to plastic converters to certify rheological properties of recycled plastic. The process is adaptive which allows it to be modified and to reach desired target viscosity of recycled plastic via smart addition of various compounds within the batch or batch to batch variations. However, if the feedstock is severely degraded or contaminated to begin with a high-quality product is not likely to be achieved, unless significant amount of virgin polymer is added. To conclude, the main benefits of VAREX extrusion line compared to standard mechanical recycling is the in-line data collection with so called "on the fly" addition of compounds to enhance the quality of the final product. (Rytöluoto & Pelto, 2022)

Funded by the European Union

2.2.5. Solvent-based chemical recycling

Depolymerisation or solvolysis is one of the solvent-based chemical recycling technologies for plastics. The principle of the technology is depolymerization of polymers into monomers using solvent and relatively high temperatures (Jiang, et al., 2022). Solvolysis allows selective monomer recovery. Recovered monomers can be further purified from additives and colorants. Purified monomers can be then repolymerized to virgin-like polymers. Some of the common solvolysis reactions are hydrolysis, glycolysis, ammonolysis and methanolysis. The reactions brake chemical bonds such as ether, ester and acid amide bonds and therefor the technology is limited to condensation polymers. Hence, research has been focusing mainly on PET, polyurethane (PUR), polyamides (PA), polycarbonates (PC) and polylactic acid (PLA). (Vollmer, et al., 2020)

In addition to solvolysis there is selective dissolving methods. Selective dissolving differs from solvolysis by not depolymerizing the polymers. Thus, whole polymers chains are recovered rather than just monomers. As in the solvolysis the recovered material can have virgin-like quality. Selective dissolving can be applied when the feedstock contains polymers with large enough difference in solvation. Selective dissolving seems to be interesting especially because of its potential of applying it to two- or multi-layer materials by dissolving the material layer by layer or polymer by polymer (Pohjakallio;Vuorinen;& Oasmaa, 2020).

Good example: CreaSolv solvent-based recycling

CreaSolv® is a selective dissolution process developed by Fraunhofer Institute for Process Engineering and Packaging IVV (Figure 8). The process can be classified as a separation process or as a direct recycling process. The process produces high quality recycled plastic with virgin-like material properties. Various contaminants and additives such as printing inks and brominated flame retardants (BFRs) are removed in process. In addition, targeted plastics can be removed in mixed plastic waste including composite plastic such as laminated films and waste electronic and electrical equipment (WEEE). Therefore, developers claim it to be the first process for closed-loop recycling of contaminated plastic waste. (Fraunhofer IVV, n.d)

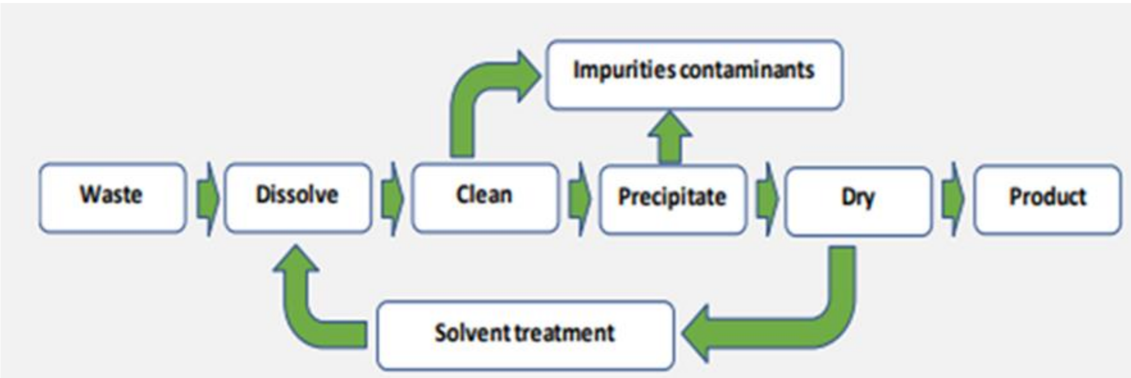

Figure 8. Illustration of CreaSolv® Process (own illustration, modified from Fraunhofer IVV, n.d.)

The solvent based CreaSolv® Process begins with selective dissolving of the target polymer. Important note is that only non-hazardous solvents certified with Globally Harmonized System (GHS) criteria are used to ensure safety of users, operators, and the environment. Solvent is recovered from every step and distilled, which allows its reuse. After the dissolving step the material is cleaned. Mechanical separation is done for undissolved material and special purification steps at the molecular level are performed to the dissolved material, such as removal of non-target polymers, inks, and hazardous substances. Solution containing macromolecules of the targeted polymer with size and molar mass distribution that corresponds to virgin material, is removed from the solvent by precipitation and then dried. Achieved product is high quality plastic recyclate that can be used for new material production. (Fraunhofer IVV, n.d)

2.2.6. Pyrolysis

Pyrolysis can be used for thermochemical recycling of almost all kinds of organic material including plastics (Krause;Carus;Raschka;& Plum, 2022). Pyrolysis is a process where material is heated and degraded in relatively high temperature in the absence of oxygen (Figure 9). The product of plastic waste pyrolysis is a mixture of hydrocarbons in the form of gas, liquid and solid. The mixture of hydrocarbons can be used as a feedstock for new virgin-grade polymers. (Pohjakallio;Vuorinen;& Oasmaa, 2020)

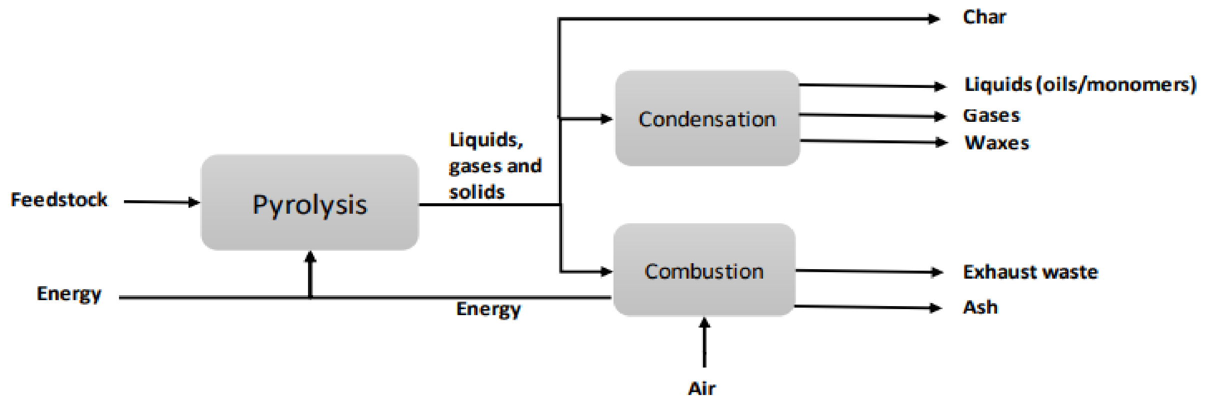

Figure 9. Typical process diagram of plastic waste pyrolysis (modified from Krause;Carus;Raschka;& Plum, 2022)

The working principle of pyrolysis reactor is to process plastic waste into vapor, under high temperature exposure and usually with the aid of catalyst. The vapor consists of hydrocarbons with carbon numbers ranging from 1 to over 20. The heavier hydrocarbons can be condensed into liquid or wax, while lighter fraction that is non-condensable remains as gas. The gas fraction has a relatively high heating value of approximately 25-45 MJ/kg. The high heating value makes it a suitable energy source that can be circulated it back to the process, making it self-sustainable in terms of energy but in the process suffering from relatively high material losses. (Qureshi, et al., 2020)

The product distribution is affected by various factors such as waste feedstock, catalyst, reactor type, operating conditions (mainly temperature), residence time and heating rate. Generally liquid fraction or pyrolysis oil is the desired product, but the process can be also optimized into production of wax, monomers, aromatics, or selective chemicals by using suitable catalysts. (Qureshi, et al., 2020)

As discussed, pyrolysis oil is a mixture of hydrocarbons, thus it resembles crude-oil. This potential makes it a great raw material to be refined into fuel or preferably to new monomers and polymers (Vollmer, et al., 2020; Pohjakallio, Vuorinen, & Oasmaa, 2020). Polymers refined from pyrolysis oil have virgin grade properties and could be used in production of new high-quality plastic products. While pyrolysis oil could be converted to monomers in similar way as from crude oil, the production of monomers directly from pyrolysis is desired option for economic reasons as additional steps are would be avoided. However, the direct monomer production from pyrolysis seems to be limited to certain feedstock such as PS. (Vollmer, et al., 2020)

The feedstock of choice for pyrolysis can be more flexible than for example mechanical recycling. Separated or even mixed polyolefins are considered as an ideal feed for pyrolysis (Qureshi, et al., 2020). Polyolefins can be converted directly into monomers by pyrolysis but with rather low yield of around 35 wt%, thus further refining of carbon rich product is often required. Additionally, to some extend more contaminated plastic waste can be fed into pyrolysis reactor without major issues (Pohjakallio;Vuorinen;& Oasmaa, 2020). However, there are some limitations in terms of monomer production from pyrolysis. For example, PET and PVC are almost impossible to process into monomers without additional pre-treatment steps of selective removal of formed HCl in the case of PVC presence (Vollmer, et al., 2020). PET on the other hand decomposes into phthalic acids which also worsens the oil quality (Qureshi, et al., 2020).

Good examples for pyrolysis: Polyfuels, INEOS, and Pyrowave

Polyfuels, in collaboration with the Nagata corporation (Japan) and engineering partner Watec Solutions, have developed a high-end quality pyrolysis system with a proof-of-concept plant of 2 tonnes per day production capacity for plastic recycling with no oxygen presence and minimum emissions. The technology is based on multiple-stage reactors that provide the refined end-product. The machine structure involves several machines that are connected into a larger production unit. The machines still run separately, where the individual machine can be shut down and run up independently of the others in connection with maintenance and repair. This provides high operational reliability/"redundancy" and the ability to process several different types of plastic simultaneously. The process results in high yield of pyrolysis oil, theoretically up to 96%. The low operational temperature in pyrolysis process produces high quality oil and prevents dioxin formation. Through the processing of plastic waste under low pressure and relatively low temperatures (370-440˚C), the processes that today generates oil from carbon in nature are recreated.

INEOS Styrolution has developed a proof of concept for depolymerisation technology of polystyrene waste. The feedstock must be sorted and shredded before feeding into the depolymerisation process. The process can handle contamination of polyolefins but is limited to <1% of PET and ABS content. The process requires high temperature of 500-700˚C and as short as possible residence time to depolymerise PS into its monomers. The end product is crude styrene oil that needs to be purified by distillation before repolymerisation. According to the research led by the company, up to 75 % of the product can be fed into distillation and polymerised to new PS. Life cycle assessment (LCA) was conducted for the technology and showed around 35 % savings in greenhouse gas (GHG) emissions compared to fossil-based monomer production. (Krause;Carus;Raschka;& Plum, 2022)

Another technology to depolymerise PS is developed by Pyrowave which is a catalytic microwave depolymerisation (CMD) technology. Similarly to INEOS, the technology feedstock needs to be shredded and cleaned from contaminants such as labels and films. The technology uses microwave energy to transfer heat to the reactor by mixing silicon carbide in the feedstock. Obtained monomers are purified by distillation to produce styrene oil. Up to 95 % of styrene monomers could be achieved by Pyrowave. Compared to styrene production from crude oil, the energy demand is 15 times less for said technology. (Krause;Carus;Raschka;& Plum, 2022)

2.2.7. Gasification

Gasification is a process where organic material is converted into a gas known as syngas. Syngas or synthesis gas contains manly hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and nitrogen (N_2) (Lopez, et al., 2018). The focus of plastic waste gasification has mainly been energy production, energy carrier or chemicals by refining the syngas (Lopez, et al., 2018). However, novel technologies such as Olefy technology have emerged to produce virgin-grade olefins that can be used in production of new polymers (VTT, 2022).

Gasification is an energy intensive process. A typical operating temperature is over 700˚C (Krause;Carus;Raschka;& Plum, 2022). The advantage on the of gasification process is even more flexible in feedstock requirements compared to for example pyrolysis. The feedstock for gasification can be plastics of different composition, mixtures or mixed with another organic feedstock (Lopez, et al., 2018). The product that is syngas may need purification such as N_2 removal or adjustment in concentration and ratio of CO and H_2 depending on the intended use (Krause;Carus;Raschka;& Plum, 2022).

Good example for gasification: Olefy technology

Olefy technology is single step gasification process for plastic waste. The technology can recover over 70 % of virgin grade plastic and chemical raw material components from plastic waste. The company claims the gasification technology to be an economically viable way for plastic waste recycling. The input requirement for the feedstock is only minimal sorting by consumers or businesses, thus, tolerating contaminants to some extent. The technology requires an equal amount of PE or PP waste to produce a ton of virgin grade olefins as the amount of naphtha would be required in traditional way of olefin production. Additionally, the company claims to have lower costs of olefin production than in the case of traditional process. The process is also self-sufficient in terms of energy as it produces enough excess energy to be circulated back into the process. The Olefy pilot is running at VTT Bioruukki Pilot Centre in Espoo Finland, and its first industrial demonstration is expected to begin operation in 2026. (VTT, 2022)

2.3. Ecodesign and good practices from circular plastics

The new proposal for a Regulation on new Ecodesign requirements published March 30, 2022, aims at reducing the life cycle environmental impacts of products sold in the EU. To do so, the expected Ecodesign Regulation will set new requirements on the basis of sustainability and circularity parameters. It underlines factors such as: durability reusability; upgradability and reparability, recycled content of products, products' carbon and environmental footprints, and so on.

By bringing lifecycle and circular thinking into product design (i.e., design for recycling) substantial future waste, pollution and toxins could be avoided. An example of a problematic product designs are multilayer materials (e.g., high-performance food packaging) that are made of multiple complex layers of different plastics. The multilayer packaging structure consists of mostly PE due to its cheap price, but other plastics such as PET for toughness and ethylene-vinyl alcohol (EVOH) for blocking oxygen are layered on top. The separation and thus recycling of these layers is often difficult or impossible. (Ragaert, Delva, & Geem, 2017)

Moreover, the addition of harmful or toxic additives makes recycling even more challenging. Precise control and separation for waste flow into recycling plant is needed to ensure safety and good product quality that some additives may compromise. These products are often waste from construction and demolition, automotive or WEEE. There is no one technology or exact solution for transition to solve all challenges related to transition to circular economy of plastics, rather there is a need for joint actions across the whole value chain including manufacturers, consumers, recyclers, and policies. (Tenhunen & Pöhler, 2020)

Ecodesign is mostly applied to plastic packaging, where the aim is to minimise the environmental impacts of plastic packaging and packed goods over their entire life cycle. The ecodesign of packaging, which currently makes up a significant part of municipal solid waste, is also covered in the proposed revision of packaging and packaging waste directive (PPWD) (Nov. 2022), which requires all plastic packaging placed on the EU market to contain certain minimum amount of recycled content recovered from post-consumer plastic waste" as of January 2030. Moreover, EU's Strategy for Plastics in a Circular Economy (CE)" (2018) stipulates that all plastic packaging placed on the market in the EU should be either reusable or recyclable in a cost- effective manner by 2030.

As for recyclability, multilayer packaging poses a specific problem. Multilayer packaging combines different polymeric and other materials such as paper or aluminium, which enables customized property profiles with low material consumption. Multilayers can reduce the cost, e.g., by replacing expensive polymers with less costly ones, reducing film thickness, or using recycled materials. According to Schmidt et al (2022) ca 17% - 20% of plastic packaging consists of multilayer packaging, major brands recognise the need to shift towards higher recyclability (Grau, Auer, Maletz, Jörg, 2022). Many of the biggest producers are making a shift from plastic to bio-based packaging and/or to monolayer (or nearly monolayer) materials that are more easily recycled within existing streams. Packaging World has presented mono-layer materials such as microwavable monolayer PP pouches for rice dishes (Amcor, JM Packaging) and Unilever Japan personal care pouch by Toppan fitting the PET stream thanks to its thin, vapor-deposited barrier layer (Reynolds, Packaging World, 2021).

Good examples

The Pantene stand-up pouch is a PE/PE adhesive lamination where the adhesive provides barrier yet does not interfere with the PE recycling stream. The idea here is for the consumer to pour the contents into a reusable rigid container and then dispose of the pouch in the PE recycle stream.

The challenge that the packaging provider had with this monomaterial pouch development was selecting the proper materials with only the use of adhesive, ink, and barrier materials of less than 5% by weight, that still provided durability for the liquid. (Reynolds, Packaging World, 2022)

Figure 10. Pantene stand-up pouch (Reynolds, Packaging World, 2022)

Good examples: Recyclable biobased packaging

Several cellulosed based alternatives to traditional plastic applications have entered the market the last five year. Paptic manufactures cellulose-based, recyclable flexible packaging for various purposes, bags, pouches mailers and dry food. Though product applications are typical single use items, Paptic® products can be reused several times before directed to recycling with packaging papers and cardboard. Main raw material is wood from certified forests and does not compete with agricultural resources for food/feed. Important is that recycling guidance is clear to avoid it will not end up as contamination in plastic recycling. (Paptic, n.d.)

Fibrease® by Stora Enso is made from up to 98 % renewable materials and can replace PUR foams and expanded polystyrene (EPS). Fibrease resembles viscoelastic foam and can be shaped by cutting and thermoforming. Due to its insulating properties, the material is suitable, for example, for cold-heat pack-aging used in online grocery stores and pharmaceutical transports. It can be recycled together with paper and cardboard or in a closed cycle into new material and new products. (Stora Enso, n.d.)

Good example of ecodesign complementing circular business model: CLUBZER0®

CLUBZER0®, based in United Kingdom, offers a returnable packaging service for drinks, providing cup traceability through radio-frequency identification (RFID) technology and cloud-based internet of things (IoT) software. (Reflow, n.d.)

Considering the ecodesign, CLUBZER0® makes reusable cups out of 70% recyclable virgin material and 30% recycled material food grade PP. The lids are made from low density polyethylene (LDPE). Reusable cups and lids have the lifetime of 250-1000 uses before recycling. (Green Brown Blue, n.d.)

With the reusable product, CLUBZER0® leverages its circular business model to eliminate single-use package. The cups and lids are embedded with RFID tags that allows product traceability throughout the journey. CLUBZER0® partners with brands across retail (restaurants and cafes), non-retail (offices and universities) and delivery (online food delivery platforms) to distribute the reusable package to customers. After consumption, customers can access CLUBZER0 IoT platform to check out, return used package at drop-off locations and earn rewards. The platform also provides real-time data on location and quantity of products for optimising the collection and drop-off scheme to be as eco-friendly as possible. The reusable packages are washed and undergo quality check before return-ing to the circulation. (CLUBZERO, n.d.; Green Brown Blue, n.d.)

In United Kingdom, the package return rate is at 95%. CLUBZER0® has served over 3,000 customers across cities in Europe and North America, saving 34 tonnes of CO_2 and over 2.2 million items of single-use plastics. (CLUBZERO, n.d.)

Part III: Repurposing end-of-life electric vehicle batteries

3. Repurposing end-of-life electric vehicle batteries

The TREASoURcE project focuses on the repurposing as the circular strategy with end-of-life EV batteries. Next, the repurposing and circular business models are further examined. Then the technologies in place for repurposing will be explained, which is finally followed by ecodesign practices. All chapters include good practices as examples to inspire and illustrate functional circular economy practices and businesses.

3.1. Circular business models

The global demand for batteries is expected to rise 14-fold by 2030 (World Economic Forum, 2019). By then, around 965 GWh of annual battery production capacity is expected in Europe, accounting for 28% of 2030's announced global capacity of around 3,500 GWh and increasing 20-fold from 2020 (McKinsey & Company, 2022)

To obtain the batteries needed, it has to be ensured that they can be manufactured – this sets requirement for battery cell production, which in turn sets a demand for raw materials. To secure market acceptance, reuse and recycling processes should also be considered accordingly. The mission of the European Battery Alliance is to ensure an unbroken value chain in Europe that can supply the market with all the batteries it needs – with the smallest environmental footprint possible. The challenge is multi-dimensional including i.e. technologies, business models, supply chains, human capital, regulation and industrialization – so indeed, innovative cooperation is needed as **Error! Reference source not found.Error! Reference source not found.** demonstrates. (European Battery Alliance, n.d.)

Figure 11. Value chain interlinkages related to EV production and 2nd life (European Battery Alliance, n.d.)

By 2030 the volume of battery packs reaching end-of-life in Europe is expected to reach 250,000 tons per year and Western Europe alone is expected to reach a battery EV market share of 60%, or 8.4 million vehicles. 2nd life of EV batteries is a huge opportunity on pack, module and cell levels prior to material recycling and remanufacturing. For instance, as per the guidelines of Original Equipment Manufacturer (OEM), EV batteries should be replaced at their 70-80% usage capacity – however, these batteries have still sufficient capacity in them to use for other applications, i.e. energy storage systems. (Dhage, 2022)

In particular circular business models based on remanufacturing and reuse can lead to major cost savings in addition to reductions in environmental load. Figure 12**Error! Reference source not found.** presents circular economy strategies for lithium-ion batteries. The numbers in parentheses describe the number of examples found in practice by OEMs in EU (see also Table 1 for reference). Some OEMs, such as Daimler and Renault, have already internalized circular business models by expanding to the energy business and incorporating second-life application. Closed-loop initiatives are also popular among vehicle OEMs such as Nissan, BMW, and Renault. Circular business models based on energy storage solutions can lead to new value propositions, such as grid stabilization, back-up power, peak shaving, and local solar power production support (Albertsen, Richter, Peck, Dalhammar, & Plepys, 2021).

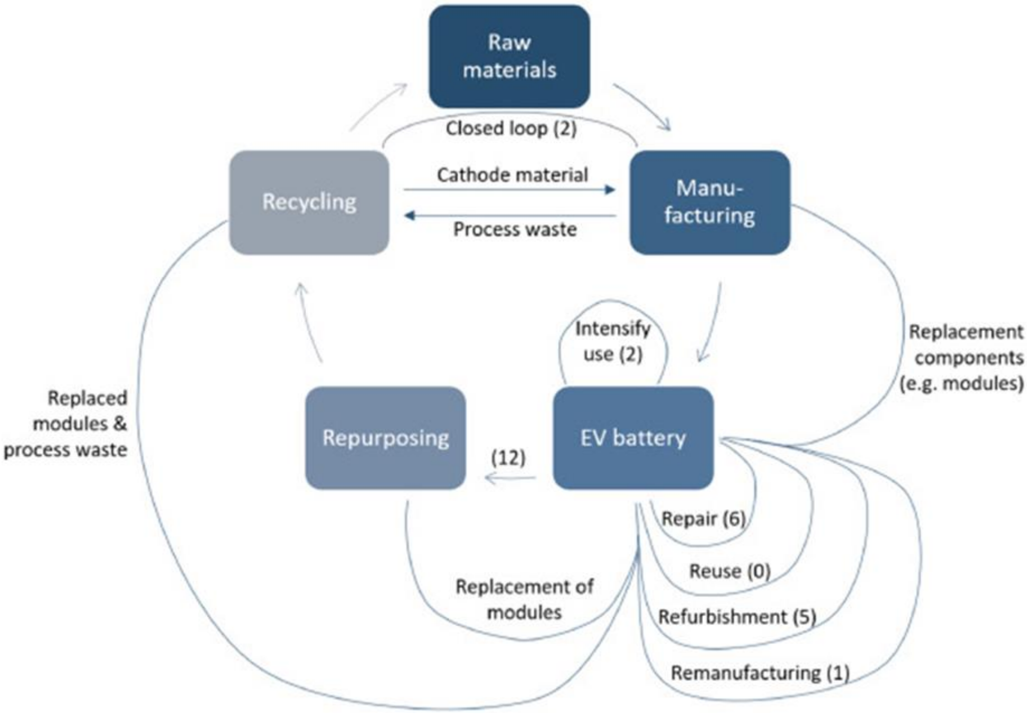

Figure 12. Circular economy strategies for Li-Ion batteries (Albertsen, Richter, Peck, Dalhammar, & Plepys, 2021)

Table 1. Table of deployed CE activities at vehicle OEMs in EU (an x indicates there was no available information on the activity type (Albertsen, Richter, Peck, Dalhammar, & Plepys, 2021)

Company/Group	Intensifying use	Repair	Refurbish	Reman	Repurpose	Closed-loop recycling
ADL	x	x	x	x	x	x
BAIC	x	x	x	x	x	x
BMW	x	x	x	x	Yes	Investigations
BYD	x	x	x	x	x	x
DAF	x	x	x	x	x	x
Daimler AG	x	Yes	Yes	Yes	Yes	Investigations
Ford	x	x	x	x	x	x
Honda	x	x	x	x	Investigations	Investigations
Hyundai	x	x	x	x	Yes	x
Irizar	x	Yes	Yes	x	Yes	x
Jaguar Land Rover	x	x	x	x	Yes	x
LEVC	x	x	x	x	x	x
Mitsubishi	x	x	x	x	Yes	x
Nissan	Yes	x	x	x	Yes	x
PSA Group	x	x	Unclear	x	Investigations	x
Renault Group	Yes	Yes	Yes	No	Yes	Yes
Solaris Bus & Coach	x	x	x	x	Investigations	Unclear
Streetscooter	x	x	x	x	x	x
Tazzari	x	x	x	x	x	x
Tesla	x	x	x	x	No	Envisioned
Toyota	x	x	x	x	Investigations	x
VDL Bus & Coach	x	Yes	Yes	No	Yes	Investigations
Volkswagen Group	x	Yes	Yes	No	Yes	Yes
Volvo Cars	x	x	x	x	Yes	x
Volvo Group	No	Yes	Investigations	Investigations	Yes	Investigations

Figure 13 and Figure 14 present the ongoing battery projects and battery recycling projects in EU as of July 2022, Norway has a lot of active projects in this space (Dhage, 2022).

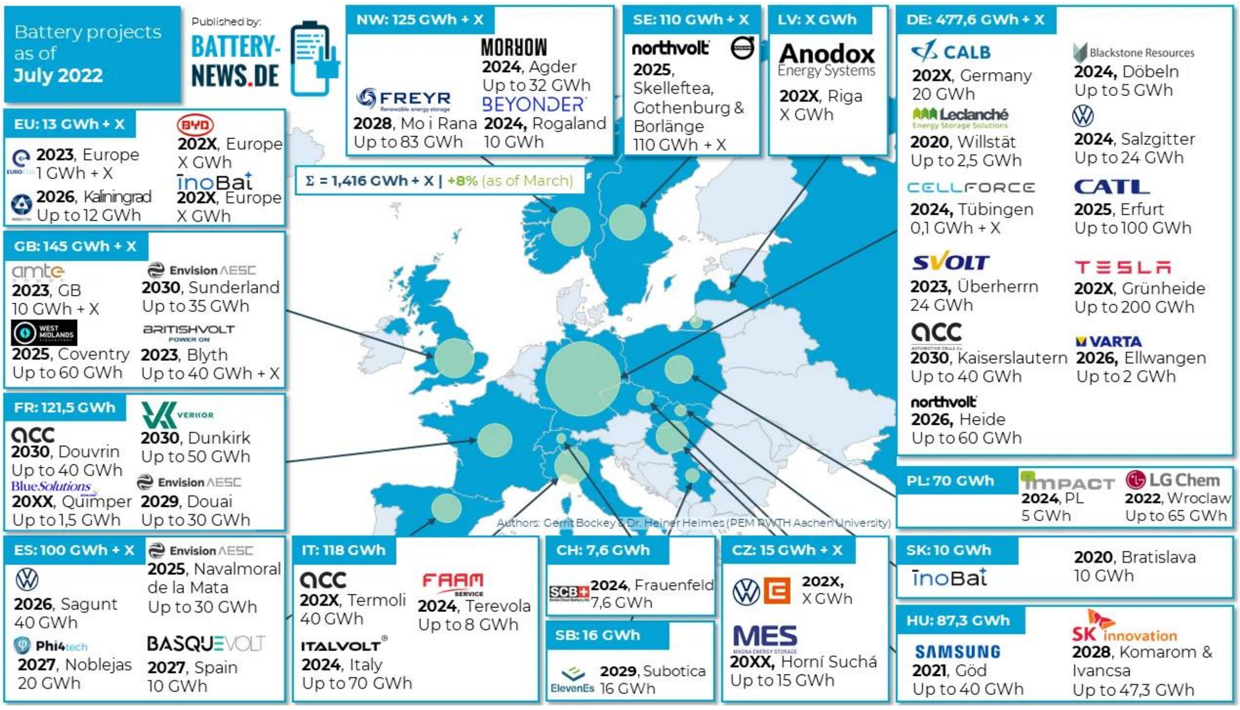

Figure 13. Ongoing battery projects in Europe (July 2022) (Dhage, 2022)

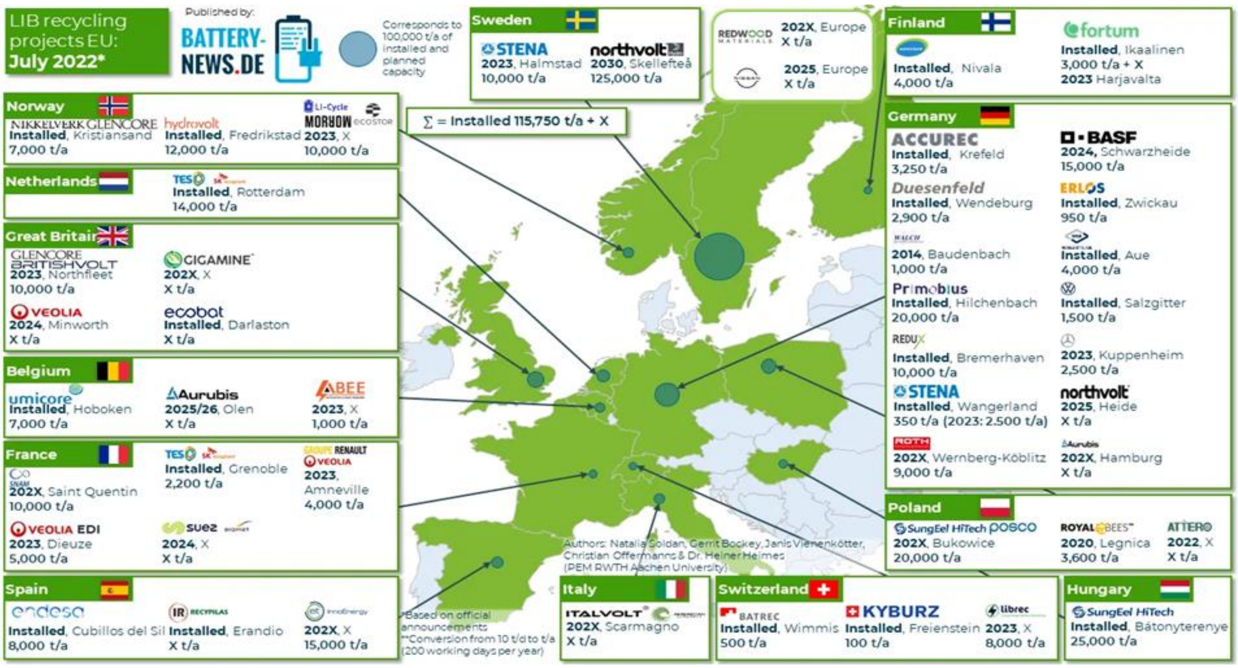

Figure 14. Ongoing battery recycling projects in Europe (July 2022) (Dhage, 2022)

Business models in Norway

The global availability of used EV batteries is still relatively low. However, with the increasing numbers of EVs sold worldwide in addition to the electrification of other sectors, the available 2nd life capacity is predicted to grow significantly. McKinsey predicts that 2nd life battery supply could surpass 200 GWh by 2030 (Figure 15). (H. Engel, 2019)

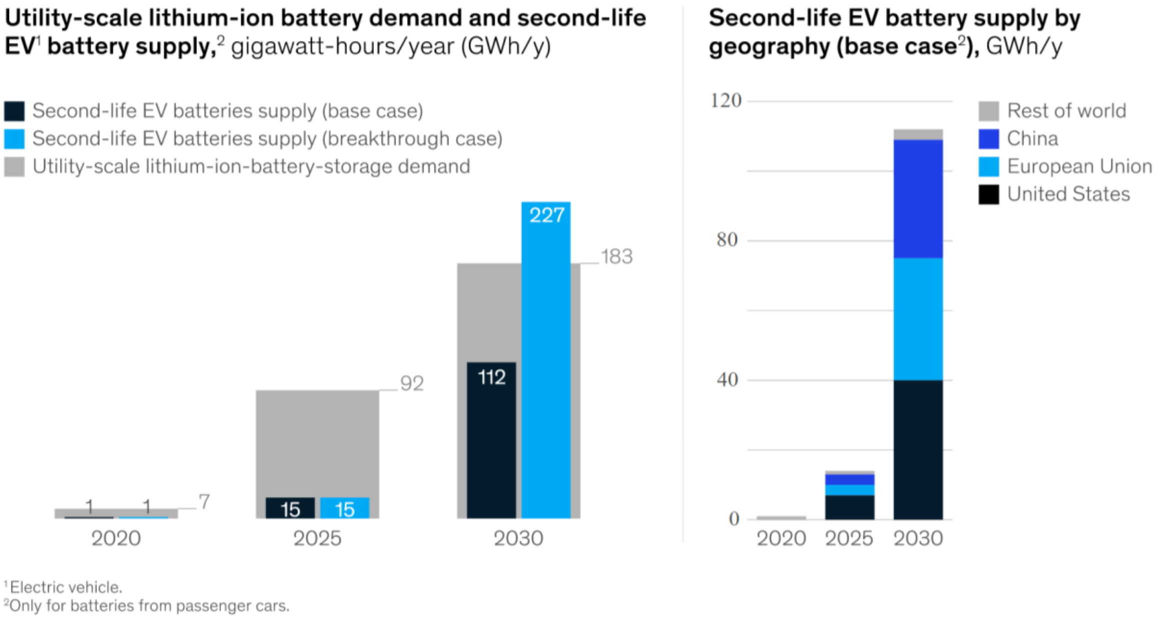

Figure 15: Second-life LIB supply estimated by McKinsey & Company, showing utility-scale LIB demand and 2nd life EV battery supply (H. Engel, 2019)

Norway is in a particularly favourable position to take the lead in the development of 2nd life battery applications considering the large number of EVs on the road. Indeed, since the market launch of the Nissan Leaf in 2011, nearly 700 000 EVs (either pure battery or plug-in hybrid) have been registered in Norway as of May 2023. (Elbilstatistikk, 2023) Of those vehicles, over 140 000 have been in operation for more than five years, meaning that their batteries are approaching or have already reached the EOL for use in traction systems. Several companies are now exploiting this opportunity in Norway, and we see an increasing number of installed battery systems based on used EV batteries.

Good examples from Norway

In Norway, the non-profit organization Autoretur AS, which is owned by Bilimportørenes Landsforening (BIL), is responsible for collecting and recycling all used cars. Autoretur AS is authorized by the Directorate for the Environment as the sole company responsible for recycling cars, including EVs. It is, however, the authorized car collectors which receives the used EVs and handles the dismantling and collection of the batteries. During the disassembly of the used cars, the battery is removed, checked for damage and then shipped to Batteriretur Høyenergi AS, which takes care of the recycling of the batteries. (Autoretur AS, 2023)

There are several companies in Norway that offer energy storage systems based on used EV batteries, including Eco Stor, Hagal, Evyon, Eaton, ChainPro, and Battkomp. Eco Stor and Evyon both have signed MoUs with OEMs, where Eco Stor collaborates with Nissan and use Nissan Leaf batteries, while Evyon uses Mercedes batteries.

Eco Stor is also working in close collaboration with Norsk Gjenvinning and Agder Energi in addition to Nissan. These four companies signed an MoU in 2021 with the intention of developing circular economy business models for used EV batteries. (Kretsløpet, 2021) In this collaboration, all parties are in charge of different areas. Nissan, in addition to providing the batteries, provides technical expertise on the EV batteries as well as knowledge on collection, and grading and sorting. Agder Energi is responsible for the financing models, energy market and application data, in addition to storage markets and recycling of materials. Norsk Gjenvinning is responsible for evaluating and selecting used batteries, in addition to logistics and recycling stations. Eco Stor provides market data for energy storage, selection and integration of the used batteries as well as the repurposing and recycling process. The energy storage systems provided by Eco Stor reuse the whole EV battery pack without disassembly. The battery packs are tested to verify SoH and estimate remaining useful life before they are cleaned and repurposed into stationary energy storage systems. Eco Stor's battery system utilizes the original battery management system (BMS) of the Nissan Leaf battery. In addition, the system incorporates an energy management system (EMS) that can be configured to meet the specific application requirements and integrate with the building management system. (Eco Stor, 2023)

Hagal and Evyon on the other hand, disassemble the battery packs to different levels. Hagal disassembles down to a cell level, while Evyon reuses the battery modules. Evyon delivered their first pilot industrial battery system to a customer in February 2023. The systems, which are delivered with inverters and an EMS, are digitally optimized through Evyon's battery cloud, a platform that provides real-time information and updates to maximize the safety, lifetime and performance of the system. (Evyon, 2023)

While Eco Stor, Evyon and Hagal all aim for delivering larger battery systems for stationary energy storage, Battkomp has adopted a different business model. They work with batteries in the size range 0.5 to 10 kWh for mobility applications. They design, produce and repair smaller batteries used in i.e. electric scooters, bicycles, electric wheelchairs and golf carts. (Battkomp, 2023)

Business models in Finland

Overall, EV battery reuse and repurposing business environment is changing quickly in Finland. To understand potential business models, it is essential to understand the current end-of-life process based on producer responsibility. EV battery recycling for end-of-life vehicles is coordinated on the behalf of EV manufacturers by organisation called Finnish Car Recycling Ltd. Batteries are collected by scrap car collection network for free of charge and recycled by recycling operators. If vehicles are still in usage phase certified repair shops handle the batteries. Repair shop tests and returns batteries to OEM. Returned batteries can be reused or recycled depending on their condition. (Finnish Car Recycling Ltd, 2023)

This process binds OEMs closely to battery end-of-life activities, which is why the OEMs would have good opportunities to do business with the 2nd life batteries. In spite of that, some companies that have started battery repurposing business in Finland are not OEMs. Still, quite many of them are doing co-operation with car manufacturers.

The Finnish battery strategy that was launched in 2021 identifies several key strengths. These include the reserves of battery metals such as nickel, cobalt, and lithium, expertise in producing and recycling battery metals, cooperation between the public and private sectors, and socially and ecologically sustainable production. The strategy also presents the main Finnish operators such as repurposing operators as repurpose operators include Merus Power, Wärtsilä, Fortum, and Helen. Wärtsilä is collaborating with Hyundai Motor Group to repurpose their EVBs for second-life energy storage system (ESS). Fortum has worked with Volvo Cars and Comsys to pilot second-life solutions for batteries.

Good example: Cactos

Cactos Oy is a start-up company that gives the second life for electrical vehicle batteries. Batteries are used for example as building's energy storages. It is good to note that the company has mainly used Tesla batteries transported from Norway. Cactos Oy's technology is based on dismantled battery modules that are placed on the rack (Cactos Oy, 2022). It has developed a cloud service for the battery that utilises artificial intelligence as well as internal and external data such as electricity price and weather information to control the battery system (Arvinen, 2023). Cactos Oy's business model is based on battery leasing. The company combines each battery unit to virtual asset that is used to balance the electricity grid. Price of the monthly fee depends in which share of revenues from grid balancing activities customers want to receive. Smaller share means smaller price. (Cactos Oy, 2023)

Good example: CeLLife

Start-up company called CeLLife Technologies Oy remanufacturers new battery packs from used battery cells. It has developed technology to match identical battery cells into second life battery packs and to extend the lifetime of battery cells. The company started as Tampere university research project and was established in 2022. (CeLLife, 2023)

Good example: Fortum

Energy company Fortum is currently piloting several second life solutions for used EV batteries with co-operation with car manufacturers. In 2021, Fortum announced they will do the second life pilot to use batteries as energy storage at hydropower plant. The pilot is done with co-operation with Volvo Cars and Comsys. Target of the pilot is to do a research how used batteries perform in that kind of application. (Fortum, 2021) Fortum does not have battery production itself, but it offers recycling services for lithium-ion battery manufacturers and acts as recycling operator for Finnish Car Recycling Ltd. (Fortum, 2023)

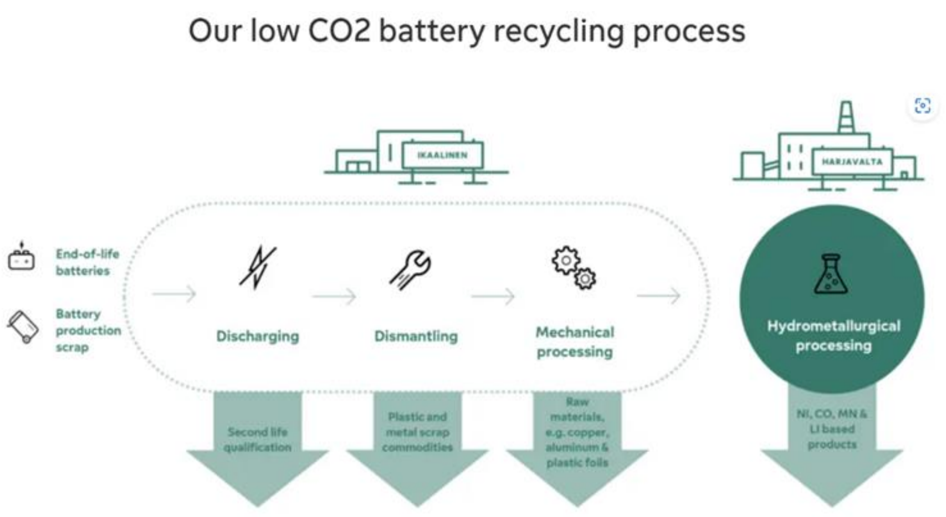

Figure 16. Fortum's battery recycling process (Fortum, 2023)

Good example: Wärtsilä

In 2018, Wärtsilä announced to start co-operation with Hyundai Motor Group to utilise the 2nd life batteries in energy storage products (Wärtsilä Corporation, 2018). However, up-to-date information about the continuation of the business could not been found. There are only couple of EV manufacturers in Finland: Valmet Automotive and Linkker. Valmet Automotive is a contract manufacturer for example for Mercedes-Benz's AMG GT hybrid versions (Valmet Automotive, 2022). It also has two EV battery manufacturing plants (Valmet Automative, 2023). Mercedes-Benz has started the second-use battery business, but the operations are not placed in Finland (Mercedes-Benz, 2022). It is noteworthy to mention that in Finland there are a lot of working machine manufacturers that have electrified working machines in their portfolio and need for batteries for their applications.

Further good examples

Good example: Cling Systems

Cling Systems, a Stockholm-based start-up, is developing a trading platform for the purchase and sale of used EV batteries. Their aim is to digitize battery trading and waste management, connecting the battery ecosystem and promoting reuse, repurposing, and recycling. Cling Systems focuses on three core values to enhance battery circularity and market development. Firstly, their platform minimizes market friction by connecting industry players and establishing terms that distribute risks among multiple participants. Secondly, it improves transparency by tracking and tracing the movement of end-of-life batteries. Lastly, it reduces logistics costs by efficiently clustering and consolidating the fragmented supply chain. (Cling Systems, n.d.)

Good example: BroadBit Green Battery Technologies

BroadBit, a technology company based in Finland, is at the forefront of revolutionizing the battery industry. Their focus lies in developing novel batteries that utilize innovative sodium-based chemistries to power the future green economy. With successful production of high-performance lab samples, BroadBit is now actively engaged in commercializing their battery technology for various applications such as next-generation electric vehicles, portable electronics, starters, and grid energy storage. The batteries developed by BroadBit utilize metallic sodium and other widely available and plentiful compound, including sodium chloride (NaCl), commonly known as table salt. Compared to traditional Lithium-ion technology, BroadBit Green Battery Technologies offer numerous advantages, including enhanced range/use time, extended lifespan, cost reduction, environmental friendliness, and scalability to meet any production volume. (BroadBit, n.d.)

3.2. State-of-the-art of the technologies

The state-of-the-art review of repurposing electric vehicle batteries (EVBs) for energy storage applications starts with the battery technologies and configurations to get an insight into the technical details of the repurposing process. Then, the EVBs repurposing process and its technical challenges are discussed, and possible solutions are introduced. Lastly, second-life energy storage applications of the repurposed EVBs and good practices are presented.

3.2.1. Electric vehicle batteries

Among all batteries, the lithium-ion battery (LIB) is the leading battery technology in commerce for automotive sectors thanks to its superior performance, particularly with regards to specific energy and specific power density. Previous battery technologies, such as lead-acid and nickel-based (i.e. Ni-Cd, Ni-metal hydride) batteries suffer from significantly lower energy density and specific energy compared to state-of-the-art LIB. While lithium-metal batteries, specifically solid-state batteries, show great promise in further increasing energy density and electric vehicle (EV) driving range, additional research and development are necessary to meet lifetime, fast-charging, and cost requirements. (Wei, Placke, & Chau, 2022)

A lithium-ion cell consists of cathode, anode, separator, electrolyte, and two current collectors, see Figure 17 (Roy & Srivastava, 2015). During discharge, the stored chemical energy is converted to electrical energy: lithium ions (Li^+) move from the anode to the cathode through the electrolyte, resulting in a flow of electrons from the anode to the cathode in an external circuit. Since this process is reversible, the opposite occurs during charging. (Ghiji, et al., 2020)

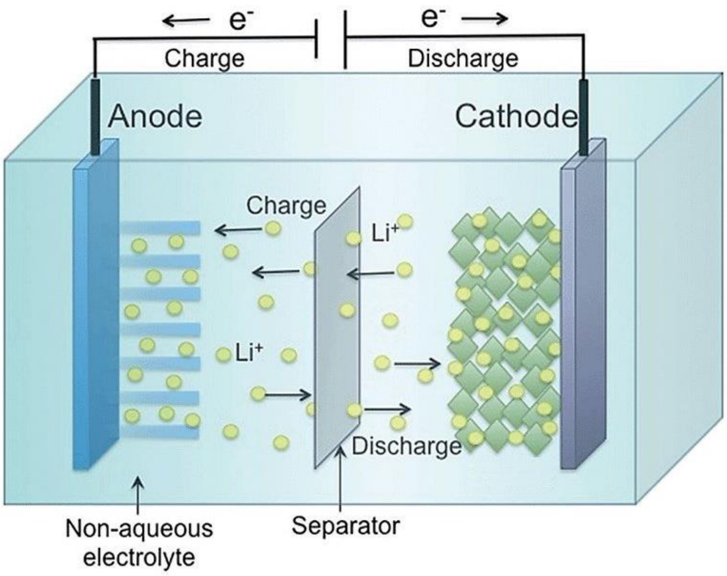

Figure 17. A lithium-ion battery cell (used with the permission of (Roy & Srivastava, 2015))

The cathode chemistry of LIB is a crucial determining factor for battery performance and material requirements, with the three most important cathode chemistries for automotive applications being lithium nickel-manganese-cobalt oxide (NMC), lithium nickel-cobalt-aluminum oxide (NCA), and lithium iron phosphate (LFP). Nickel-based chemistries, such as NMC and NCA, offer high specific energy density, resulting in longer driving ranges, and have become increasingly dominant, accounting for 85% of EVBs demand in 2021. The remaining 15% of demand is covered by LFP chemistries, which have seen a resurgence in recent years due to their lower cost, longer cycle life, and greater stability, reducing the risk of fires. However, their specific energy density is typically only 65-75% compared to NMC. (International Energy Agency, 2022)

The three main cell configurations for LIB are cylindrical, prismatic, and pouch. These configurations differ in size, geometry, and individual cell parameters such as capacity and supplied power. A single lithium-ion cell is not enough to power an EV. Therefore, several cells are combined in series and/or in parallel to form modules, which are assembled into a battery pack (Kampker, et al., 2016). A battery management

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system (BMS) is also incorporated into the battery pack combined with a cooling system and a series of sensors to monitor i.e. temperature and voltage of the cells during use. The primary function of the BMS is to ensure safe and reliable operation, but it also enables more efficient performance and a longer battery lifetime. The BMS also provides essential information on different parameters, such as the state of health (SOH), which determines the remaining capacity of the battery compared to its initial value. (Maiser, 2014)

As EVBs undergo discharge and charging cycles during automotive operation, it slowly degrades and loses its capacity, i.e., the ability to store energy (Roschier, Pitkämäki, & Jonsson, 2020). The complex battery degradation mechanisms include both chemical side reactions (solid electrolyte interphase formation, lithium plating, dendrite formation, etc.) and physical structural changes (changes in crystal structure, particle cracking, fragmentation, delamination, etc.). These mechanisms result in three degradation modes: 1. the loss of lithium inventory, 2. the loss of active material, and 3. the increase of internal impedance, all of which ultimately lead to capacity and power loss of the EVBs. (Zhu, et al., 2021) The EVBs should be replaced once their SOH reaches 70-80%, which is insufficient to ensure proper performance (Rallo, et al., 2020). Also, when the EVBs degrade beyond 70-80%, their behavior becomes more unpredictable and unsafe to be used in EV. For these reasons, the EVBs have reached their end of life (EOL) and need to be repurposed or recycled. EVBs are expected to last 8-10 years (Hua, et al., 2020). However, EVBs can also reach their EOL due to traffic or other accidents (Roschier, Pitkämäki, & Jonsson, 2020).

3.2.2. Repurposing process

The repurposing of EVBs is still an emerging technology, and technical procedure information is typically unavailable. Based on accessible literature, Zhu et al. has established a general overview of the repurposing procedure. The procedure consists of five main steps: 1. incoming assessment, 2. disassembly, 3. evaluation of mechanical, electrochemical, and safety performance, 4. sorting and re-grouping, and 5. developing control strategies for second-life applications, see Figure 18 (Zhu, et al., 2021). Next, each step is described in more detail.

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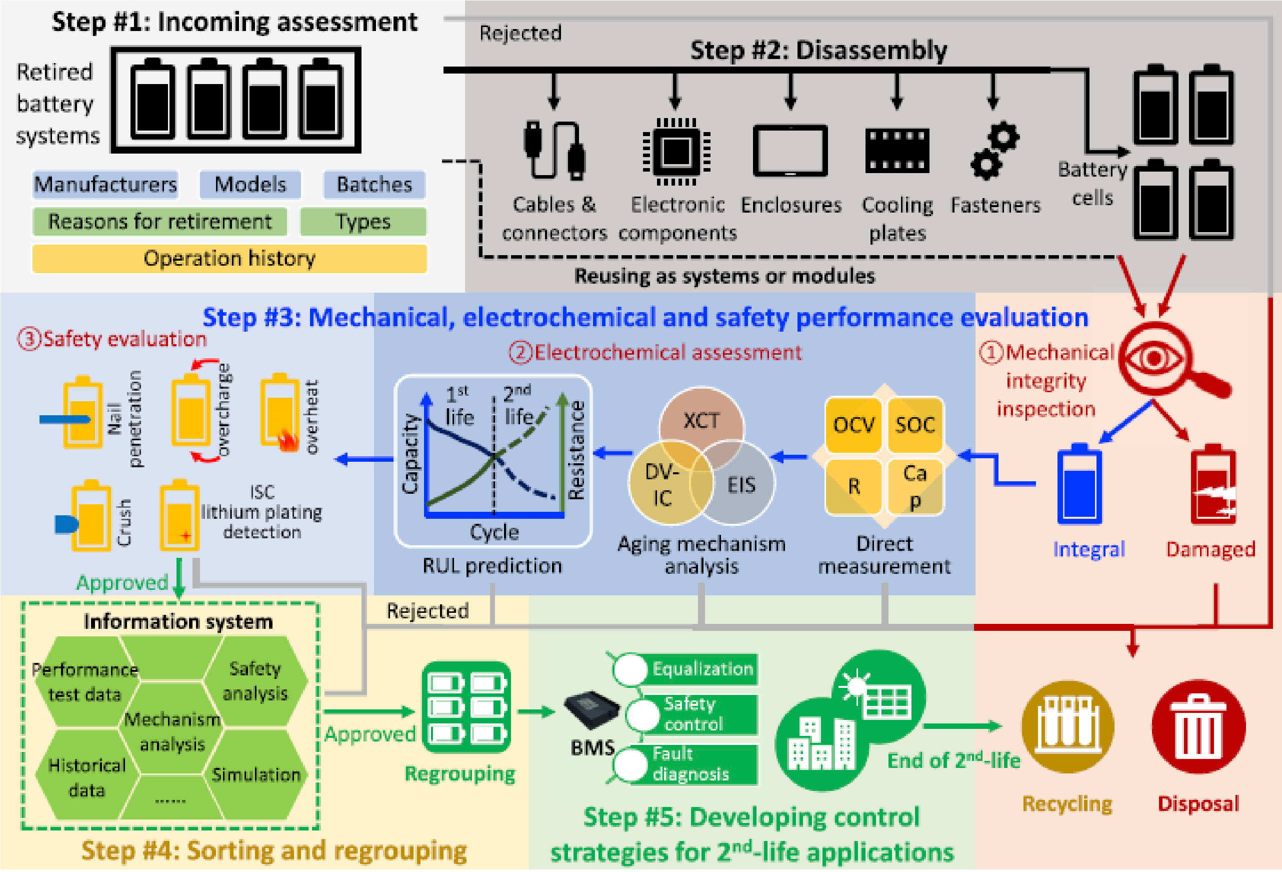

Figure 18. A general overview of the repurposing process and its steps (Zhu, et al., 2021)

To understand the condition and remaining potential of EOL EVBs, they must undergo an incoming assessment (step 1), for which historical battery information is essential. Among others, these include manufacturer, model, batch, date of manufacture, battery type, operation history, and reasons for reaching EOL. For electric vehicles and battery manufacturers, this information is readily available. However, the lack of battery information is a challenge for third-party operators, as information is typically not provided when EOL batteries are procured. Costly physical testing must be performed to assess the remaining value. (Zhu, et al., 2021) The uptake of data-driven approaches, such as the battery passport, electronic exchange system, and QR code labelling introduced by the Battery Regulation, could help streamline the initial assessment. Furthermore, blockchain technologies also have the potential for tracing battery components through their life cycle and other relevant information like origin, health, and past application (Shahjalal, et al., 2022).

Once it has been determined at which level the EVBs is to be repurposed – pack, module, or cell – the disassembly process (step 2) can begin. The procedure includes opening the battery pack casing, removing electrical and mechanical connections between the cells, and removing the auxiliary parts (Harper, et al., 2019). Currently, the disassembly process is done manually, thus, relies heavily on human labour, which is expensive and time-consuming compared to an automated process (Haram, et al., 2021). Therefore, the maximum level of disassembly, i.e., cell-level, typically results in greater costs and takes more time. It is preferable to repurpose either the EVB packs or modules to minimize costs. (Zhu, et al.,

2021) Sometimes EVB packs can be directly repurposed, avoiding the expensive and lengthy disassembly. This approach is used by the Norwegian company Eco Stor, which is a partner in the TREASoURcE project. Still, dismantling is typically required due to the inconsistency of the battery cells (Shahjalal, et al., 2022).

The greatest challenge for disassembly stems from the various EVB pack designs (Harper, et al., 2019). This complicates the current manual and the possibility of an automated disassembly process, as there are no general steps for different battery packs, and each pack requires specific procedures. For instance, cylindrical cells are the most difficult to dismantle in cell-level disassembly, followed by the pouch and then prismatic cells (Haram, et al., 2021). Thus, standardization of the EVB pack design plays a vital role in facilitating the disassembly process. Due to the large variety in shapes and sizes of EVBs, this will be a huge challenge as most EV batteries are designed and built to fit the specific car.

After cell-level disassembly, it is followed by the mechanical, electrochemical, and safety performance evaluations (step 3). The aim is to screen out cells that do not meet specific criteria and are unsuitable for second-life applications. In the first screening (step 3.1), the mechanical integrity of cells is evaluated by visual inspection. Cells with mechanical deformation are a safety risk for internal short circuits, thermal runaway, and fire. Cells that show leakage or damage are disposed of and sent to recycling. Currently, visual inspection is done by human workers, which makes it expensive, unreliable, and unsafe. Digital image-based approaches, X-ray-based techniques, and acoustic tools are promising alternatives for overcoming the shortcomings of manual labour. (Zhu, et al., 2021)

In the second screening (step 3.2), battery cells are assessed by their electrochemical performance based on direct measurements such as open circuit voltage, internal resistance, capacity, and temperature. The screening is done according to predefined criteria by the inspector. After that comes the accurate assessment of battery degradation, which is essential for estimating the SOH and predicting the remaining useful life (RUL) of the EVBs. The RUL is the duration between the point of observation and the EOL, marked by either the first occurrence of equipment performance dropping below the failure threshold or the first arrival time of such an event. (Wang, Jin, Deng, & Fernandez, 2021) This step is especially challenging due to the complexity of battery degradation and the need for non-destructive assessment techniques to enable commercial repurposing operations. (Zhu, et al., 2021)

According to (Zhu, et al., 2021), there are three methods for evaluating battery degradation: 1. post-mortem examination-based, 2. charge-discharge curve-based, and 3. electrochemical impedance spectroscopy (EIS) and equivalent circuit model (ECM) based. However, post-mortem examination is typically related to destructive testing, which includes opening the battery, thus, is not suitable for commercial operations. Instead, non-destructive X-ray computed tomography (XCT) is more appropriate but not a very established technique. The second method comprises differential voltage and incremental capacity (DV-IC) analysis, and the last method depends on the EIS test results. The key in the latter two methods is to correlate the measured electrical response with internal chemical and physical changes. XCT, DV-

IC, and EIS-based techniques are currently only used for research or in the laboratory and are not yet suited for commercial use. (Zhu, et al., 2021) Thus, the development of non-destructive assessment methods is important for repurposing.

The SOH assessment differs for the various battery types and chemistries, an additional complication resulting in higher costs (Shahjalal, et al., 2022). Standardization rises again as a solution for easing the SOH assessment. In addition, currently, there are no standards or reliable guidelines for assessing the SOH and RUL, which creates unreliability that could be an issue for potential customers. (Haram, et al., 2021) Another problem with inaccurate SOH and RUL assessments is that EOL batteries might not find the optimal second-life application. RUL assessments also face the challenge of the non-linear aging process of LIB, as second-life batteries (SLB) are more likely to face the knee point, after which the capacity will undergo accelerated degradation (Hua, et al., 2021). Historical operation data could ease the SOH and RUL assessments, but this information is not easily available. However, the new Battery Regulation will require that repurposing operators can access the BMS of the EVBs, which stores relevant parameters for assessing the SOH and RUL. This could facilitate the assessment processes.

Finally, batteries undergo a safety evaluation in the last screening (step 3.3). Currently, conventional safety tests such as thermal, electrical, and mechanical abuse tests for new batteries are also being used for testing EOL batteries. However, after their long operation period of hundreds or even thousands of cycles, the internal and external characteristics of EVBs have changed dramatically, leading to more significant safety risks (Hua, et al., 2021). Harsh operation conditions can result in minor abuses such as local internal short circuits, gas generation, or lithium plating. The changes in a battery's safety depend highly on the degradation history and mechanism. As batteries undergo complex and varying degradation processes, accurately estimating safety is challenging. Therefore, more advanced tests should be developed to detect minor defects in EOL batteries. In addition, due to the inconsistencies in EOL batteries, sampling algorithms are needed as safety tests should be performed on batteries with the lowest stabilities. (Zhu, et al., 2021)

After the screening processes, the eligible cells are sorted and regrouped with similar qualities to ensure pack homogeneity (step 4). During their first life, EVBs experience harsh operating conditions leading to inconsistencies in battery cells and modules. Cell-to-cell and module-to-module variations harm battery life and performance, so sorting is crucial for second-life applications. The first challenge is selecting appropriate indicators, which depend highly on cell type, battery chemistry, and demands of the second-life application. Some typical indicators include SOH, the voltage of pulse discharge, internal resistance, EIS fitting parameters such as charge transfer resistance and lithium-ion diffusion coefficient, and thermal behaviour. The other challenge is finding an effective and efficient sorting algorithm. There are two types: pursuing simplicity and high efficiency or solving high-dimensional problems with powerful but expensive statistical tools. (Zhu, et al., 2021) Moreover, the repurposed EVBs need to meet the physical dimensions of the energy storage applications, which may be challenging due to the various EVB designs (Hossain, et al., 2019).

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Second-life applications require control and management strategies (step 5). First, as repurposed batteries have low energy and power capabilities, optimal battery sizing and appropriate control are necessary for smoothing power output, avoiding overcharge or over-discharge, and extending the life cycle. Second, once the second-life ESS is in operation, the emerging inconsistencies in cell-to-cell or module-to-module require active equalization strategies to ensure adequate and safe performance. Third, in addition to voltage, current, and temperature controlled by the BMS, repurposed battery systems also need advanced fault-diagnosis algorithms to rapidly detect internal short circuits, lithium plating, and gas generation. Multi-sensor-based algorithms combining data from voltage, current, temperature, and gas sensors are promising solutions. (Zhu, et al., 2021)

In conclusion, the main challenges of the overall repurposing process are costly human labour-based operations, lack of automation, absence of standardized indicators and models, and lack of high-efficiency algorithms. Solutions to improve the repurposing process include automation of battery disassembly and inspection, using advanced statistical algorithms for fast screening and sorting, assessing SOH with non-destructive acoustic waves, standardization of EVB pack designs, utilization of EIS-based and DV-IC techniques for modelling battery degradation, and incorporation of data-driven prognostics for determining RUL. However, further technological advancements are required until these solutions can be implemented. (Zhu, et al., 2021)

3.2.3. Second-life energy storage applications

Second-life energy storage applications can be categorized by different criteria such as application area (residential, commercial, and industrial) and usage (grid stationary, off-grid stationary, and mobile), or mobility (stationary, quasi-stationary, and mobile) and user (grid operators and utilities or behind-the-meter customers) (Shahjalal, et al., 2022; Haram, et al., 2021; Hua, et al., 2021). For this review, the categorization by usage is chosen for introducing various energy storage applications of the second-life battery (SLB).

Grid stationary applications are typically large, in the MWh range. With the penetration of intermittent renewable energy sources (RES) like solar and wind energy, grid stability and integrity are at risk. Therefore, SLB can be used for renewable energy farming, i.e., reducing the adverse effects of RES by storing excess energy when renewable generation ramps up and vice versa, providing energy when renewable generation ramps down. Another application for SLB is generation-side asset management, in which the battery provides energy when the main power generation is momentarily suspended due to maintenance or other reasons. Third, SLB can be utilized for energy arbitrage, i.e., storing electricity during off-peak hours and consuming stored electricity during peak hours. This includes peak shaving and load levelling applications, which reduce the need for peaking units and postpone investments in additional generation capacity (Hitachi Energy, n.d.). Finally, SLB is suitable for frequency regulation, which is about maintaining the nominal grid frequency in an acceptable range, and for real and reactive power injection that both help ensure grid stability. However, these applications are deemed potential, assuming SLB costs less than new batteries. (Hossain, et al., 2019)

Off-grid stationary refers to isolated grids like microgrids that are small-scale electricity networks of consumers and local electric supply. Microgrids can be connected to the national electric grid and/or operate in standalone mode. When microgrids operate independently, the system stability and integrity face a challenge, especially with intermittent renewable production from i.e. solar and wind power. Thus, SLB can improve power quality and reliability with accurate and rapid responses by which short-duration disturbances can be prevented. In addition, repurposed batteries can be used for load following, where they are discharged and charged to alleviate demand fluctuations, and as spinning reserves, which in the case of a generation outage, can supply power to maintain grid stability. Again, the lower cost of SLB is essential for the feasibility of these applications. Regarding mobile applications, SLB can be used as EV charging stations and for short-range vehicles such as delivery vehicles, forklifts, and e-scooters. (Hossain, et al., 2019; Hitachi Energy, n.d.) Another application area, which is quickly growing is semi-stationary batteries used for construction sites. They are termed semi-stationary as they are containerized and can be moved from one site to the other as necessary. Construction sites often need large amounts of power for limited periods of time, and batteries can supply this power during the construction period.

Good examples of second life energy storage for grid stationary applications

Since 2018, the Johan Cruyff Arena in Amsterdam has been utilizing a 3 MW/2.8 MWh ESS consisting of new and repurposed batteries. Specifically, there are 590 battery packs, of which 250 are SLB. The ESS provides additional backup power, peak shaving, and grid stabilization services. The ESS stores energy from the 4,200 solar panels or the grid during low-demand periods. During an outage, the ESS supplies sustainable power, reducing the use of diesel generators. In addition, the ESS is discharged during high peak consumption, which reduces the load on the electric grid. This project is a collaboration between The Mobility House, Eaton, Nissan, and BAM. (Eaton, n.d.)

The installation of Eaton's xStorage Buildings system at Bislett Stadium in Oslo has provided significant benefits as a grid stationary application. This ESS consists of a 100-kW power conversion system and three racks containing 30 Eaton battery packs, which are composed of second-life Nissan LEAF battery modules. The stadium has 1100 m^2 of solar panels that were installed in the summer of 2018, capable of producing 150,000 kWh annually. The xStorage Buildings system can store up to 109 kWh of produced renewable energy, and it is also easily scalable to meet future needs. By utilizing renewable solar energy stored in the Eaton battery packs during peak energy usage, the Eaton's xStorage Buildings works to reduce energy consumption from the grid, while simultaneously supporting the grid's power supply. This effective management of stored energy promotes responsible distribution, ensuring a robust and stable power supply. (Eaton, n.d.)

Good examples of second life energy storage for off-grid stationary application

Jaguar and Pramac have collaborated to develop an off-grid battery ESS powered by Jaguar Land Rover's EOL I-PACE batteries. However, the current units utilize I-PACE batteries from test and prototype vehicles. Each ESS unit consists of 50 modules coming from the I-PACE batteries. The mobile and self-sufficient ESS, charged by solar panels, delivers zero-emission electricity in places without access to the grid. The flagship ESS system has a capacity of 125 kWh. The unit proved successful in testing in the UK and Spain in the 2022 ABB FIA Formula E World Championship, where it was used to power the Jaguar team's diagnostic equipment to analyse the race car's performance and supply auxiliary electricity to the pit garage. (Jaguar, 2022)

Good example: Eco Stor energy storage system at Tiller Highschool, Trondheim, Norway

TREASoURcE partner Eco Stor use Nissan Leaf batteries in their 2nd life energy storage systems. One example of an Eco Stor installation is in Trondheim, Norway, where a 450 kWh battery is installed at Tiller Highschool. The school has more than 600 kWp of solar panels on the roof. And during the summer months the electricity production exceeds the school's power consumption and it's not possible to sell all the electricity back to the grid without being registered as a power producer, which requires paying additional fees. Thus, the battery is installed to store excess electricity during the day, which can be used in the evening or at night when there is no production from the solar panels. In the wintertime, when the electricity production from the solar panels is low, the battery is used for peak shaving during the day. The batteries can then be charged from the grid at night when electricity prices are low and provide additional support during the day when the school needs more power. The two main uses of the battery at Tiller are peak shaving and increased utilization of electricity produced from solar panels, leading to a reduction of electricity use from the grid by 31 180 kWh per year. This amounts to a total reduction of carbon emissions of 374 000 kg CO_2-eqv per year. (Enova, 2022)

Good examples of second life energy storage with different battery types

In the previous examples, only LIB was used in the second-life applications for grid stationary and off-grid stationary. In October 2022, Toyota and JERA introduced a 485 kW/1,260 kWh second-life battery ESS utilizing different battery types (lithium-ion, nickel-metal hydride, and lead acid), which is novel to the sector of repurposing. The so-called Sweep Energy Storage System is located at Yokkaichi Thermal Power Station in Nagoya, Japan, and is used for recharging and discharging operations. In addition, the ESS is equipped with a function called sweep, which enables the existence of differences in battery performance and capacity. The sweep function also allows series-connected batteries to be bypassed in microseconds. (Toyota Motor Corporation, 2022) This technological advance could solve the challenges arising from the high variability of EVB packs while also enabling the use of different battery technologies, which typically is not the focus of repurposing operators. (Jaguar, 2022)

3.3. Ecodesign and sustainable circular design of batteries

In general, ecodesign is an approach to include environmental requirements into product development process. Environmental impacts are considered during the whole life cycle of the product. Ecodesign supports circular economy as it is also encouraging reuse and recycling of materials. (Doorsselaer & Koopmas, 2020) EU regulates ecodesign by the Ecodesign Directive (2009/125/EC). Its aim is to improve energy efficiency by integrating environmental issues and life cycle thinking in product design phase. The Ecodesign Directive is a framework directive, and it is implemented through product specific regulation. (Ministry of the Environment, 2023) EV batteries do not have product specific requirements yet. (Energy Authority, Ministry of Environment of Finland, 2023) In March 2022, the European Commission established a proposal for a new directive. As the focus of the current directive is more on energy efficiency the proposed directive will take into account circular economy more thoroughly. It aims to provide products that have less environmental impact, use less energy and natural resources, have long lifetime as well as being easy to repair and recycle. (Energy authoriy and Ministry of Environment of Finland, 2023)

In general, repurposing of EV batteries extends the use phase of batteries and helps to avoid resource scarcity. (Baazouzi;Rist;Weeber;& Birke, 2021) Still, the proper product design and design for repurposing can reduce environmental impacts during the battery second life.

3.3.1. Design for disassembly and modularity

One of the key steps in the EV battery repurposing is the disassembly process. The product design has great impact on this phase as the difficulty to separate parts from the original product can limit the remanufacturing possibilities as well as increasing number of steps required and energy used during the process (MARBEL, 2021). Currently battery designs are not supporting the disassembly process very well: packs have different types of materials and joining connections and they cannot be accessed from the same direction. (Chew, et al., 2022) OEMs have their own battery design, battery chemistry and structure that makes standardisation of the process difficult. In cell level there might be challenging to find the correct type of replacement cells for the battery system. In addition, cells are often connected by welding or glue. If batteries with different conditions are grouped together the risk of accelerated aging and functional failures increases. (Hua, et al., 2020)

As described, there are a lot of potential for improvement in battery design in terms of disassembly. The use of Design of disassembly method's rules could streamline the process. Design of disassembly is a general development method that aims for easy disassembly of parts. Its key elements are to simplify and standardise the process and eliminate work phases and tools needed. The method recommends limiting types of connecting techniques, use uniform tools, prefer connections that are visually and physically accessible as well as avoiding gluing or welding. (Doorsselaer & Koopmas, 2020)

In addition to the design of the battery pack, the remanufacturing strategy also determines how much environmental impact the process causes. Disassembly to module or cell level needs more processing steps and might require more energy and equipment than using the original battery pack as it is. Disassembly of the battery pack also requires that the new and re-assembled battery pack must be re-certified, which is both costly and time-consuming. While reusing the battery pack as is, avoids this additional effort. However, material losses might be bigger when the battery pack or module is used. Failure in one cell means that the whole module becomes useless (Kampker;Wessel;Fiedler;& Maltoni, 2021).

Good example: Modular battery swapping

Review of products on the market did not reveal solutions that would directly support easy disassembly for second life purposes. A company called Ample has developed a modular battery swapping service for electrical vehicles during the battery first life. The service contains fully automated battery swapping stations that use renewable energy. The EV is charged in the station by swapping the recharged battery to a new fully charged one. Ample promises less than 10 minutes lead time for the process. The battery design is based on modularity. Needed battery size can be accomplished by using a different number of battery modules.

Figure 19. Amples modular batteries (Ample, 2023)

There are no research data available for environmental impacts of Ample’s design. However, the product design seems to be one step closer to eco-design practices such as design for disassembly and modular design: Battery modules are easy to disassemble from the car. Modularity makes it easier to do the repurposing as modules are individual components and one can build the needed size battery system by combining modules. (Ample, 2023)

3.3.2. Monitoring of the battery state

As described in chapter 3.2, the repurposing process includes several steps for measuring and evaluating the battery health and condition. The number of tests carried out could be reduced if the company handling the used batteries for repurposing had easy access to the first life user data stored in the battery management system (BMS). It is however, not trivial to access historical data for the batteries. Additionally, current BMSs are not designed for optimizing use in both first and second life, nor providing estimation of degradation rates in 2nd life use (MARBEL, 2021). Proposal for new EU Battery directive will support the usage of BMS’ data for repurposing. The proposal requires that EV battery BMS should store the data related to state of health and expected lifetime of batteries. Read-only access should be provided to end-user or any third party acting on its behalf for facilitating the preparing for reuse, repurposing or remanufacturing. (European Commission, 2023)

The precise estimation of battery state and development of BMS algorithms for estimating remaining useful life (RUL) are challenging: Batteries have a limited number of measurable parameters and EVs are used in various conditions and changing temperatures that makes modelling difficult. (Xjong, 2020) Batteries are closed systems with complex chemistries and a simple SoH measurement cannot necessarily provide information on the degradation mechanisms leading to the decreased capacity. Based on a study by Wei et. al. (2022) research related to artificial intelligence (AI) and BMS is on-going in many places. Combining AI-tools with cloud computing and block chain technology could enable the development of digital twins that could offer more accurate estimation for the battery state. (Wei;Placke;& Chau, 2022)

Good examples: AI powered software functions

Some companies have already released control solutions that are based on algorithms and AI powered software functions.

A Dutch company called NXP Semiconductors has developed solutions for EVs where the BMS is connected to the cloud to leverage an AI powered digital twin. Digital twin enables better control and monitoring of the battery and thus extend the battery lifespan and performance. The solution can provide more precise estimation of remaining useful battery life. (NXP Semiconductors, 2022)

A company called Eatron's has a solution where AI based functions are used to run diagnostics in real time in vehicle and in large scale in the cloud. Software can be used for example to predictive cell diagnostics and remaining useful life estimations. (Eatron Technologies, 2023)

3.3.3. Optimised charging

From an environmental point of view the major impact from the second life use phase is related to charging of the battery. Thus, environmental impacts depend highly on the production method of the used electricity. (Ahmadi;Young;Fowler;Fraser;& Achachlouei, 2015) Smart charging is technology that is used for grid connected batteries and makes it possible to adjust how much energy is used by the battery based on the grid performance. For example, the battery can be charged at the right time when the production of renewable energy is the highest. The battery can also provide electricity to the grid to avoid need for peaks at fossil plants. (MARBEL, 2021)

If the battery system is connected to solar panels and to the electricity grid, an increasing share of solar energy can reduce the impacts in the reuse phase. For example, using solar energy instead of electricity grid mix is usually a more environmentally friendly option. Thus, the battery size should be dimensioned so that the usage of solar energy is optimised. However, the bigger battery would also mean bigger impacts on sustainability during the battery first life manufacturing as well as recycling phases. (Thakur;Leite de Almeida;& Baskar, 2022)

3.3.4. Digital battery passport

Product digital passport is a tool to support the traceability and transition to more sustainable and circular products. It will not automatically make repurposing more environmentally friendly, but it can offer information that enables the systematic development work. EU's proposal for the new Battery Regulation will require that EV batteries have a digital passport that includes information about the battery model, chemistry, where the materials are sourced, production site, user data, etc. All EV batteries placed on the market or put into service from 42 months after the regulation has entered into force need to have a battery passport. (European Commission, 2023)

To be useful a passport should include meaningful data to support decision making. The research made by Berger et. al. (2022) presents a concept for the data passport should include. According to the study there are several stakeholders in the EV battery value chain that could utilize the information stored in the passport. OEMs can use the data to minimize the battery's environmental impacts and improve the value chain performance. Users can use it to select the product that best fits to their purposes. The passport could make the recycling process significantly less complex as the battery chemistry and design would be known. Also, regulatory bodies could better follow-up products' circular performance and adjust the current legislation as needed. (Berger;Schoggl;& Baumgartner, 2022)

Research has identified a number of categories where information is needed. These include battery chemistry and system, sustainability and circularity, diagnostics, performance and maintenance as well as value chain actors. Battery information includes product information such as application type, battery chemistry and battery structure related specifications. Sustainability and circularity mean information about environmental and social impacts, lifespan as well as the battery assembly process to ease the disassembly. Third category, diagnostics, maintenance and performance include information about the battery health, maintenance history and delivered performance. The value chain actors category has data on those who have been involved at any point in EV battery's life cycle. (Berger;Schoggl;& Baumgartner, 2022)

Proposal for the new EU Battery Regulation's requirements seem to support the research findings. According to the proposal the battery passport should include information related to product technical features and structures, environmental impacts, dismantling and battery health to name a few. Some information will be available for all. Some information will have a limited access. (European Commission, 2023)

Part IV: Circular biobased side and waste streams for biogas and fertilizers

4. Circular bio-based side and waste streams for biogas and fertilizers

The TREASoURcE project focuses on the increasing the circularity of bio-based side and waste streams. In this section, the focus is especially on biogas and fertilizers. Next, different types of circular business models are further examined. Then the technologies in place for repurposing will be explained, which is finally followed by ecodesign practices. All chapters include good practices as examples to inspire and illustrate functional circular economy practices and businesses.

4.1. Circular business models

Circular bio-based business models give multiple advantages such as reduce dependence on non-renewable, unsustainable fossil fuels, secure food and nutrition, increase competitiveness and create new jobs, manage natural resources sustainably, bring a positive impact on the environment, support the modernization and strengthening of the industrial base (Circular Bio-based Europe Joint Undertaking, 2023).

Circular business models have induced interest among businesses (Geissdoerfer;Pieroni;Pigosso;& Soufani, 2020), but these models focus mostly on some dimensions of sustainability, but not all the areas of sustainability (De Keyser & Mathijs, 2023). Previous study by Valve et al (2021) highlighted that little attention has been given to the differentiating capacities of business models to enhance circularity so far (Valve;Lazarevic;& Humalisto, 2021). Especially in the agricultural sector and primary producers, CE models are not well known. Holistic business model typologies in the bioeconomy are still scarce. For example, anaerobic digestion plants have several challenges such as the improvement of economic viability and life cycle impacts (De Keyser & Mathijs, 2023).

A first innovation level of business models is the technological level. A biogas plant can create value from biobased side and waste streams and at the same time producing renewable energy from biogas. Business models can be designed from different perspectives. For example, biogas plant is established to convert crops that are grown with the sole purpose of turning them into biogas and fertilizer, the innovation aims at renewable energy production. In another way, if a biogas plant is built to use biobased side and waste streams from food production and consumption, the innovation aims at creating value from waste. The social level and the technological level have a part-whole relationship: the technological level represents an accumulation of different business model types on the social level. In a mean of circularity, the speed of the resource cycle can be impacted by the social level, e.g. a company can raise awareness about overconsumption by encouraging sufficiency. Social innovations of the business models indicate new ideas that meet social needs, create social relationships and form collaborations. Social innovation level can be looked at from the perspective of the provider of the technology and by their value creation for customers. A sustainable circular technology provider can deliver functionality rather than ownership, adopt a stewardship role or encourage sufficiency (De Keyser & Mathijs, 2023).

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Cascading is a resource-efficient and circular use of any type of biomass. Cascading principles can be grouped by approaches for sustainability, resource and energy efficiency, circularity in every stream at every step, new products and markets as well as subsidiary. (European Commission, 2018) Biobased side streams are valuable raw materials for use as such, for example for fertilization or soil improvement, and there is also a demand for them for further processing in industry. The best benefit can be obtained from side streams when raw materials are primarily used for products with a high degree of processing, which are first used, then reused or recycled and only finally utilized in the final purposes that are not possible to circulate anymore, energy production, for example. By-fractions are utilized and further processed for, among other things, biogasification, recycled fertilizers, soil conditioners, bedding, and raw material for biochar. (European Commission, n.d.; Vanhamaki, et al., 2019; Virtanen, Luste, Manskinen, & Vanhamäki, 2020; Mendoza, Aznar-Sánchez, Gallego-Schmid, & Velasco-Muñoz, 2021)

Those who adopt cascade methods first gain an advantage over other actors (Vanhamaki, et al., 2019; Wiel, et al., 2019; Jarre, Petit-Boix, Priefer, Meyer, & Leipold, 2020). As an example, anaerobic digestion and biogas production can reduce the need for external inputs, e.g. energy and fertilizer, as a method of avoiding overconsumption and reusing organic material. Anaerobic digestion and biogas plants are considered sufficiency business models if their value proposition intends to contribute to an increase in on-farm or regional energy or fertilizer self-sufficiency. Farmers can benefit financially from if they adopt a proactive corporate sustainability strategy (De Keyser & Mathijs, 2023; Karlsson, 2019). The results of sustainable business model productivity values depend on the scale of time and scope considered. For example, a farmer can use a purposeful business model aiming to survive and continue its operations while maximizing social and environmental benefits (i.e., subsistence model). Or alternatively, with sustainable business model, the aim is to generate a stable base of cost savings (i.e., income model). (De Keyser & Mathijs, 2023; Vanhamaki, et al., 2019; Wiel, et al., 2019)

Good examples: Business models from Finland

Soilfood utilises industrial by-products from the forest, bioenergy, food, mining, chemical and environmental industries. The by-products are recycled, e.g. into soil improvers and recycled fertilisers. This significantly reduces the greenhouse gas emissions of both agriculture and industry. Fertilisers are produced from biogas rejects, processed into pellets which are compatible with farmers' normal fertilization schemes. Again, the use of soil improvers adds carbon to the soil, which increases the carbon uptake capacity and results in better soil fertility, crop performance and soil biodiversity. Soilfood's soil improvement product is based of wood based (fiber) byproducts from forest industries. based on the soil's improved capacity to act as a carbon sink, Soilfood has also opened the sale of carbon sinks at the Finnish Puro.earth marketplace. The revenues are divided equally between the farmer, the industrial operator and Soilfood. For industries, their previously valueless by-products are now acquired and spared from landfills. The farmers can acquire a sustainable agricultural input, many of which are suitable for organic farming. Soilfood's operational model is to utilise side streams with reuse opportunities for added value, creating new regional value chains. For farmers, Soilfood offers holistic consultation services on regenerative agricultural practices. (Soilfood, n.d.) Sitra has evaluated that the company's share of the circular economy solution of total business or operations is 100% (Sitra, 2020).

Sauter Biogas Finland is a biogas plant construction company that´s roots are in Germany, Bayern. Sauter Biogas Finland was founded in autumn 2020. The goal of the company from the beginning has been developing a digester without internal technical components. The first biogas plant with this type of *'Sprinkled, not stirred!'* system was set up in 2006 and ever since more than 80 biogas plants with this system has been built all over Europe. The system is controlled by a pump system and jets and the liquid substrate is sprinkled onto the substrate surface and then extracted again from the bottom of the digester. This process instead of traditional mixing ensures that different stages of the digestion process take place in different zones within the digester and different sprinkler intensities within the zones ensure a controlled digestion process. Active and not completely homogenised biomass particles predominantly sit at the top of the digester and the substrate discharged from the lower area is almost completely digested and this is what enables optimal gas yields to be achieved. In addition, the Sauter Biogas system provides the basis for a very simple solids input unit using a feeding pit or screw feeder and a hydrolysis and acidogenesis zone that is created around the feeding unit. Consequently, a reservoir of fresh biomass builds up in the digester and from this reservoir, organic acids, which have been generated through the sprinkling process, are distributed in the digester eliminating the need for expensive bunker and sprinkler technology. The Sauter Biogas system can use slurry, manure, clover or grass and change it into gas. The company offers biogas plants to a single farm or a coalition of farms and to food industry. In Finland companies like bean curd factory Oy Soya Ab, brewery company Hartwall and potato company Pohjolan Peruna are customers of Sauter Biogas and have Sauter´s biogas factories in their premises. (Sauter Biogas Finland, n.d.; Sauter Biogas GmbH, n.d.)

Yara is working with farmers and leading food value chain companies in various ways to improve productivity and quality while reducing the environmental impact – an essential aspect is enhancing sustainability and traceability. This can be achieved for instance through efficient use of nutrients, reducing carbon footprint and water use and assuring a healthy soil by enabling regenerative practices. Yara's main products include both farming and forest fertilizers. Yara's green fertilizers already have a low carbon footprint but still, the fertilizer production relies on fossil fuels. Next year Yara will bring to market fossil-free, green fertilizers produced by using renewable electricity. These green fertilizers will have an 80-90 percent lower carbon footprint than fertilizers produced with natural gas. Yara offers for instance ash-derived forest fertilizers where they utilize ash coming from bio-based (wood) energy production and organic fertilizer products where the by-products of Honkajoki are utilized. (Yara, n.d.)

Fortum has a wide and versatile product portfolio regarding the utilization of bio-based side streams. For instance, they have a BIO2X concept for high-value products from biomass. They have developed a new kind of biore-finery concept where underutilized biomasses are given a second life as high-value raw materials for a wide range of industries. Their product portfolio consists of raw materials from ligno-cellulosic biomass: cellulose pulp, lignin, and biochem-icals. In comparison to conven-tional material options, these biobased raw materials can significantly improve the sustainability of the end applications. (Fortum, n.d.)

One ongoing example of bio-based side stream utilization is the zero fiber treatment operation that is starting in Hiedanranta area in Tampere, Finland. Zero fiber is situated in the lake nearby Hiedanranta area and it derives from the active years of the old pulp mill that was situated in Hiedanranta – it has been estimated that around 1,5 million cubic metres of zero fiber is sedimentated in the Hiedanranta bay. Fortum Waste Solutions is now starting operations on treating the zero fiber and utilizing it in energy production and soil improvement. (Haapala, n.d.)

Good examples from Norway

In Norway, the development and upscaling of circular business models are high on the political and industrial agenda (Norwegian Environmental Agency, 2020). Norway aspires to become a low-emission society by 2050, aiming to reduce emission by at least 50 % by 2030, and at least 90 % by 2050, compared to 1990 levels. Alongside other elements, biogas is highlighted as an important part in reaching this goal and a means to utilize resources in a CE manner (Ministry of Climate and Environment, 2021). Regarding the utilization of biowaste and bioeconomy, the financial schemes Innovation Norway and Enova supports projects and companies aiming to increase value creation based on resources from the sea, soil and forest and using side streams for new products (Innovation Norway, n.d).

Disposal of residual waste from households and industries was banned in Norway in 2009. The waste-heat from combustion is used for electricity generation and district heating, which are sent out to cities and local communities. Central authorities and Norwegian municipalities argue that such recycling is wise, since a large amount of this residual waste cannot be materially recycled and will be incinerated anyways (Norsk Fjernvarme, 2017). For example, Trondheim, mid-Norway, have had district heating facility generated by waste-heat through incineration of residual waste since 1982, and today, energy from these facilities cover approximately 30 % of the city's heating needs. To ensure that these facilities are as good as they can be in terms of greenhouse gases, there are also ongoing projects to develop carbon capture and storage/utilization (CCS/CCU) (Statkraft Varme, n.d).

The use of animal manure in the production of biogas is elevated as important in Norway. The Norwegian government increased the subsidy for delivery of manure to biogas facilities through the agriculture agreement of 2020-2021, which stimulates both for more animal manure to be included in biogas production, and for increased production of biogas. However, the most common substrates used for biogas production today is sewage sludge and food waste.

At the end of 2018, the world largest production plant of liquefied biogas (LBG) was put into operation in Skogn, Nord-Trøndelag, Norway, by the company Biokraft. The raw materials for the biogas production come from waste and by-products from nearby industry, including fish-farming and forestry, and is to be used to replace fossil fuels in heavy road-transport. Moreover, the facility will also produce climate-neutral fertilizers for agriculture and have ambitions to utilize other raw materials from e.g., forest waste and marine energy crops in the production of biogas. (Ministry of Climate and Environment, 2021; Biokraft, n.d)

KUKRAFT, a project from TINE, Norway's largest producer, distributor and exporter of dairy products, will produce biogas from cow manure in combination with food waste, with the aim to transition their car fleet from fossil fuels to renewable energy. They have calculated a reduction of greenhouse gas emissions of 4.3 tons of CO2 per cow per year if the cow manure is used for biogas production, and with manure from the 200 000 cows which are under TINE are used to produce biogas, the Norwegian agriculture industry could reduce its CO2 emission per year with 860 000 tons. (TINE, n.d)

The Norwegian company Ecopro, located in the mid parts of Norway use organic waste (such as animal by-products), food waste, industry bio waste (such as waste from the aquaculture, dairy facilities, and slaughterhouses), and sludge to produce fertilizers for the agriculture. The facility was established in 2002 and started up in 2008, as one of Norway's first plants of its kind. It is owned by an inter-municipal waste company and Steinkjer municipality, which means that 52 municipalities cooperate to treat approximately 40.000 tons each year. The plant meets strict national and international requirements on the treatment of most types of organic waste and is a good example, and proof, that Norwegian municipalities can cooperate in developing sustainable solutions to waste challenges. (Ecopro, n.d)

Biogass Oslofjord is a regional network between 6 counties surrounding the Oslo fjord, Norway. It was established in 2018 with the aim to promote and strengthen the utilization of biogas and renewable organic energy resources in the region, in both value chains, on a political level and in society. Moreover, they also want to facilitate knowledge creation and sharing on the role of biogas in the CE and bioeconomy, as well as taking a holistic approach to the establishment and expansion of infrastructure for the production and use of biogas. The network argues that to become a zero-emission society, biogas plays a crucial role as is has multiple cross-sectoral potential for emissions reductions, as well as providing long-term value creation from Norwegian energy resources. (Biogass Oslofjord, n.d.)

Another example of a joint entrepreneurial activity happening in Norway related to biogas side and waste streams is the Grødaland treatment plant, located on the south-west coast of Norway. This is one of Norway's largest treatment and biogas facility and is built by the company IVAR, which constructs and operated municipal facilities for waste, wastewater and general waste from 12 municipals. They produce around 4 500 00m3 biogas yearly from sludge, food waste and other organic waste and upgrade it for sale to the energy company Lyse AS. Lyse AS have an already operating infrastructure connected to natural gas, and the biogas produced at Grødaland is distributed through this infrastructure and used towards transportation sectors on land and at sea, agriculture and district heating. (IVAR, 2021)

Good examples from Estonia

Estonian biotech company Fibenol implements new technology that utilizes wood residues to produce bio-based raw materials like lignin, wood sugars, and specialty cellulose. Their innovative fractionation process converts more than 90% of woody biomass into high-value materials with minimal environmental impact. These sustainable bio-based materials can be used as replacements for fossil-based chemicals to produce cosmetics, plastics, construction materials, and many other products. (Fibenol, n.d.)

Bioon, initiated in Estonia, is an organic fertilizer derived from agricultural biogas plant digestate. Biogas is produced by anaerobic digestion of biodegradable waste and residues at a temperature of 40°C for 40 days, with the biodegradable feedstocks being broken into small pieces in a hammer mill. After 40 days of fermentation, bioon undergoes further treatment in a hygienisation unit, where it is maintained at 70°C for an hour, at which point all pathogens are destroyed and the weed seeds lose their germination. Subsequently, the dry and liquid bioon is separated by a screw press and packaged. The solid bioon is packed in 25 l plastic bags and the liquid bioon in 5 l canisters. Both liquid and solid bioon can be applied to enhance soil properties, promote plant growth, and optimize agricultural outcomes, whether in open fields or greenhouses. (Bioon, n.d.)

Nutriloop is an Estonian environmental movement dedicated to circulating the nutrients and carbon present in biowaste towards regenerative food production, thereby supporting the sustainability of soils, people, and the planet. By manufacturing and distributing biowaste-based fertilizers, known as biofertilizers, Nutriloop actively promotes the adoption of regenerative agriculture. This transition away from synthetic fertilizers not only facilitates a more efficient nutrient cycle but also fosters the cultivation of local, nutritious food. Nutriloop operates under a community bio-circular model, which involves collecting biowaste from restaurants, offices, and vegetable growers, followed by biowaste transportation, valorization using bacteria and earthworms, production of biofertilizers, application in regenerative agriculture and sustainable food distribution to consumers. (Nutriloop, n.d.)

4.2. State-of-the-art of technologies used for bio-based side and waste streams to produce biogas and circular nutrients and fertilizers

Relevant technologies and good practices relating to circular bio-based side and waste streams (BSWS) for biogas and circular nutrients and fertilizers are reviewed from the value chain perspective of collection and sorting, valorisation, and upgrading.

4.2.1. Collection and sorting

It is mandated in Waste Framework Directive 2018 that biowaste must either be separately recovered at source or separately collected by 2023. BSWS separate recovery at source is mostly done through home composting or community composting. The challenges for the BSWS separation and recovery at source lay in awareness of waste classification, and knowledge for self-recovery practices to ensure process and product quality. (European Environment Agency, 2020)

When it comes to separate collection, besides the traditional truck collection approach, the potential alternatives are pneumatic waste collection system and optibag system. Pneumatic waste collection system involves the use of waste inlets connected to an underground pipe network transportation. The waste inlets are emptied using negative airflow that sucks the waste bags to a collection station. The collection station can be located remotely from the central urban area that reduces the impact of traffic jams, noise and air pollution. Optibag system involves the use of different colored bags for different collected waste streams, which can be put into the same waste bin and then sorted by color code at the optical processing facilities. (Envac, n.d.) The challenges for adopting separate collection are the initial investment costs for the changing collection and transportation system and new infrastructures required (European Environment Agency, 2020).

Good practice of collection and sorting: Optical sorting plants in Olso

Due to limited space and heavy transport in Oslo, the municipality chose optibag system for waste management. Optibag system allows for the use of same bins and vehicles for waste collection and transportation that keeps the logistics at minimum. The first optical sorting plant, Haraldrud, opened in 2009, making Oslo the first major Scandinavian city to adopt the system. A second plant, Klemetsrud, was deployed in 2012, providing optical sorting to the entire municipality. The plants sort food waste, plastics, and other materials into three fractions. Food waste is converted into biogas and biofertilizer, plastics are recycled, and the remaining fraction is energy recycled. Pre-treatment sifts remove non-bagged materials, while a wind sift refines the plastic fraction. In 2017, 46.4% of all food waste in Oslo was sorted in the green bags, which is the best result in Scandinavia. (Envac, n.d.)

Though separate collection is preferred, due to factors such as user convenience, collection system consideration, and the increasing variety of materials being recovered, sorting technologies have evolved in recovery facilities to prepare the highest quality of recyclable materials for valorisation process. Within the recovery facilities, the heterogenous waste are processed through the pre-shredding and bag opening processes using trommel screens, ballistic screens, star screens, and waste vibrating screens to separate waste into distinct size streams. Then, magnetic separation (iron extraction), eddy current separation (metals extraction), air separation (paper extraction), optical sorting (plastic extraction), and possibly artificial intelligence robot sorting systems are employed to segregate bio-based streams and other extractions. (MSW Sorting, n.d.)

Besides, the widespread use of digital technologies has been enabling the smart waste management. Utilizing artificial intelligence, robotics, the Internet of Things (IoT), and blockchain can ensure waste recyclability and traceability throughout the waste management process from collection and classification to treatment. During the collection phase, IoT technology, which combines sensors, software, and other digital technologies, allow for monitoring, collecting, and analyzing data in real-time. This can significantly reduce inefficiencies in waste collection, thus optimizing the process. (PICVISA, 2022)

Good practice of digital application in waste collection: ConnectedBin

ConnectedBin is a start-up company that develops and supplies IoT platform for waste management. Their initiative utilizes the sensor device attached to the waste container to send real-time information on waste monitoring to the digital platform (ConnectedBin, n.d.). Through the platform, the waste collector can access all data (waste segregation and its quantity, location, waste filling level, waste collection time and frequency) to determine the optimum logistics scheme. By monitoring waste, further data analytics can be conducted to predict waste generation for determining waste container distribution plan, transportation route and collection scheme. In addition, this smart waste management supports the introduction of Pay-As-You-Throw (PAYT) strategy to charge people according to their waste monitoring. As a result, PAYT incentives people to produce less waste. (SENSONEO, n.d.)

4.2.2. Valorisation

The generalization of the current established and emerging technologies to valorise bio-based side and waste streams for biogas and circular nutrients are categorized into biological conversion (composting, Black Soldier Fly Treatment, and anaerobic digestion) and thermo-chemical conversion (pyrolysis and hydrothermal carbonization) (Figure 20). The valorisation process is outlined from BSWS input, conversion process, product to end-use. In the following sections, this flow will be reviewed for each technology in addition to its advantages and disadvantages.

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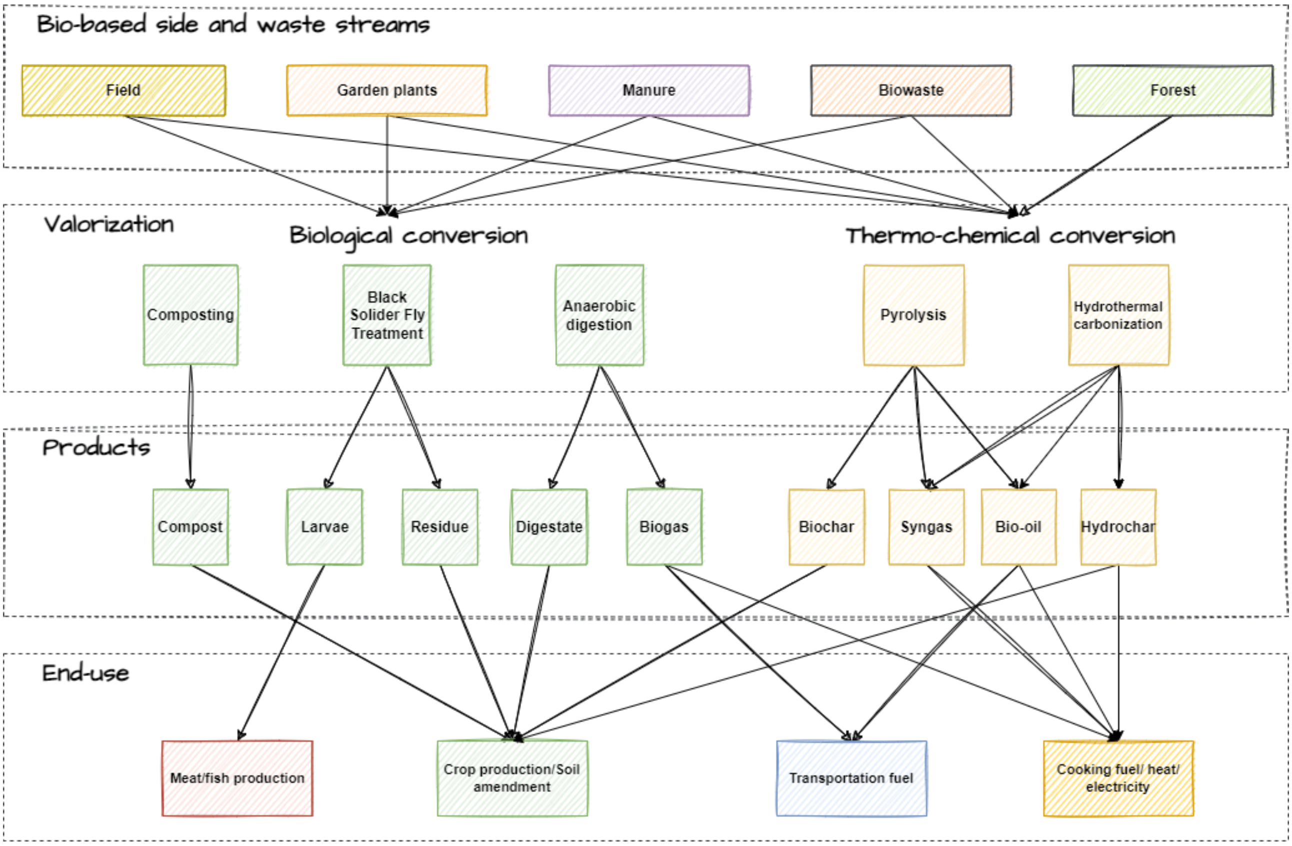

Figure 20. Overview of valorisation technologies (adapted from Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017)

4.2.3. Biological conversion

Biological conversion is defined as the transformation of materials by living organisms. Considering biogas and nutrient recovery practices, biological technologies include composting, anaerobic digestion and black soldier fly treatment. Among all technologies, composting and anaerobic digestion are the dominant treatments. Accounting for the separate collected biowaste, around 71 million tons were valorised through composting and anaerobic digestion annually in Europe. Out of that, composting represents 59% of treatment capacity and anaerobic digestion accounts for 41%. (European Compost Network, 2022)

Composting

Composting is an aerobic process in which microorganisms through their complex metabolic processes decompose the organic material in the presence of oxygen (Sayara, Basheer-Salimia, Hawamde, & Sánchez, 2020). The input materials for composting are varied within the condition of high moisture nature for microbial growth environment. Food waste, garden waste, agricultural waste, and manure are ideal substrates whereas mixed BSWS such as municipal waste are not encouraged due to low product yield. (Epstein, 2017)

The composting process undergoes 3 main stages which are (1) mesophilic stage, (2) thermophilic stage, and (3) cooling and maturation phase. In the first state, the microorganisms break down the easily degradable organic content. These microbial activities generate heat and increase the temperature passing through the mesophilic range (25-45 ℃) to enter the thermophilic stage (45-65 ℃). However, over 65 ℃ can kill the essential microorganisms for decomposition, hence, the temperature and aeration in addition to other predominant parameters such as moisture, pH, and organic composition (carbon-nitrogen ratio) need to be controlled to keep the environment in the optimum range. (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017) In the second stage, the high temperatures help eliminate the pathogen and ensure improve hygiene of the compost material. As the degradation of the organic matter becomes exhausted, the supply of heat from microbial activities decreases and the cooling and maturation phase is reached. In the maturation phase, the organic decomposition still occurs naturally with low microbial activities and the process ends when the inner temperature reaches the ambient temperature (Sayara, Basheer-Salimia, Hawamde, & Sánchez, 2020). The main output of composting is compost, a stable, nutritious, and contaminant-free soil-like texture. Compost is rich in nitrogen, phosphorous, potassium, and beneficial minerals and microorganisms which can be utilized as a soil amendment and organic fertilizer for plant growth (Polprasert & Koottatep, 2017).

Composting can be conducted in various scales from small household composting bins to the large industrial composting reactor. It has the advantages of simplicity, low operating cost, and robust technology. However, its challenges are the segregation of pure organic input to ensure high quality compost results, the long processing time of several months, and the lack of control in the microbial biological process causing nuisances such as odour and vermin. (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017; Epstein, 2017)

Anaerobic digestion

Anaerobic digestion (AD) is the biological decomposition of both liquid and solid organic matter by microorganisms in the absence of oxygen to produce biogas (Molino, Nanna, Ding, Bikson, & Braccio, 2013). The input organic materials for AD process are varied ranging from agricultural, and municipal to industrial BSWS as the single substrate or in co-digestion with high methane conversion potential substrate such as animal manure to improve the product yield (Rocamora, et al., 2020). Lignin-based BSWS like forest residues are not suitable substrates because their nature cannot be decomposed by microbial activities (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017).

The AD process involves a series of microbial activities: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the first hydrolysis stage, the bacteria convert the insoluble complex organic matter (lipid, protein, carbohydrate) into simpler soluble compounds such as amino acids, sugars, and long-chain fatty acids. In the acidogenesis stage, these compounds are continuously broken down by acid-forming bacteria into volatile fatty acids (VFAs) with ammonia, carbon dioxide, and hydrosulfide as by-products. It is followed by the acetogenesis stage where VFAs are further decomposed by acetogenic bacteria into acetic acid, carbon dioxide, and hydrogen. In the last stage, the methanogenic bacteria degrade acetic acid into methane and carbon dioxide. In addition, methane can also be produced by the reduction of hydrogen with carbon dioxide. (Molino, Nanna, Ding, Bikson, & Braccio, 2013) The typical processing time is 30 days. The output of AD process is the biogas containing methane (55–60%), carbon dioxide (35–40%), and other impure gases such hydro sulfide, hydrogen, and nitrogen. The biogas can be burned directly for heat generation or can be put into gas generators for electricity. Moreover, the biogas can be upgraded to biomethane (90-95% methane) which can then be used as vehicle fuel or can be supplied to the natural gas grid. Another product is the digestate which is rich in nitrogen and can be used for agricultural enrichment. (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017)

The advantages of AD are its widely adaptative application for different scales and feedstocks, a sustainable technology to convert BSWS into renewable energy and plant nutrient. On the other hand, the process challenge is the low biogas yield which could be solved by feedstock co-digestion with energy-rich organic waste materials to improve product yield. (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017) Other process upsets are VFAs generation causing foaming and over-acidification which can inhibit microbiological activities (Moeller & Zehnsdorf, 2016).

4.2.4. Biogas upgrading

Biogas produced from AD can be upgraded into biomethane (above 90% methane) through mainly CO_2, H_2S, and other impurities removal technologies (Kapoor;Ghosh;Kumar;& Vijay, 2019). Biogas upgrading technologies include physical technologies (water scrubbing, pressure swing absorption, cryogenic separation, membrane separation), chemical technology (chemical scrubbing), and biological technologies (chemoautotrophic methods, photosynthetic upgrading, desorption) (Ahmed, et al., 2021). Commercially established upgrading technologies are water scrubbing, pressure swing adsorption, amine scrubbing, membrane processes, and cryogenic separation (Kapoor;Ghosh;Kumar;& Vijay, 2019). Among them, water scrubbing is the simplest and most common technology which accounts for approximately 41% share of the global biogas upgrading market (UNIDO, 2017). There are emerging upgrading technologies such as hybrid methods (integrating membrane gas permeation with water scrubbing, amine absorption, or cryogenic separation). Though the potentials for less energy usage and high efficiency are demonstrated, those technologies are not yet popularized and remain at pilot level. (Kapoor;Ghosh;Kumar;& Vijay, 2019)

There are significant limitations of biogas upgrading including excessive resource consumption, the use of hazardous chemicals, and inefficient strategies. For instance, while water scrubbing is a simple method for biogas upgrading, it has limitation such as the significant methane loss from water adsorption, resulting in a low product yield. As for chemical scrubbing technology, its operation requires high energy consumption and the chemical agents utilized are carcinogenic and pose risks to human and environmental health. Additionally, upgrading technologies encounter substantial economic obstacles, due to the costly nature of operations, maintenance, and biogas utilization. (Ahmed, et al., 2021)

Black Soldier Fly Treatment

Black Soldier Fly Treatment (BSFT) is an emerging technology in BSWS treatment that transforms organic material into insect biomass of protein and oil (Kim, et al., 2021). The input materials for BSFT are diverse. Livestock manure, food waste, vegetable waste, compost, and municipal organic waste can be suitable feedstock (Cai, et al., 2018). The moisture level in the feedstock is an important factor that larvae develop better under moist environments. Ideally, wet, and dry matter can be mixed to generate better larva feed (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017).

Considering the conversion process, the black soldier fly, *Hermetia Illucens* larve have the appetite for decaying organic matter which is taken advantage of to feed organic matter for incorporating nutrients into growing the insect biomass of extra protein and fat (Cai, et al., 2018). The total larval development lasts for about 20-35 days (Zhou, Tomberlin, Zheng, Yu, & Zhang, 2013). The optimum temperature and moisture level during the process are 26–27 °C and 60–70% respectively. Furthermore, larval density needs to be controlled to prevent the insect competition that adversely decreases larval survival rate. The effective ratio of the number of larvae to grams of feedstock is 2:1. The output of the BSFT is the larval biomass as the main product and residues. The high protein and fatty acid content of larvae make them a great nutrient source for animal and fish feedstocks. In addition, the larvae can be extracted for oil for further biodiesel production. The quality of lipids contained in the larva is comparable to the conventional biodiesel. (Kim, et al., 2021) The residues from BSFT still retain nutrients and can be applied as a soil amendment. However, because of the short processing time, the residues must undergo a maturation phase to prevent oxygen depletion in the soil that can inhibit seed germination and suppress root and plant growth. (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017)

BSFT is a novel technology with high potential for industrial application and economic success. The process advantages include short processing time, high nutrient conversion rate, and economic-attractive products. However, the challenges remain in the large space required and the highly skilled labor needed to control the insect behaviour and ensure the larval survival rate due to the insect colony. In addition, because the larvae are utilized as animal feed, hygiene factor needs to be concerned, which can be solved by eliminating contaminant feedstock for growing black solider fly in the first place. (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017)

Good practice of Black Soldier Fly Treatment: Volare

Volare is a spinoff startup from VTT, which refines food industry side streams through the natural bioreactor, black soldier fly. Volare production utilizes food industry side streams such as the non-edible part of grains as inputs for black soldier fly farming (VTT, 2021). Through a combination of proprietary and existing BSFT technologies, Volare facilities enable the mass-scale production of high-quality protein meal, oil, and organic fertilizer. Insect protein can be served as aquafeed and pet foods while insect oil is rich in lauric acid which can be replaced for palm kernel and coconut oil. Volare's pilot plant is fully functioning and automated. Volare first industrial-scale plant is planned to be built in 2023. Compared to traditional alternatives, Volare production is energy efficient, and the associated environmental impact is negligible. (Volare, n.d.)

4.2.5. Thermal-chemical conversion

Thermo-chemical conversion is the process that uses heat to foster chemical reactions to convert materials into value-added products. The valorisation processes for circular nutrients involve pyrolysis and hydrothermal carbonization.

Pyrolysis

Pyrolysis is the thermal decomposition of organic materials under the absent oxygen condition. The process uses heat to disintegrate the weak thermal stability of chemical bonds and transform the material into new molecules (Zaman, et al., 2017). The input materials for pyrolysis are BSWS that meet the requirement of dry and homogeneous substances. Wood waste, paper and cardboard, lignocellulosic biomass from garden waste, and agricultural waste are suitable inputs (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017). High moisture stream can also be applied with pre-treatment of drying to a suitable range of 10-15%. In addition, pre-treatment includes the grinding of material into smaller sizes and delignification for more efficient pyrolysis conversion. (Isahak, Hisham, Yarmo, & Yun Hin, 2012)

Pyrolysis conversion undergoes complex thermal decomposition to break down large complex hydrocarbon molecules of biomass into smaller and simpler molecules of gas, liquid, and char (Basu, 2013). Pyrolysis conversion is divided into fast pyrolysis and slow pyrolysis processes. In a fast pyrolysis process, the input is quickly heated to high temperatures between 650-1000°C in seconds. The fast pyrolysis results in the main product of bio-oil and a lower yield of biochar and gas. On the other hand, slow pyrolysis operates in longer residence times (range from minutes to days), and lower temperatures (300-500°C) to convert biomass into the main product of biochar, gas, and lower bio-oil yield (Zaman, et al., 2017). The outputs of the pyrolysis conversion are solid (biochar), liquid (bio-oil, tar, and water), and a mixture of non-condensable gases (H_2, CO, CO_2…) (Basu, 2013). Biochar can be applied for soil amendment, burning fuel, adsorption media, and carbon sequestration (Krueger, Fowler, Templeton, & Moya, 2020). Bio-oil can be used as combustion fuel in boilers, and engines or upgraded to biodiesel for transportation fuel. The gases can be utilized directly for heat generation and gas power generators for electricity or to produce individual gas components. (Kan, Strezov, & Evans, 2016)

Considering the advantages, in comparison to other biological or physical treatment methods, the high-temperature operation in pyrolysis provides highly hygienic products, and the rapid retention time of the pyrolysis process requires smaller space and size of the reactor (Krueger, Fowler, Templeton, & Moya, 2020). In addition, the storage, transport, and usage of the pyrolysis products are also simplified by their reduced volume and biochemical stability (Krueger, Fowler, Templeton, & Moya, 2020). When it comes to the challenges, the process is energy intensive due to high-temperature operation. There is a need for

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flue gas treatment for carbon monoxide and particulate matters. The potential formation of organic contaminants such as polycyclic aromatic hydrocarbons (PAHs) in biochar also needs to be considered. Another barrier is the undesirable properties of bio-oil which induce costly and complex upgrading efforts. (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017)

Good practice of pyrolysis: Carbofex

Carbofex operates one of the Europe's largest continuous pyrolysis plants dedicated to producing biochar. Since its commercial launch in 2017, the plant has maintained 95% availability and has been producing CO_2-negative district heat since November 2018 (Puro.earth, n.d.). The plant is energy efficient as it generates more energy than it consumes. The excess renewable energy can be utilized for heating, cooling, or desalination. The Carbofex pyrolysis plant converts up to 500 kg of wood chips per hour, resulting in 140 kg of biochar and 1MW of clean energy power. By adding an electrostatic oil separator, the system can also produce 100 litters of high-quality pyrolysis oil. The plant has the capacity to yield 1000 tons of biochar and 600 tons of oil annually while providing up to 8000MWh clean energy to the municipal heating network. (Carbofex, n.d.)

Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a thermochemical conversion process that converts wet biomass feedstocks into hydrochar using heat. HTC is versatile and can handle a wide variety of feedstocks, including aquatic biomass, agricultural residues, and industrial and animal wastes. (Sivaprasad, Manandhar, & Shah, 2021)

The process is conducted in a reactor under autogenous pressure and temperatures ranging from 180 to 250°C, with a feedstock residence time between 0.5 to 8 hours (Ahmad, Silva, & Amâncio, 2018). During the process, hydrolysis, dehydration, decarboxylation, and aromatization reactions occur. HTC produces gases (mainly CO_2) and an aqueous slurry consisting mainly of water with a small fraction of organics and solids. The aqueous slurry is then separated into process water and wet cake via centrifugation or filtration. The wet cake is dried to produce hydrochar, which has properties suitable for a variety of applications, such as solid fuel, adsorbent, and soil amendment. The distribution of solid, liquid, and gaseous products is primarily influenced by the choice of feedstocks and process conditions, particularly temperature and residence time. (Sivaprasad, Manandhar, & Shah, 2021)

HTC's major advantage over other thermochemical conversion techniques is that it operates at lower temperature, allowing energy saving and can treat moisture feedstocks, allowing for feedstocks to be converted without pre-drying. Water acts as a good medium for heat transfer in HTC, however, mass transfer limitations may occur if the feedstock particle size varies too widely, or the reaction time is short. Therefore, particle size should be uniform to ensure even heat and mass transfer. (Sivaprasad, Manandhar, & Shah, 2021) Although HTC appears to be a promising solution for BSWS valorisation, more comprehensive techno-economic analysis is needed to evaluate its feasibility for large-scale operations (European Environment Agency, 2020).

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4.3. Ecodesign applied in bioeconomy

In ecodesign, environmental aspects are considered in the entire product development process and the aim is to create products that cause as little environmental impact as possible during their life cycle (European Environment Agency, n.d.). The bioeconomy is a renewable part of the circular economy, which makes it possible to convert waste generated in the economy into reusable resources, develop new and innovative ways to produce food, products and energy without exhausting limited natural resources, and replace products based on fossil natural resources with bio-based alternatives.

Biogas plants are one example of the bioeconomy and, in the best case, they function as efficient recyclers of nutrients in addition to energy production in their area. The operation of biogas plants requires that they have a steady supply of feed various materials suitable for biogas production, and that the logistics solutions are economically viable and functional. The location of key players in the immediate vicinity of the biogas plant increases not only positive environmental effects but also cost savings in, for example, logistics, heat energy and waste management. With good, planned land use, resource-efficient symbioses can be achieved. In planning, for example, the utilization of waste heat, material synergies between companies, smooth logistics and surrounding housing must be considered. (Satakunnan bio- ja kiertotalouden kasvuohjelma, 2019)

Good example: Agroecological symbiosis

A good example of bioeconomy ecodesign is Palopuro Agroecological Symbiosis in Hyvinkää. It has been a pilot site for projects that aim to find a functional and sustainable food system model. Research into the Palopuro model began in a pilot project funded by the RAKI program of the Ministry of the Environment in 2015. The producers and processors of Palopuro, the University of Helsinki and the Natural Resources Institute Finland (LUKE) were involved in the project. The research continued in the years 2017-2020 in another project, the aim of which was to scale the model of agroecological symbiosis from one place to a wider one by building a network of similar projects. (University of Helsinki, n.d.)

The Palopuro model is a good example of the need for cooperation between producers, processors, companies and consumers in order to increase sustainability. The local food model, local circulation, is built on the cooperation of farmers and other companies. It minimizes nutrient loss and relies on local energy. Palopuro Agroecological Symbiosis consists of a network of several organic producers and processors. Knehtilä's farm is at the center of the cooperative's food production system based on energy and food self-sufficiency. The goal of the project is to produce local, organic food with bioenergy and recycled nutrients. In the system, the grain from the field is ground on Knehtilä's farm and baked into bread in the organic bakery operating on the farm. The losses caused by grinding and baking can be used as feed for the chickens on the neighboring farm. They can also be used as energy sources for biogas production. The biomass of green manures from Knehtilä's organic farming cycle, combined with chicken manure and manure from local horse stables, is processed using an anaerobic digestion method.

The result is biogas, which is used as energy for grain drying, bakery ovens, running agricultural machinery and sold for passenger cars. The nutrient-rich digestate residue from biogas production is used as organic fertilizer and soil conditioner in fields. (University of Helsinki, n.d.)

The idea driving this cooperative is to locally recycle the nutrient flows generated in the production, and fully utilize the bioenergy potential in the biomass flows. This system of producing organic food considers all aspects of production and strives for maximum sustainability at every step of the production and process. By recycling organic materials there is an inherent increase in soil productivity and health. This system also conserves natural resources. With the Agroecological System model, the biomass loops will be closed, and the cooperatives can operate sustainably. Combining food processing, bioenergy production, and cooperation between different stakeholders enables more sustainable local food systems. (University of Helsinki, n.d.)

Ecodesign and profitability

Profitability of the biogas industry has generally been low, both in farm scale and in centralised industrial production, mainly due to high investment costs and low prices of the final products (Winquist;Rikkonen;& Varho, 2018). Gate fees for biobased waste provide a possibility to enhance profitability, due to which several operators use municipal solid waste and waste waters as feedstock in biogas production. The biomasses with most biogas production potential, still in limited use, are in agriculture (Rasi;Markkanen;Pyykkönen;Aro;& Seppänen, 2022). Upgrading of biogas (see chapter 4.2.4. Biogas upgrading) is another possibility to add value, although in most cases requires high investments in technology. Liquefaction of biogas for example, is costly and has high purity requirements, but has also market potential, as it is used by heavy transport (Rasi;Markkanen;Pyykkönen;Aro;& Seppänen, 2022).

Agricultural side streams utilized in biogas production are often geographically dispersed, therefore transporting side streams can be inefficient and expensive. Decentralized biogas production is an example of ecodesign in agricultural side stream utilization with improved profitability, as the transportation system has been intensified (Rasi;Markkanen;Pyykkönen;Aro;& Seppänen, 2022). It also enables larger material volumes to be used as feedstock for overall production.

Good example: Decentralized biogas production

In Finland the biggest dairy company, Valio, is creating an extensive decentralized biogas production system. Suomen Lantakaasu Oy, owned by Valio and an energy company St1, is targeting to produce 1TWh of transport fuel from biogas by utilizing decentralized biogas production (Valio Oy, 2022). Their concept is to produce biogas in satellite plants which use manure from several farms as feedstock. From the satellite plants, the biogas is transported to a central biogas plant where the biogas is liquefied. The nutrients from the manure are returned to the farms as bio fertilizer, increasing the circularity of biomass. Suomen Lantakaasu Oy aims to include hundreds of dairy farms into the biogas production. This is a new example of ecodesign in Finland which enables biomass and nutrient cycling on large scale. The extent of the system enables better profitability and also makes the system significant in terms of circular bioeconomy.

Hydrogen and biomethane are another upgrading possibilities for biogas. The industry in both is developing rapidly and the number of projects is constantly growing. In Finland, there are over twenty large scale hydrogen projects planned worth over 10 billion euros (YLE, 2023), which implies of the potential predicted. These projects though are not based on biobased side stream utilization. In Finland, Doranova and Q Power are both doing research to develop technologies for methanation processes utilizing agricultural side and waste streams (Q Power, 2023; Doranova, 2023). Both companies have background in biogas production and are developing commercial processes for methanation. Methanation could enhance the profitability of biogas in agriculture and therefore have potential to enhance circularity of biomasses and nutrients.

Part V: Cross-cutting issues and pushing transitioning to circular economy forward

5. Cross-cutting issues and pushing transitioning to circular economy forward

Circularity is seen as a prerequisite for climate neutrality that requires cross-cutting actions. Synergies between circularity and greenhouse gas emission reduction are proved but need to be further understood and promoted. Even though the TREASoURcE project's targeted value chains are very different, there are commonalities between the value chains and cross-cutting issues. Identifying cross-cutting issues are crucial since the resources for investment are often limited. Cross-cutting actions addressing the value chains' overlapping pain points can then optimise the resource usage to create significant impact and push the transition to circular economy forward.

Most obvious matter is of course that the end goal is ultimately the same – transitioning from linearity to circularity. However, there seems to be also competition between different circular strategies as they are based on same resources. Legislations play a key role in both promoting and inhibiting circularity where targets and mandates e.g. on recycled content are set. For example, as the Waste Directive only prioritises in hierarchy prevention, reduction, recycling, recovery (energy) and disposal, the complementarity and cascading use of resources from higher circularity towards lower circularity is still somewhat missing.

It also seems to be a commonality that economic viability and profitability are challenging to reach as virgin materials are of much lower costs and the operational costs are typically larger for circular strategies rather than linear operations.

For the TREASoURcE value chains, an overview of the main characteristics regarding competitive circular strategies, value or criticality of the material streams as well as the main direction of the current legislative actions are summarised in Table 2. In Table 3, we present an overview of political, economic, social, technical, environmental and legal cross-cutting themes and issues that have been collected as part of reviews and from project interviews and workshops.

Table 2. An overview of the characteristics of the targeted waste streams in TREASoURcE

	Competitive circular strategies	Value or criticality of the material streams	Legislation
Plastic waste streams	Most focus is put on recycling than other higher level circular strategies Some prioritisation occurring between mechanical and chemical recycling	Challenges with feedstock quality and quantity, and batch-to-batch variation Lower quality feedstock has lower value, higher	Supports mostly recycling, but also reusable packaging is foreseen

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	Issues seen in energy production (incineration) as high-energy value input is directed for recycling	quality and technical plastic recyclates have higher quality and higher value	
End-of-life EV batteries	More focus is directed at recycling rather than repurposing or reusing Decoupling from virgin materials unlikely, high demand on virgin raw materials	Critical raw materials with higher prices compared to the other streams, much business interest in these streams	Introduces recycling targets and recycled content mandates, little efforts towards repurposing or other higher circular strategies Digital product passport improving battery data transparency for recycling
Bio-based side and waste streams	Cascading approaches, no competition per se Recovered biogas as vehicle fuel may compete with electric vehicle	Abundant resources but some streams lack circularity management Economic profitability uncertain in less valuable streams	Lack of incentives, unharmonization regulations, many permits required, end of waste criteria expansion for bio-based streams needed

Cross-cutting themes and issues that have been collected as part of reviews and from project interviews and workshops are presented in Table 3.

Table 3. Outputs from the TREASoURcE project: Cross-cutting themes and issues

	Theme	**Related issues**
Social	*Consumption and use phase*	• Sustainable consumption and use, circular consumption and use. • Consumer demand and awareness of circular economy, circular products and services • Safety
	Education, training, skills development	Circularity will affect jobs in the linear economy, therefore, training and education and development of skills will be needed to ensure employment and skilled workers for circular businesses.
Political	*Geography*	• Spatial distribution of the produced material streams • Decentralised production and low volumes
	Initiatives	• Initiatives to boost circularity focus on certain circular strategies, which increases overall circularity, but on the other side, takes focus away from other higher level circular strategies, e.g. New Plastics Alliance for plastic recycling.
	Lobbying	• Bigger companies have more resources to promote the circular strategies prominent for them than smaller companies like SMEs, e.g. New Battery Regulation where recycling is targeted - bigger battery material recyclers vs. small repurposing operators.
Economical	*Financing and funding*	Transition requires careful yet decisive measures to steer financing towards more sustainable production and consumption patterns (European Commission, 2020)
	Circular business strategies	• Scaling solutions to the markets • Economic viability against virgin materials • Technology readiness levels (TRLs)
	Logistics	• Emissions from transportation

<table>
<tr><td rowspan="2">Environmental</td><td></td><td>Sustainability of transporting material streams
Long distances
Low volumes produced decentralised, critical mass
Often a key enabler for circularity</td></tr>
<tr><td>Sustainability and environmental impact</td><td>Sustainable production, sustainable resource use, resource efficiency
Pollution
Greenhouse gas emissions and contributions to climate change
Biodiversity
Decreasing dependency and use of virgin materials</td></tr>
<tr><td rowspan="4">Technical</td><td>Digitalisation and data</td><td rowspan="2">Need of data and information. Information is mostly confidential earlier on in the value chains. It is typical that information is finally lost during use phase and end-of-life management operators like plastic recyclers and battery repurposing operators have limited information flow as data is mostly unavailable. Tracking is also in a critical role to understand where material streams are created and how to ensure that they remain in circular economy. Monitoring goes hand in hand with safety aspects.</td></tr>
<tr><td>Tracking and monitoring</td></tr>
<tr><td>Scale of operations</td><td>Need for smaller scale decentralized operations and material processing options also
Bigger scale operations require high quantity and quality of input feedstock as well as high investments</td></tr>
<tr><td>Research, development and innovation</td><td>New innovations are needed for different circular strategies, implementation of circular solutions requires typically cross-disciplinary and multistakeholder approaches (European Commission, 2020):
novel materials and products
substitution and elimination of hazardous substances
circular business models
new production and recycling technologies
digital tools and digitalisation</td></tr>
</table>

		• development of skills, training and mobility of researchers
	Ecodesign	• Technical innovation in sustainable material and product design needed • A new Ecodesign for Sustainable Products Regulation will be the cornerstone to set requirements and have more environmentally sustainable and circular products on the markets. (Directorate-General for Environment, 2022)
Legal	*Targets, mandates* *Restrictions, bans*	• Support the development of some circular strategies, in some cases on the other circular strategies expense
	Fast changing legislative environment	• Changes in the focuses of strategies, e.g. EU's direction away from biogas cars, and bans on certain products (like single-use plastics directive)
	Unharmonized legislation *Policies support linear models*	• Contradictory legislations • Value chains in many cases are across countries • No end-of-waste legislation for all material streams, waste-product interface is challenging

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