

## Material Flow Analysis of the Recycling Pathways for Advanced (Nano)Materials

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# MATERIAL FLOW ANALYSIS OF THE RECYCLING PATHWAYS FOR ADVANCED (NANO)MATERIALS

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## 2 Introduction

European Union's circular economy strategy is key to addressing resource scarcity, climate change, environmental degradation, and biodiversity loss induced by consumption (European Commission, 2020b). A circular economy aims at keeping products and materials in use for the longest time possible, as well as minimize flows of materials by using less materials and energy to produce new products. To promote circularity the European Framework Directive<sup>1</sup> 2008/98/EC introduces a pyramidal hierarchy of waste<sup>2</sup>, and instructs on process prioritization.



Figure 1. Waste hierarchy set by the EU

To make the idea of circular economy a reality, the EU has set ambitious sustainability targets for 2030 and 2050, particularly in the areas of solid waste management and CO<sub>2</sub> emissions. Within the Circular Economy Package many waste categories received collection and material recovery targets within a given timeframe. If not a specific number, then guidelines for handling specific types of waste, complete with the responsibilities of each stakeholder are delegated. Most of these targets were defined in the European Green Deal, adopted in 2019 but some from even earlier, which aims to transform the EU's economy into a resource-efficient one, decoupling economic growth from resource use and achieving net-zero emissions by 2050 (Kazak, 2022). Furthermore, in May 2022, the Eighth Environment Action Programme entered into force (European Parliament, 2022), aiming to align European environmental policymaking with the European Green Deal's ambitions and the Sustainable Development Goals, by striving for significant decrease the EU's material and consumption footprints and bring them within the 2050 vision. In summary, these policies and targets seek to contribute to more sustainable consumption by supporting pathways aimed at

- (1) consuming differently by shifting to less material-intensive options and using renewable or recycled materials,
- (2) consuming less through, for example, longer product lifespans or through sharing models that can reduce the demand for new products, and
- (3) scaling up circular product design that enables circular consumption and reduces environmental impact.

More specifically, The EU's committee have placed EU's 2030 circularity targets for the collection and recycling for each group of materials as divided in:

- Batteries and accumulators,
- Biodegradable waste



- End-of-life vehicles (ELV),
- Municipal waste,
- Packaging and packaging waste,
- Construction and demolition waste,
- Waste electrical and electronic equipment (WEEE)
- Ships
- Waste containing POPs
- Waste oil
- Hazardous waste
- Sewage sludge
- Polychlorinated bisphenols and polychlorinated terphenyls (PCBs/PCTs)
- Landfill waste
- Mining waste.

## 2.1 Advanced (nano) Materials (ANM)

One way to achieve EU's targets is to invest and support the usage of new materials with a smaller footprint that at the same time allow multiple and futuristic utilizations. A group of materials of great interest for this segment are the so-called advanced (nano) materials. Advanced materials are those materials which, through the precise control of their composition and their internal and external structure, are deliberately structured or designed in such a way that they meet new functional requirements (Schwirn K. et al. 2023). Advanced (nano)materials, henceforth referred to as ANM, are a subset of advanced materials characterized by their nanoscale dimensions (1-100 nanometres) that impart unique properties. They have become a very interesting domain in the industry because it allows for cheaper materials with a high performance and a plethora of different characteristics. More often than not they are embedded in a matrix of more familiar materials and enhance its properties in ways unimaginable until now. These hold significant promise for promoting sustainability by minimizing waste, optimizing resources and high-performance delivery with reduced environmental impact. Therefore, EU's zero carbon emission targets for 2050 largely widen the demand for nanomaterials. One such material of great interest seems to be graphene, currently being worked on within the Graphene Flagship project launched in 2013 as part of the EU's Horizon 2020 funding framework. The project aims to success in scaling up graphene production and make it widely available.

## 2.2 Graphene

Graphene is at the top of the list of considered ANM to help the green transition. For example, it finds use in electric vehicles whose battery uses graphene as an anode material. A market analysis suggests this use alone is largely responsible for the expected market growth of graphene globally by 32% by 2033 (Aliofkhazraei M. et al., 2023) even if it currently has minimal market penetration. This material, also sometimes referred to as a 'supermaterial', stands out from the rest and has very large potential for industrial use, due to its cheap starting material and superior characteristics.

These excellent characteristics allow for its usage in sporting goods, batteries, R&D, electronics, automotive, paints and coatings, textiles, drilling fluid, medical applications, tires, construction, filtration, aerospace and wind turbines, as identified by Hong, H., Part, F., & Nowack B., 2022. The same study looks deeper into graphene's market and the prospect of the

amounts produced and used by 2030 via conducting a prospective, dynamic, and probabilistic material flow analysis (pDPMFA), where the recycling processes weren't considered in depth.

### 3 Advanced (nano)Materials in circular economy

As mentioned, ANM are one the most forthcoming solutions to be employed when high consumption cannot be stopped. However, this begs the question about the circularity of these materials. The waste management sector cannot always confirm the presence of all the additives, nanomaterial or otherwise, and therefore the ANM remain unaccounted for and might find their way back on the market in unintended places. Furthermore, even if the material is detected, Nowack, B. et al., 2015 found that analytical tools available are not yet capable to distinguish the naturally occurring from the intentionally placed engineered nanomaterials (ENM) at the low concentrations expected in complex matrices. The same study suggests that modelling of the flows could help distinguish between the two because estimates of an ANM are given beforehand, whose presence can then be confirmed by physical characterisation. Therefore, in order to track the ANM lifecycle and foresee their movements through the circular system Material Flow Analysis (MFA) studies are conducted.

Material flow analysis (MFA) is a method of depicting the flow of materials in the anthroposphere and the environment to support environmental management (Wang & Ma, 2018). It takes a modelling approach to assess where the mass of this material is at a certain point in time and possibly the form in which it persists. The MFA process involves:

- (1) defining a system boundary,
- (2) capturing the system structure and flows,
- (3) investigating database and calculation, and
- (4) analysing material system processes and performing system balances (Brunner and Ma, 2004).

Consequently, this approach has been applied to diverse materials such as metals, steel, rubber, and nanomaterials, enabling comprehensive analyses of their use and potential environmental emissions (Hatayama et al., 2010; Hong et al., 2022; Nakamura et al., 2014; Sieber et al., 2020). This is of great interest because then their potential environmental emissions and other contemporary environmental concerns can also be predicted (Sun et al., 2017). In fact, most of these studies regarding ANM are currently prospective since the ANM are only just starting to enter the market and haven't reached the end-of-life stages in big quantities yet. A Prospective MFA (pMFA) which bases its mass values on the expected market and uses of a material can reveal where the ANM ends up after its production including the emissions generated during the production process. To account for uncertainties when a prospective approach is used the model needs to take on probabilistic values. These values would come in a range of uncertainty with randomized values within that range and the values obtained give an average that is the most probable outcome. MFAs performed in this way are called probabilistic (PMFA). Since advancement is never constant, a dynamic model has to be employed, where future trends in regulations, using either a top down (looking into the market trends and market penetration of the ANM itself) or bottom up approach (assuming a market penetration of the nano-enhanced version of an application in a traditional market), related to the target material are taken into account as accurately as possible (Caballero-Guzman A. and Nowack B., 2018). The integration of dynamic material flow modelling with probabilistic modelling has led to the development of the Prospective Dynamic Probabilistic Material Flow Analysis (pDPMFA)

method, which allows for the consideration of temporal dynamics and uncertainties in input parameters (Bornhöft et al., 2016). Dynamic material flow analysis (MFA) is a valuable method for evaluating the stocks and flows of various materials over time, providing insights into past, present, and future material usage (Müller et al., 2014).

## 4 Knowledge gap

Reviewed studies on MFA of nanomaterials (the most notable of which are found in Table 1) all have acknowledged, the advancement of material flow analysis methods is of high relevance to addressing emerging environmental challenges. Its importance is particularly highlighted in assessing the environmental risk of engineered nanomaterials and predicting their flow within post or pre-consumer waste treatment systems (Rajkovic et al., 2020; Wang & Nowack, 2018). However, the recycling sector has been overlooked in many of them. Literature research suggests that although it is included in some ways, the actual process of recycling isn't considered in many.

*Table 1. Most relevant studies reviewed to identify knowledge gap*

Studies selected for review	Performed MFA	Included collection target	Included recycling target	Included recycling technology	Included more than one recycling technology	Included graphene	Included side processes	included ANM
Zheng Y. and Nowack B. (2021)	X			X				X
Adam V. et al. (2018)	X			X				X
Sun T.Y. et al. (2014)	X			X				X
Adam V. et al. (2021)	X			X				X
Hong H. et al. (2022)	X			X		X		X
Rajkovic S. et al. (2020)	X			X				X
Hansen, S.F., (2022)	-			X	X	X		X
K.M. Cochran and T.G. Townsend (2010)	X	X	X	X				
Furberg A. et. Al. (2016)	X							X
Caballero-Guzman et al. (2015)	X			X				X
Arturo A. Keller (2024)	X							X
Wang Y.and Nowack B. (2018)	X		X	X	X			

Different recycling treatments with very different process parameters exist on the market for a single material at the same time. In reality, flows of waste could be split between different treatments, with varying market shares, for a given geographical scope. Furthermore, process parameters could greatly change the flows of the material as well as any possible chemical changes. Not only that, but also in most cases, especially in post-consumer waste, where waste is wrongly disposed of. To address these flows, there is a need to compile recycling technologies, including their side processes, which will indicate the pathway of current and future flows of ANM, intact with characteristics of the processes as to give an idea if the ANM would stay intact and appear as a contaminant in new products or will accumulate in the environment. Furthermore, realistic collection as well as the targeted one needs to be looked into to assess how much material ends up in improper disposal.

## 5 Research question

To overcome the knowledge gap the following research questions were selected:

1. What are the current and future recycling pathways and technologies for all post-consumer waste types where ANM can be contained?
2. What are the process parameters of these technologies?
3. What are the material flows for graphene in the EU's circular economy model?

Answering these questions will be done in such a way that the processes will be outlined and finally a pDPMFA model of graphene will be formed as a case study to show how including the recycling pathways could change or confirm the previously assumed final placement of an ANM. This will be done by updating upgrade the work of Hong, H., Part, F., & Nowack, B., 2022 whilst taking into account EU's sustainability goals.

The paper by Hong et al. presents an assessment of the environmental releases of graphene-based materials (GBMs) using dynamic probabilistic material flow analysis. The study models the use, consumption, and environmental impact of GBMs in Europe, predicting that by 2030, over 50% of GBMs will be incinerated, 16% landfilled, and 1.4% released into the environment. The findings provide valuable data for future environmental risk assessments and fate models of GBMs. It considers different product categories to compute its results, and while it does consider sorting and reprocessing, the actual process parameters are omitted as well as the multiple options that exist for reprocessing. Further, the only improper disposal of waste it considers is that the waste will end up in the mixed waste fraction.

## 6 Methodology

### 6.1 EU categorization by waste type

First and foremost, to look into current and future technologies, the categories where these materials can be found need to be identified.

The easiest waste division can be split in three categories: industrial, construction & demolition waste, communal. Industrial will not be considered for this study as it usually comes from the product's production and manufacturing stages. These are usually well documented and explored in other studies as well. Construction and demolition, as the name suggests, alludes to any waste material obtained from the alteration, construction, destruction, rehabilitation, or repair of any manmade physical structure including houses, buildings, industrial or commercial facilities, and roadways.

Lastly, the biggest waste category is communal waste. This observes the following subcategories: biodegradable waste (food scraps, yard trimmings, organic waste), recyclable waste (paper and cardboard, glass, metals, plastics), hazardous waste (chemical waste, batteries, medical waste, paints and solvents) waste electronic and electric equipment (consumer electronics, home appliances, lighting), textile waste and mixed residual waste (non-recyclable plastics, composite materials, household waste). There are other complex wastes such as automotive with separate collection, however once disassembled, the materials extracted go through the same waste streams as other subcategories of communal waste and demolition waste (CDW).

For more specific waste categories as included in the European Waste List refer to Annex.

All of these wastes are present in a mixed way in different collected categories of post-consumer waste as they have been stated in the Introduction. Therefore, these wastes will be discussed within the collected waste types. It is noteworthy to state that only solid wastes were taken into account. Therefore, wastes such as waste oils weren't considered.

To account for the predicted dynamic change in the system, this model will look into collection and recycling rates according to the type of matrix the ANM had been used in. However, it will only consider post-consumer communal and construction waste, since post-consumer waste is harder to track than industrial waste (Sinha P. et al., 2021).

## 6.2 Decision tree

The recycling streams diagrams for each post-consumer category, as presented in the Results section of this study, do not consider all the possibilities there are for ANM mass flows. Therefore, a decision tree (Figure 2) is needed to explain all the other segments that need to be considered before one looks for recycling stream diagrams for a specific kind of waste.

The input of the system is decided by its first category, where the user should consider the Commercial Product where the ANM is placed. This segment is used so that the correct waste stream will be chosen, regardless of the matrix the ANM is placed with. Further, the segregation is done by the application of the complete product (categories are looked into as a computer in WEEE rather than just metals or plastics) because this is how collection and recycling rates are defined by the EU. Once the correct stream is chosen in the beginning, the user would have to follow along the algorithm in the graph and only look for the corresponding recycling diagram once it reached the recycling stage.

There is a question following this segregation, which alludes mainly to the use phase of the product. This is placed to encompass all the ANM which have controlled release schedules or are let out of the product on purpose at specific times. If the answer is yes, then the use phase must be represented as a Stock. A Stock is a type of compartment in the DPMFA where the material is kept for a certain period of time but will still continue its flow later on. There is a certain accumulation of material in this compartment which must be represented when discussing results. Additionally, it should be investigated under which conditions these emissions occur as well, since then multiple compartments that come later on might need to be converted into Stocks, like for example Landfill.

Depending on the types of release the ANM could be a direct emission, which could result in an accumulating concentration in the environment, or it would undergo chemical changes after which the ANM does not exist in the same chemical form anymore (Nowack B., Caballero-

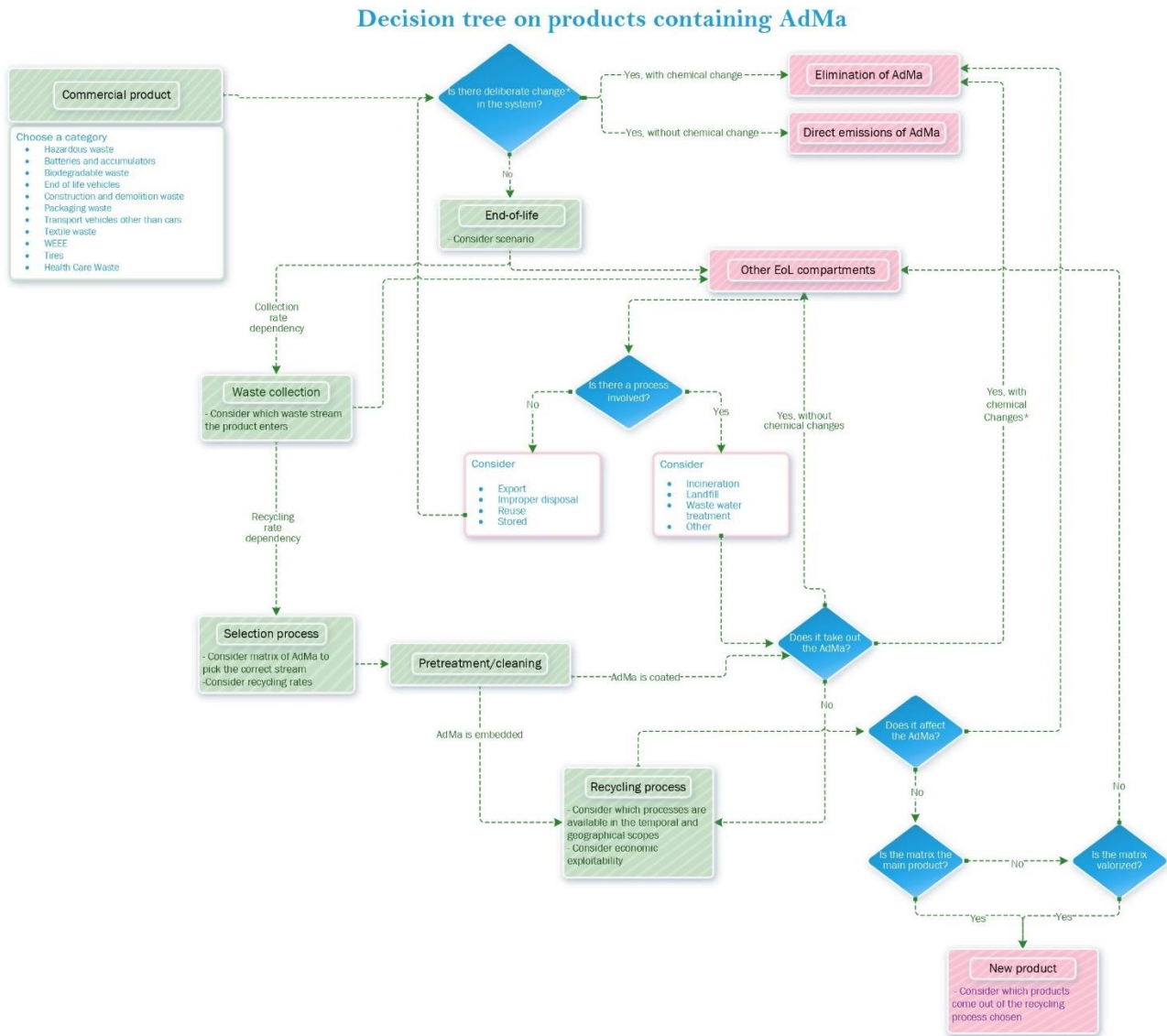


Figure 2. Decision tree for recycling diagrams

Guzman A., Adam V., 2018). This would mean that there is no presence of it in the environment, rather the emissions are as a different and usually simpler compound. These two outcomes represent the first two types of so-called Sinks (colored pink) used in the DPMFA study. Sinks are defined as compartments in the DPMFA where the material settles and has no further flow. A Sink could be used when there is no more information on how to proceed or when further explanation is out of scope.

If there is no change during the use phase, then the ANM will reach the End-of-Life (EoL) Flow Compartment (where a material only flows through and is not kept for a longer amount of time) together with the matrix it was used in, intact in the complete commercial product. From this point on there are 3 scenarios that could take place, each with different transfer coefficients. The three are given to the prospective part of the study, as all three have possible future outcomes. The scenarios will be presented later. The product can go two ways from there. Either it will go to its proper waste collection with intent for recycling, depending on its collection rates, or it could go in a different EoL pathway. Of course, proper waste collection does not necessarily mean it will all be fully recycled, which is why there is still a chance that

even if the product enters the correct waste stream, depending on economic, regulatory, or other reasons, it could still not end up at its recycling procedure. This will be calculated according to the recycling rates. These other EoL pathways or compartments may include a process or not, which could in turn again define where or in which form the ANM will be kept or released in the environment or elsewhere.

If the ANM follow along on the recycling path, it will first get to the selection process. This Flow Compartment symbolizes the simple division of products into their founding materials. This process could be done manually or automatically, or a bit of both, which would influence how well this step is performed. It is expected that most processes performed here have a purely mechanical nature, and therefore there is little chance of change to the ANM system; however, this step greatly narrows down which recycling process will be used later.

Following the selection, there is an option of pretreatment. Not all facilities utilize one. However, the purity of the recycled product is much better if one is in place. This step mainly focuses on the surface or interlayer of the product, and it is therefore vital to know if the ANM is embedded into its matrix or it is used as a coating, since coatings have a much higher chance of getting removed or altered during this step ([Mickelson & Haag, 1997](#)).

If the pretreatment does not disturb the ANM, embedded or coated, it will continue to a recycling process. This is when a specific scheme of recycling should be consulted from the ones presented in the results. As this is a prospective study, both current and possible future recycling techniques are included. Hence, the recycling technology should be accordingly chosen by considering temporal, geographic, and economic factors. Further, the recycling process, as a Flow Compartment, has the highest probability of altering the ANM, and its parameters are of high importance. They should be compared to the parameters that the ANM can withstand. Even if the answer is that the recycling process does not induce change in the ANM, there is still the question of the matrix. If the ANM's flow had not diverged while the matrix is recycled, then it would naturally end up in the new product. Which new product it will be is decided by the chosen recycling process and the quality of the recycled matrix, with the options of open-loop (downcycling<sup>1</sup> or upcycling<sup>2</sup>) or closed-loop recycling<sup>3</sup>.

Sometimes the matrix containing the ANM is not the main material to recover in the recycling process. An example of this would be that the recovery of metals is the focal point in battery recycling and other parts, such as graphite, are secondary. This would mean that this material is undergoing a recycling procedure that is not suited to it; hence, it could either be used in a new product (the same one as the target recycling material or a by-product) or end up as waste from the recycling process. The waste would then have to go back to the EoL stage and iterate in the algorithm. It is not investigated whether the presence of ANM hinders the recycling process itself, only the mass flows of ANM.

### 6.3 Compiling recycling techniques

As mentioned, the EWL/EWC and EU collection and recycling targets served as a basis to look into different recycling techniques. The compilation came from literature review found through search or pointed out during interviews with waste experts present at the Global Methane

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<sup>1</sup> Downcycling recycles materials into products of lower quality or functionality.

<sup>2</sup> Upcycling transforms waste materials into new products of higher value or quality.

<sup>3</sup> Closed-loop recycling reprocesses materials into the same or similar products without degrading quality.

Initiative. *Global methane 2024 Conference*. 20-24 May 2024, Geneva, Switzerland. For more information look into supplementary information section 1.

## 7 Case studies with graphene

### 7.1 Graphene properties

As mentioned, it's important to know where an ANM is placed to know what can alter its flow. But separate characteristics of ANM also need to be noted to know if the process they've been subjected to can alter its fate. Therefore, graphene properties must be stated, specifically answers to the following question:

1. Is the ANM a coating or embedded?
2. What temperatures can the ANM withstand?
3. Which pH can the ANM withstand?
4. Is there anything else that can eliminate the ANM?

As illustrated by Šilhavík M. et al. (2022), graphene is a remarkably stable compound. It exhibits high chemical resistance and high thermal stability also. Depending on which type of graphene is used in the matrix, characteristics can vary to some degree., as shown in Table 2. Note that there are currently newer and improved types of graphene layers being developed that could potentially surpass the ones gathered in the table below, such as covalently cross-linked cellular graphene aerogels can resist flames in air up to 1500 °C for a minute without degrading their structure or properties or meta-doped graphene which can also reach higher temperatures.

*Table 2. Temperature characteristics for different types of graphene*

Type of graphene	Minimum ignition temperature in presence of oxygen	Reference	Minimum decomposition temperature in absence of oxygen	Reference
Single-layer graphene	500°C	(Nan et al., 2013).	Above 800°C	(Fu et al., 2019).
Bilayer graphene	600°C	(Nan et al., 2013).	1257°C	(Hattab et al., 2011).
Graphene oxide	100°C	(Eigler et al., 2014).	195°C to 216°C	(Li et al., 2021).
Multilayered graphene	800°C	(Kahng et al., 2012).		

### 7.2 Case study methodology

The case studies are conducted to show how to use the diagrams shown above and tailor them to a specific material. As mentioned before, graphene is chosen because of its superior characteristics and its expected role in the fulfillment of the energy transition goals of the EU in the time frame of 2025 - 2050. Furthermore, the case studies would link up to the values already predicted by Hong, H., Part, F., & Nowack, B. (2022) regarding the production inflows and market growth up until 2030, after which the values are kept constant.



The scope of these studies only extends to changes in the EoL segment, whilst still considering flows from other life cycle compartments, namely production and manufacturing as identified and calculated by Hong, H., Part, F., & Nowack, B. (2022), with the point of deviation indicated on Figure 3. The point of deviation means that after that point the wiring of the compartments is altered and flows as well as the final sinks will differ.

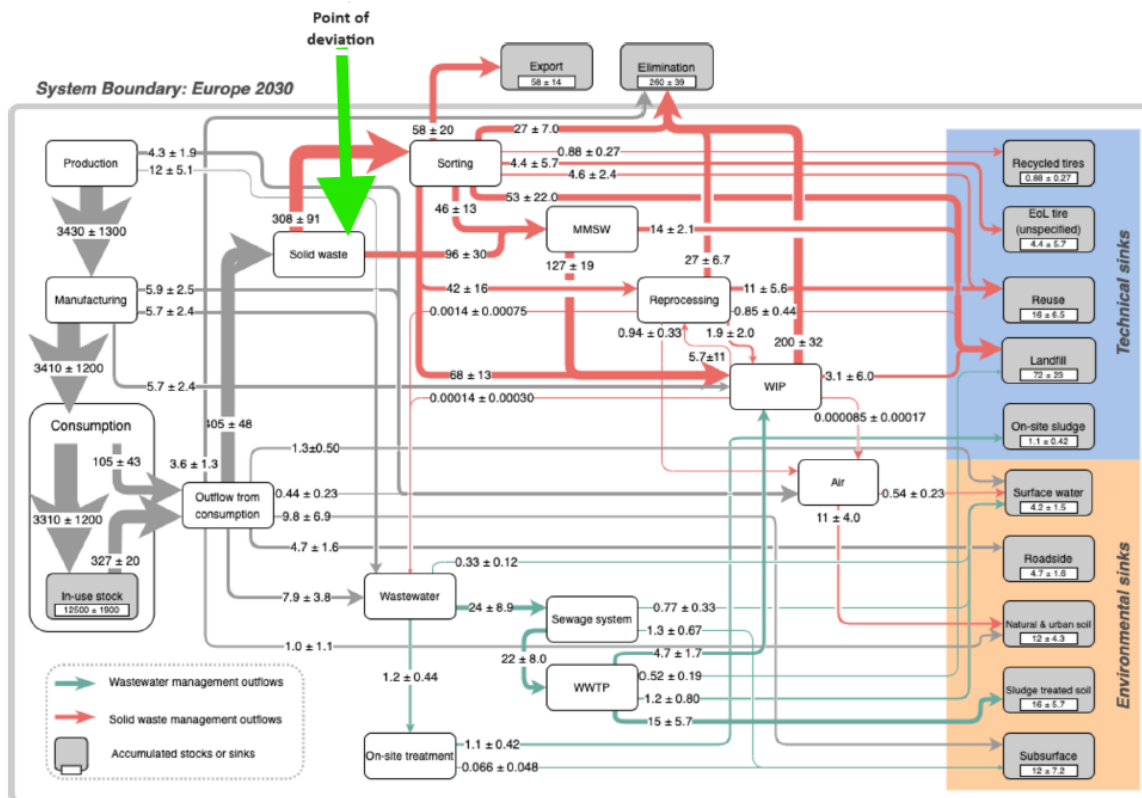


Figure 3. Point of deviation in the model of Hong, H., Part, F., & Nowack, B. (2022) [Source: Hong, H., Part, F., & Nowack, B. (2022)]

For the study of graphene 3 products were chosen to show case the consequences of the material circularity approach:

1. Tires
2. Batteries
3. Concrete

These three are chosen because they can show how products from 3 different segments can intertwine and how an ANM can contaminate other products with the implementation of circularity. The following diagram (Figure 4) shows the connections in the Tire-Battery-Concrete system.

Another point to be mentioned is that due to uncertainty of what is considered in the literature search under the term recycling, sometimes a bigger uncertainty number is given. Often times if waste is exported to be recycled or products were reused it is still considered “recycled” and not all official documents were clear on it, especially if the legislative was left to individual countries.



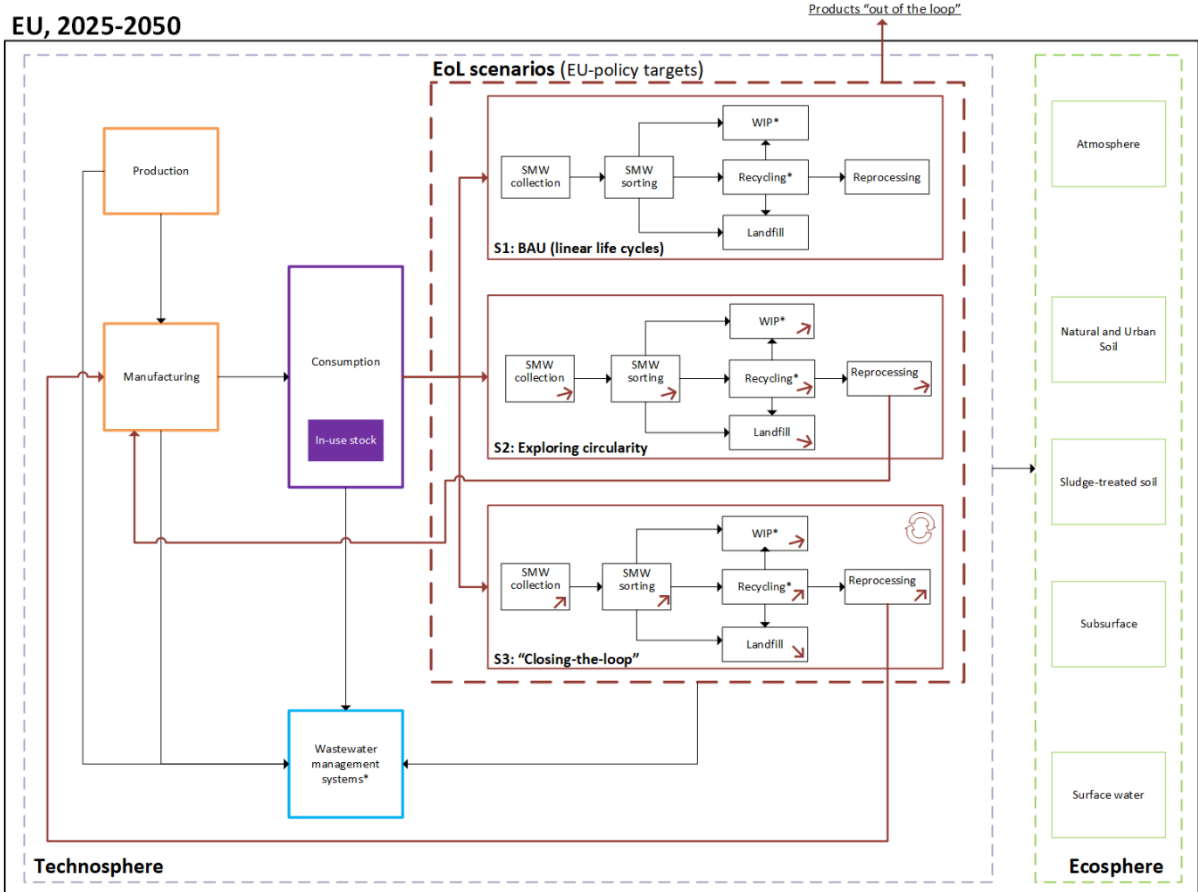


Figure 5. MFA flows and scenarios for graphene

The first, would follow the case of business-as-usual (BAU) as given by data reported on EUROSTAT. This is the most realistic of the scenarios since current information suggests that EU's targets are hard to reach within the temporal interval given. This scenario uses up-to-date achieved collection and recycling rates and their analysed annual growth.

The second scenario, named "Exploring circularity" in Figure 5 follows EU's targets and assumes they will be achieved within the agreed time. The scenario shows dynamic growth until each target is achieved after which it will keep them constant.

Finally, the third scenario of "Closing-the-loop" explores the option of maximum circularity, assuming 100%, which is the real end goal of circular economy. Moreover, for some streams this 100% is already functionally feasible (ex. Glass), while for others it's expected worked towards by both industry and research facilities. In this scenario EU's goals will be achieved within the framework and continue their growth until 100% circularity is achieved. In the case of graphene two main pathways are explored in the EoL stage - the first one being the full circularity of its embedded matrix and the second exploring the option of the circularity of graphene itself. As mentioned in the future pathways, recycling polymeric materials into graphene is an option worth entertaining in the recycling sector.

### 7.2.2 Computing of case studies

The pDPMFA model is computed in Phyton, with defined parameters based on the market and EU's goals with specific geographical and time scopes. It uses transfer coefficients after each step of the process to calculate the movement of the mass by varying them from minimum to

maximum values. Since this MFA is dynamic and prospective, the transfer coefficients have a certain level of uncertainty because of different sources, imperfect or too little information. In this case the probability function is used.

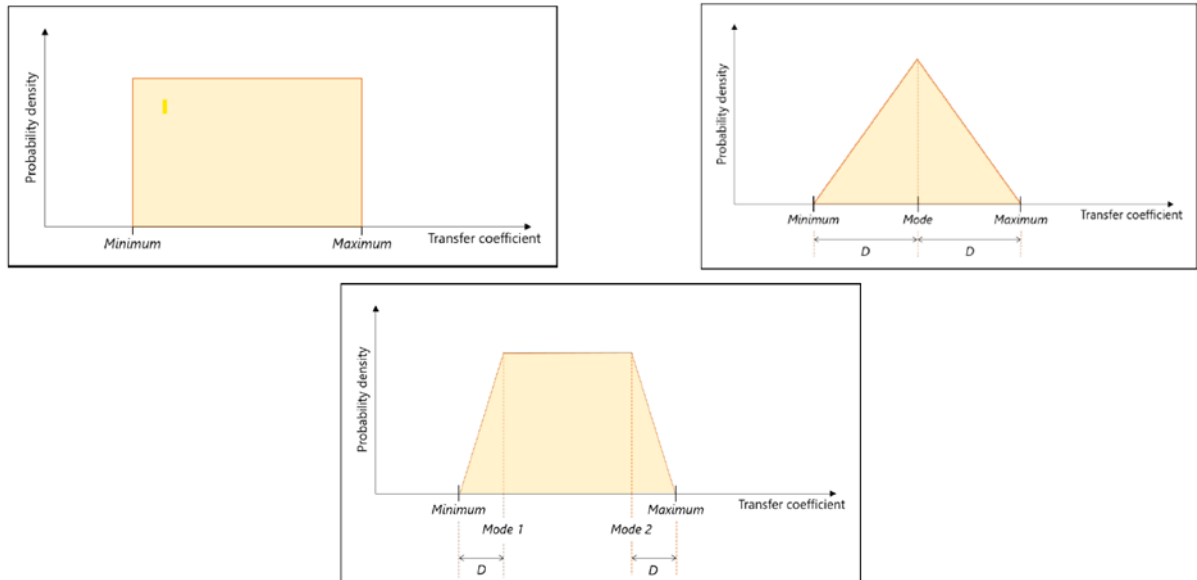


Figure 6. Triangular distribution graph b) Uniform distribution graph c) Trapezoidal distribution graph

Data quality indicator	Score			
	1 - Very good	2 - Good	3 - Poor	4 - Very poor
Geographical correlation	Same region, i.e. Europe	Socioeconomically similar region i.e. European country	Socioeconomically different region i.e. USA	Socioeconomically very different region i.e. world
Temporal correlation	Same period of time	Differs by 1 to 5 years	Differs by 6 to 10 years	Differs by more than 10 years
Scale correlation	Full scale	Pilot scale	Lab scale	-
Material correlation	Same ENM and same bulk material	Different ENM but same bulk material	Same ENM but different bulk material	Different ENM and different bulk material
Technical correlation	Describes the exact process / flow	Includes main processes / flows	Partially includes main processes / flows	Important processes / flows are missing
Source reliability	Official report, peer-reviewed documentation	Market and other reports, database	Qualified estimation	Non-qualified estimation

Figure 7. Ranking of sources for used transfer coefficients

In this way the most likely value is in fact the mode of the triangle. If one value was found for the transfer coefficient then it was placed as a mode while the upper and lower limits were given by the uncertainty of the numbers.

- Triangular Distribution

Triangular distribution was used the most often during the study. It is used when only one value is found for the transfer coefficient then it was placed as a mode while the upper and lower limits were given by the uncertainty of the number (Gottschalk et al., 2010). The uncertainties were calculated by the formulas below:

$$CV_{other} = 1.5 * \exp(1.105 * (Sco_{other} - 1))$$

$$CV_{rel} = 1.5 * \exp(1.105 * Sco_{rel} )$$

$$S_i = 0.0245 * \sqrt{CV_{other}^2 + CV_{rel}^2}$$

$$Min = Mode * (1 - S_i)$$

$$Max = Mode * (1 + S_i)$$

Where:

- $CV_{rel}$  and  $CV_{other}$  are the coefficients of variations of source reliability and other data quality indicators, correspondingly.
- $Soc_{rel}$  and  $Soc_{other}$  represent the score of source reliability, and the score of other data quality indicators, correspondingly.
- $S_i$  is the spread of data i.
- Mode is the collected value of a parameter, and Min (Max) is the left (right) value of a triangular distribution.

- Uniform distribution

Uniform distributions were used only when there was a complete lack of experimental evidence for what happens during a process. Due to no knowledge being available the transfer coefficient is varied from 0 to 1.

- Trapezoidal distribution

Trapezoidal distributions were used when the literature search resulted in two strong values or a range of values with similar data quality. Trapezoidal distribution is in fact one uniform distribution, giving the range and two triangular ones giving the uncertainties. Trapezoidal distribution is calculated by:

$$K = 0.5 * (Mode1 - Min) + (Mode2 - Mode1) + 0.5 * (Max - Mode2)$$

$$leftTD = 0.5 * (Mode1 - Min)/K$$

$$rightTD = 0.5 * (Max - Mode2)/K$$

$$middleUD = (Mode2 - Mode1)/K$$

Where:

- K is the area of the trapezoidal distribution.
- Mode1 and Mode2 are the minimal and maximal values of the two available data points.
- leftTD, rightTD, and middleUD represent the surface fractions of the left triangular distribution, the right triangular distribution, and middle uniform distribution, respectively.
- Min and Max stand for the left value of Mode1 and right value of Mode2, separately.

Moreover, the simulation was done in a Monte Carlo principle which is a computational technique that uses random sampling to estimate statistical properties. A study done by Wang & Ma, 2018 even discusses the supremacy of the Monte Carlo method over other computational methods to be used in MFA studies.

In this way it is possible to model the probability of different outcomes in a process that can't be easily predicted. The simulation was run 10.000 times and included a varying in

### 7.3 Graphene in tires

Looking deeper into the first product, graphene is added to tires to increase wear resistance, rolling resistance, and wet skid resistance, while decreasing hysteretic losses and elongation at break. (Cao et al., 2019). Therefore, it is an attractive additive for most vehicle manufacturers like the automotive industry, bicycle industry and other transport vehicles.

Hong, H., Part, F., & Nowack, B., 2022 found that graphene has been used in tires starting 2015, from where the amount of graphene allocated to this category grows by almost 40% each year., reaching a total of 250 t by 2030. Since no predictions were found for the market further that 2030, the amount reached by 2030 was kept constant in the study until 2050.

Tyres have a life span of 3-5 years, 4 in average, after which they are sent to EoL treatment. To showcase the realistic situation of 2025, data of production from 4 years back since the beginning of the time scope was taken into account, 2021, since this is when these tires will start coming into the recycling stream.

The result from the case study will be a graph, which is an adaptation of the tire graph ( See tire section below) from the tire recycling segment and the decision tree. Processes such as Incineration, Gasification and Co-combustion are grouped in the Elimination segment, while the rest of the Compartments are kept. Furthermore, products of processes which are not very likely to contain graphene have also been excluded from the graph. Examples include pyrolysis gas and liquid fractions, which stand a low chance of containing any graphene. Even so, if some graphene managed to cross over to those products, it would still be eliminated when they are used to produce energy.

The scheme was varied 3 times in regard to its transfer coefficients in order to exhibit the three scenarios mentioned before. The main difference between the 3 schemes is the alteration of the collection and recycling rate, as seen in Table 3.

Table 3. Transfer coefficients show casing collection and recycling rates for tires in 2030

From	To	Transfer coefficient			Reference
		Scenario 1	Scenario 2	Scenario 3	
Use	Improper disposal	0.064	0.05	0	
Use	Collection	0.936	0.95	1	ETRMA, EUROSTAT
Collection	Storage	0.08	0.08	0	EURIC – Mechanical tire recycling fact sheet
Collection	Reuse	0.16	0.16	0.16	Lebreton & Tuma, 2006
Collection	Recycling	0.13/0.36	0.37/0.5	0.84	Czarna-Juszkiewicz D, et al. (2023); ,EuRIC
Collection	Export	0.40	Remainder	0	

Scenario 1, representing the case of Business-as-Usual, was found to have a collection rate of 93.6%. This number was taken from the collection of ELV, since tires fall under this category. This number is also in sync with The European Recycling Industries' Confederation (EuRIC) claim of tire collection values, giving a figure of approximately 90%. It is unclear if truck tires were calculated in this number since CINEA's project Life Green Vulcan (2023) reports that 65% of them go to landfill and only 13% ends up at recycling facilities.

Scenario 2 takes its value again from the EU's targets of collection for ELV's. The recycling rate however was uncertain for the future. It is expected to grow together with the collection rates, and it is expected to grow at the expense of the Export value since various associations like EuRIC and European Tyre and Rubber Manufacturers Association (ETRMA) have been pushing for a ban of rubber Export, claiming that this harms the recycling market.

Scenario 3 assumes a complete circularity, meaning that collection rates and recycling rates both reach 100%. For the recycling rate, reuse is still considered as the material is still returning to the Use phase. This number holds true for all three scenarios and is the only one doing so because it is assumed that the same number of tires are eligible to undergo these procedures.

The rest of the transfer coefficients are related to the dynamic development of the system and are shown in section 7.1 of supplementary information.

## 7.4 Graphene in batteries

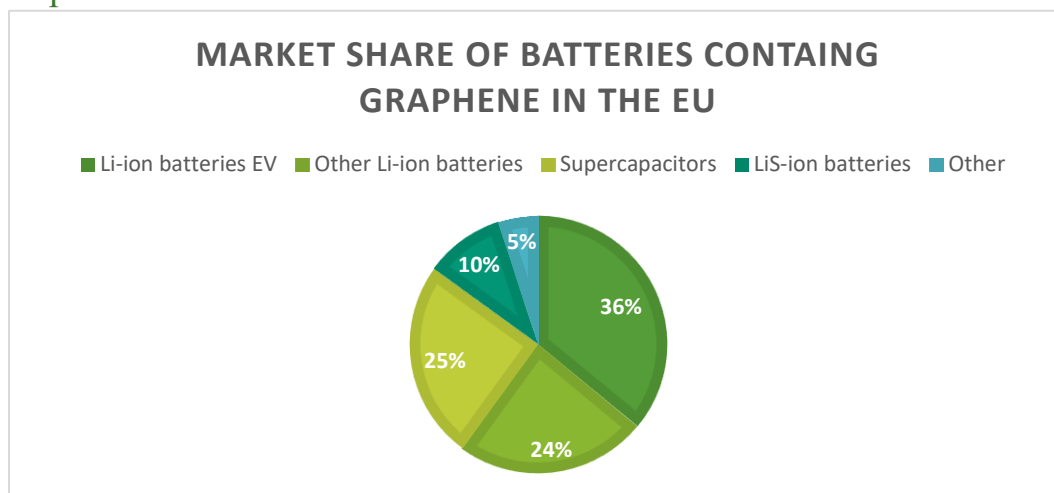


Figure 8. Current market share of battery types containing graphene electrodes in the EU

In order to follow through the recycling techniques, the types of batteries that are eligible to use graphene had to be identified. To understand their dynamic trend and implement it, their market share was also very important (Figure 8). As a way to simplify things, it is assumed that all the mass inflow of graphene stems from electrode material. It is deemed acceptable to do so because it wouldn't change too much of the mass flow and because the values weren't easily obtainable.

Of the batteries mentioned in the figure it is expected that by 2050 the lithium-ion batteries will dominate over others at around 90%. However, this doesn't mean less production of the rest, just very high demand due to the Green Energy Transition goals of the EU, signaling the increase of the market. Figuring out the market shares helped calculate some of the transfer coefficients for the dynamic transition of the flows, since recycling pathways are dedicated to different types of batteries. The market share was calculated by considering current market shares as given by Next Move Strategy Consulting (2023) report on the battery market and eliminating batteries which will not hold graphene electrodes.

The mean time of battery life calculated by market share percentage was calculated at around 7,3 years, however, to stay consistent with Hong, H., Part, F., & Nowack, B. (2022) the lifespan of batteries will be 9 years, and so the retrospective start year will be 2016. This means that the values entering the recycling stream in 2025 will in fact be the amounts produced in 2016.

The scenarios, as presented in Table 4, start off with the assumption that there is no leak of graphene from the batteries during their use. As it is the electrode, chances of emission while in use are very little. In Scenario 1 and Scenario 2 the collection rates are calculated first, and the remainder is assumed to be improperly disposed by the consumer. From the collected batteries a good deal is recycled within the EU, the rest are assumed to be exported for recycling. It is noteworthy to mention that the recycling targets for batteries focus more on recycling efficiency of the processes in regard to specific metals rather than the mass of the battery overall. Moreover, when it comes to batteries from vehicles, the collection rates keep being adapted by adding targets and definitions for different battery types. The newest regulation stepping into power on august 18, 2025 has named the following types of batteries:



- Portable batteries (collection target 63% by 2027 and 73% by 2030)
- Light means of transport batteries (LMT) (collection target 51% by 2028 and 61% by 2031)
- Electric vehicle batteries (EV)
- Industrial batteries
- Starting, lighting and ignition batteries (SLI)

The last 3 categories don't have specific targets; however, they fall under producer responsibility and have to be collected from the users free of charge. As LMT and EV's are new categories starting next year there is no data on the collection so far. Still, an average was taken for collection in 2030 to be at 67%.

*Table 4. Transfer coefficients showcasing collection and recycling rates for batteries in 2030*

From	To	Transfer coefficient			References
		Scenario 1	Scenario 2	Scenario 3	
Battery inflow	Use	1	1	1	Hong, Part, & Nowack, 2022
Use	Improper disposal	Remainder	Remainder	0	Hong, Part, & Nowack, 2022
Use	Collection	0.479	0.67	1	Lizin et al., 2017; Home   White & Case LLP
Collection	Export	0.2/0.3	Remainder	0	Expert opinion
Collection	Recycling	Remainder	0.8	1	Home   White & Case LLP

Lastly for batteries, as seen from Figure 8, batteries are the only product of the three which doesn't produce a contaminated product. That is because it is assumed that carbon material is rarely recovered in these processes even if technological advancement allows for it. Even if they are recovered it is rarely used to make new electrode material, possibly relating to the high requirement for purity from the manufacturers. Because of this, products out of the loop are more probable.

The rest of the transfer coefficients are presented in section 7.2 of supplementary information.

It should be stated that for the simplicity of presentation, techniques such as Repair, Refurbish, Remanufacture and Repurpose have been grouped in the Reuse flow.

## 7.5 Graphene in concrete

Although concrete wasn't modeled in the system due to the material's EoL being out of scope (estimated lifetime is 80 years), its pathway is clear. From Figure 4, it is understandable that most of the construction material waste will either end up being backfilled, be eliminated or will have a circular path and come back to the same use.

## 8 Results

### 8.1 Hazardous waste

Hazardous waste in the European Union (EU) is defined as waste that exhibits one or more of the dangerous properties listed in Annex III of the Waste Framework Directive. These

properties, categorized into physical hazards, environmental risks, and health-related dangers, necessitate specific treatment and disposal protocols to minimize their harmful impacts.

The first hurdle to overcome when speaking about hazardous waste is its collection. To regulate this, the EU has implemented several directives and regulations. From 2030, Member States will be required to limit the landfilling of all waste, including hazardous waste, that is suitable for recycling. Additionally, by 2025, the EU will require the separate collection of hazardous waste produced by households, which is expected to improve the management and traceability of such waste. That being said, the EU hasn't set targets for the collection of all hazardous waste types, only for batteries, ELVs and WEEEs, which unsurprisingly leads to them being the most recycled hazardous wastes standing at 90% (2018). The EU also mandates that hazardous waste must be collected separately from other waste and no two hazardous wastes should be mixed (since 1991), to prevent the forming of another hazardous substance while they are stored. Even so, an EU study done in 2017 found that very little inspection was done to understand if the Member states have been adhering to this or not.

To achieve collection, traceability of waste is important. To be able to do so, classification and reporting must be done by each economic operator. Economic operators must classify their waste using the European List of Waste, which distinguishes between absolute non-hazardous entries, absolute hazardous entries, and mirror entries that require further assessment to determine their hazard level. Since half of the EWL are mirror entries there have been some problems and criminal activities have resulted from this because of unintentionally wrong classification of the wastes. This also complicates reporting data since it is left on the judgment of the report-maker, and when two groups like the manufacturers and the recyclers report on the same materials differently there is inconsistency in the numbers. In fact, EU data indicates that 21% of hazardous waste remains unaccounted for during treatment. Other than wrong classification, this could be explained by the varying period by which the product becomes waste, imports and exports or even illegal dumping.

As a result, the EU imposed strict rules on the shipment of hazardous waste. Other than the country of origin, the waste can also be shipped to other Member States or outside the EU, but only to affirmed countries for recycling or recovery. For disposal, shipments outside the EU are limited to European Free Trade Association (EFTA) countries. Additionally, the EU imports hazardous waste from non-EU countries, further complicating the management and regulation of hazardous waste streams. The EU also plans to set up an electronic register for hazardous waste shipments, to improve trackability of the wastes. Still there is a lot of illegal trafficking of hazardous waste, where operators falsely classify hazardous waste (ex. Stating WEEE as a second-hand product or forging a laboratory test with misleading proof about a non-hazardous substance) as non-hazardous or mix it with other waste to avoid detection or dilute its concentration, further complicates the safe management of hazardous waste. This illegal activity often results in the unsafe disposal or export of hazardous waste, both within and outside the EU.

The treatment hierarchy for hazardous waste prioritizes reuse, followed by recycling, energy recovery, and, as a last resort, disposal. Naturally, the treatment will be dependent on the nature of the waste, treatment possibilities and the economic factor. Nevertheless, data reveals that more than half of the hazardous waste generated in the EU is disposed of, with only 34% being reused or recycled and also a lot of the waste incinerated isn't used for energy recovery. Moreover, the waste remaining after incineration is disposed of in landfills by default. This

discrepancy underscores the need for improved recycling practices and facilities. Besides the efforts of the EU to recycle hazardous waste, certain hazardous waste streams remain difficult or uneconomical to recycle, such as glass contaminated from fluorescent lamps with hazardous substances. Although the EU has invested in developing new recycling technologies through initiatives like Horizon 2020 and LIFE, these innovations have yet to reach industrial scale. Other hazardous waste streams, like plastics and textiles containing persistent organic pollutants and heavy metals, require decontamination before recycling. However, recent studies have found that even after decontamination, recycled materials often still contain hazardous substances. This issue is exacerbated by the lack of information available to recyclers about the chemical composition of the waste they treat and by improper waste management practices. Some of this will be mitigated by applying the digital passport to products containing hazardous waste, however that has only been applied for batteries and WEEE.

## 8.2 Construction and demolition waste (CDW)

The waste generated as a result of demolishing old structures or as a result of construction of the structures is generally known as construction and demolition waste. Waste generated from the demolishing of old structures, as adapted from Buller A.H. et al., 2020 are categorized and in the following way:

- Metals: Aluminum siding; Gas pipe/Metal pipe; Steel: structural or rebar
- Ceramics: Asphalt; Wallboard/Drywall (gypsum); Marble/tile pieces; Brick/Masonry blocks; Porcelain plumbing fixtures; Concrete blocks; Mortar
- Polymers: PVC pipe
- Wood, cardboard/paper: Doors and windows wood
- Glass: Insulating glass wool, flat glass

To start explaining the material flows, one would have to look into the waste management decisions, meaning, who collects the waste and where it is taken. The recovery rate of construction and demolition waste (CDW) in the European Union (EU-27) stood at 88 percent in 2020 (EUROSTAT). That year, Malta and Greece achieved a recovery rate of 100 percent, followed closely by the Netherlands, at some 99.7 percent. Meanwhile, Finland only recovered around 61 percent of its construction and demolition waste, resulting in the lowest recovery rate for CDW across the European Union. This is already higher than the EU's goal to achieve at least 70% collection of C&D waste in terms of weight, as stated in the Waste Framework Directive (WFD) 2008/98/EC (European Parliament and the Council 11/19/2008).

However, a paper written by Moschen-Schimek J. et al., 2023 suggests that even though EU-wide guiding documents have been prepared and such national quality reports have to be delivered, data on recovery rates published by EUROSTAT are still subject to diverse limitations that impede the transparency and a reliable comparison of recovery rates across the EU. The paper continues to argue that a lot of the mass reported as accordingly treated is backfilled. Unlike countries like Germany (Menegaki M. and Damigos D., 2018), which requires CDW sorting, and Spain with well-defined roles for all actors concerned in CDW management, low recycling holds up mostly for countries with more lenient legislative on waste management, where countries such as Greece and Malta fall under. Therefore, it can be confirmed that much of the waste that is collected will not enter the recycling stream.

Further, Sormunen P. and Kärki T., 2019 claim that CDW is among the largest in the EU, estimated to be 25–30% of all generated wastes, and pointed out that the current recycling rate only approximates 46%. Within the EU's framework, it was also decided to promote selective demolition to enable removal and safe handling of hazardous substances (mostly found in insulation materials, paints, and electrical equipment) and facilitate re-use and high-quality recycling by selective removal of materials and establishing sorting systems as explained in Directive 2008/98/EC of the European Parliament, supporting the flows as represented in Figure 9.

The outset of the flows begins with the collection of the construction or demolition waste. There is an option for on-site treatment or on-site selection of materials, which would be divided mainly into streams of: cardboard, masonry, metal, wood, and flat glass. In fact, on-site selection is mandatory in the UK. Otherwise, these materials would be sent to one recycling stream, for example, metal, where they would be divided and then sent or sold to the proper recycler company for that type of waste.

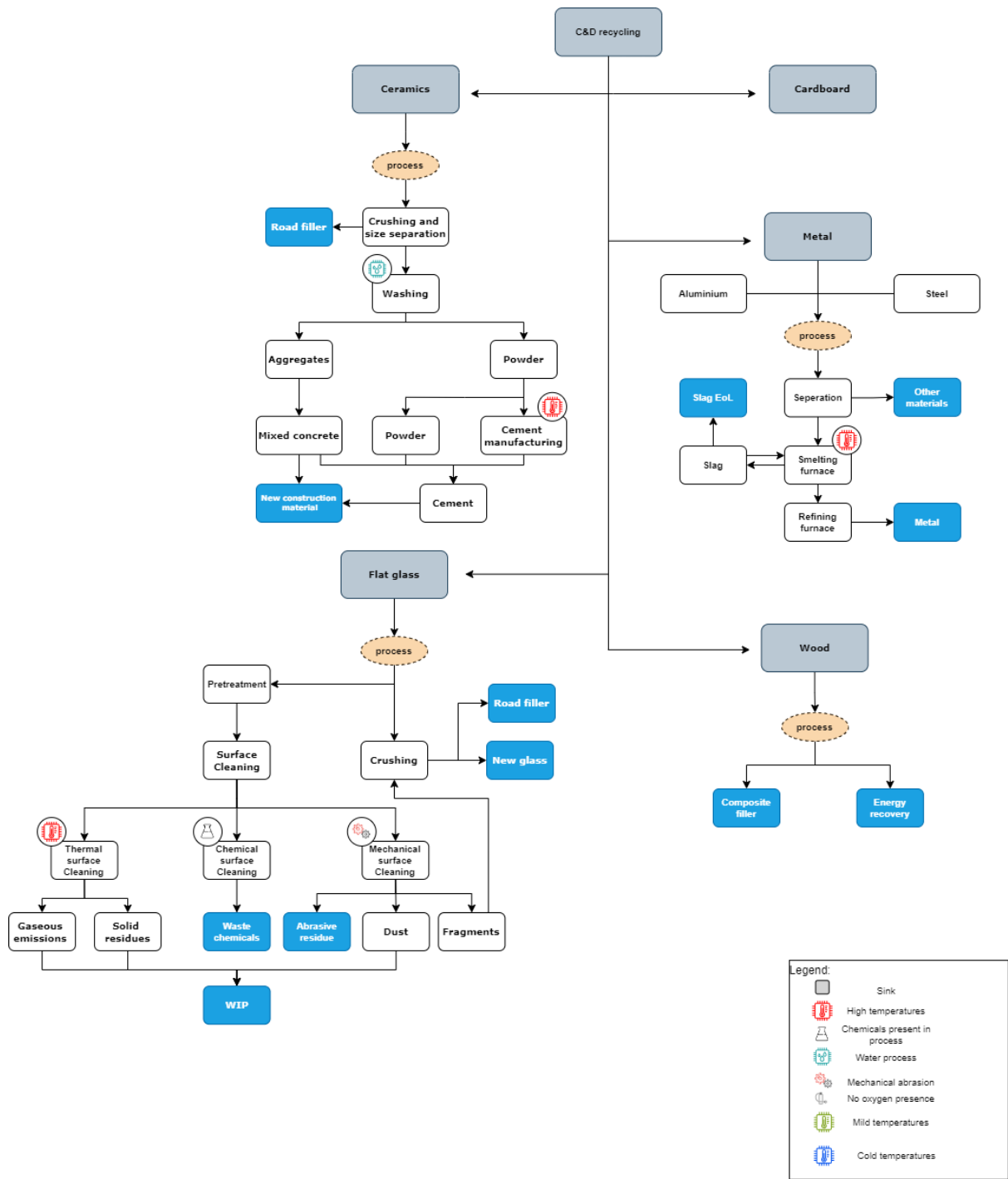


Figure 9. Construction and demolition waste flows in recycling streams

### 8.3 Ceramics

Masonry is described as either the craft or material of building and fabricating in stone, clay, brick, or concrete block, reinforced or unreinforced (Britanica T. Editors of Encyclopedia (2024, August 1)). Generally, most ceramic materials, also referred to as mineral waste, used in the construction industry can be considered in this category, since their treatment in the end-of-life will be very similar. Additionally, most ceramic materials that end up in the recycling streams come from C&D waste also, while the second biggest contributor is ceramic industrial waste.

Once the material has entered a proper recycling stream it could be downcycled as filler or recycled into a new construction material. Regardless of the end product, the first step is always size reduction and size separation. If material selection didn't occur on-site, then a selection step is needed as well. After these steps the resulting mass will be mostly mineral waste divided in aggregates (coarse fraction >5mm) and powder (fine fraction 5mm >) (Bashir et al., 2022). The aggregates are an important filling for roads and even in concrete. They are also preferred by the recycling community as they require little processing. It can be discussed that if the material is used for road filling, there is no need for size separation and even minimal material separation as everything can be used.

If the material is intended to fulfill the circular economy principles and be recycled as new concrete or cement, it could be subjected to a washing step in order to remove any unwanted substances, such as paints or left over materials from the material selection stage. If an advanced material was used in the paints or coatings of the construction material it would be removed in this step and would continue a different path. However, this step is not always employed or the washed-out impurities are treated as waste.

From there, the aggregates are usually used into mixed concrete instead of or more usually with sand. The powder, however, can be used in new cement manufacturing, soil stabilizer in cement or even be used as abrasives depending on the purity level. Newer studies are trying to also repurpose the mineral waste as hazardous chemical absorbents, as explained by Pallewatta S. et al., 2023, since they have excellent absorption properties, however since there is no confirmation from industry that this is being done on a large scale it wasn't considered for the model.

If the powder is directed to new cement manufacturing, it would be mixed with raw material and will be placed in a clinker at temperatures of 2000°C (so that the material itself could reach up to 1,450°C) (Bouchenafa O. et al. 2022). This has big potential of altering an advanced material embedded or coated on top. Even if powder is not always utilized into new cement, it is a good alternative for the cement industry since emissions and price of waste material is a lot less than sand mining and is in line with EU's requirements and was therefore included in the scheme.

Nonetheless, using these materials might decrease cement and concrete quality such as the case of higher liquid absorption, especially if there is no or minimal raw material input. As summed up by Ginga C.P. et al., 2020, the recovered coarse fraction is highly porous compared to natural aggregates, meaning that water absorption is at least 6 times higher and 19% less dense as the virgin counterpart, which limits the mass of recycled aggregates that can be used in a new material. A possible mitigation measure is the addition of more new cement. A new study done by Skocek, J. et al., 2024 suggests that the recycled material could be comparable to virgin ones if the adhered cement paste is removed with forced carbonation. Once and if this is used in the industry the cement recycling potential would certainly increase. This would also be a significant process if an advanced material is present. On the other hand, as many companies and researchers are orienting themselves to eco-design, the problem of cement becoming absorptive could be solved with additional advanced material from its production/manufacturing stage.

## 8.4 Glass

The glass found from CDW is not like packaging glass but in fact a composite usually referred to as laminated, sheet or flat glass. This type of glass is prevalent in the automotive, architectural and photovoltaics industry.

As stated by Hooper J., 1973, Laminated architectural glass refers to a type of safety glass that consists of two or more layers of glass bonded together with an interlayer, typically made of polyvinyl butyral (PVB) or ethylene-vinyl acetate (EVA). This interlayer holds the layers of glass together even when shattered, preventing the glass from breaking into large, sharp pieces. Laminated glass is commonly used in applications where safety, security, and sound insulation are important, such as in windows, doors, skylights, and facades in buildings. Additional layers or materials can be adjoined to obtain other additional benefits such as UV protection, improved acoustic insulation, decoration and enhanced resistance to forced entry.

Because it is a composite, this glass is not used to manufacture new glass but rather used in composites or landfilled, once sorted from the rest of the materials and reduced in size. Coarser fractions are often used as a filler material in concrete composites or in the production of glass-reinforced plastics (fiberglass). Glass powder or finer fractions can also be used in composites or as abrasives, although it requires energy-intensive processing to remove contaminants and ensure quality. The fine fraction is not used in concrete because of unforeseen interactions, such as the severity of Alkali-silica reaction (ASR) expansions or the effect of colored glass on the concrete. (Mohajerani A. et al., 2017)

There is a possibility to clean the CDW glass via different delaminating techniques to clean the surface of both sides of the glass, though for now this is considered vastly uneconomical. Nonetheless, the delamination techniques as given by Šooš, E. et al., 2021 are divided in:

- Mechanical separation methods

- Thermal separation methods
- Chemical separation methods
- Combined methods

Mechanical cleaning methods include innovative technologies such as the crusher developed by Donico Inter Co., Ltd. In Tokyo, that can selectively crush only the layers of glass without damaging the interlayer, after which depending on the purity of the glass it can be used like other recycled glass cullet (refer to packaging waste, glass section) (Rosenthal, J (1998)). Alternately, the complete flat glass can be broken down to small pieces and then sorting would take place. This method is more common but high purity is difficult to achieve and much dust is produced.

Thermal methods, as described by Popa CL. et al., 2018 involve applying heat to reduce the adhesion between the glass and interlayer, making it easier to separate them. This method involves heating the laminated glass and quick cooling at temperatures down to -25°C, which aids in breaking the adhesive bond. Cooling can be done with a solution of methanol and distilled water to further break the bonds.

Chemical methods involve using specific chemicals, solutions like CaCl<sub>2</sub> (calcium chloride) heated to around 60°C to weaken or dissolve the adhesive properties of the interlayer film, allowing for easier separation. Further, the method of chemical etching (Çakır, O., 2008) is put in practice when surface cleaning needs to be done to the glass. Etchant choice depends on the target material being etched. Chemical methods are often combined with other methods to improve the effectiveness of separation.

Combined methods integrate mechanical, thermodynamic, and chemical processes to achieve higher efficiency in the separation process. These methods aim to overcome the limitations of individual approaches and improve the purity of the recycled materials. The Danish company Shark Solution A/S also successfully undertakes mechanical recycling, and their patented technology produces ground glass with a particle size of 0–5 mm containing less than 1% contaminated materials and films, allowing it to be deployed in high-performance applications

## 8.5 Metals

The main metals found in CDW are steel and aluminum both of which are relatively easy to separate from the rest and treated pyrometallurgically.

### 8.5.1 Aluminum (Al)

Aluminum metal or alloys recycling creates massively smaller emissions than its primary production from ores, with up to 95% difference between the two. There are two main ways to go about recycling Al:

- Direct refining (open loop recycling)
- Remelting (closed loop recycling)



Direct refining produces casting alloys and deoxidizes Al from scraps of different compositions. Alloying elements are also added into the mix and impurities can be removed after the melting process depending on customer requirements.

Remelting on the other hand, produces wrought alloys (Polmear, I. J, 2017) in the form of extrusion billets or rolling ingots from previously cleaned and sorted Al-scrap. This approach is mainly used for the Al coming from window frames. To clean the Al-scrap other than different sorting techniques, there can also be a de-coating line. Main issues in the melting process is the possible formation of the very stable aluminium oxide, which is why oxygen levels and temperatures (have to be above 800°C) have to be controlled. There are also 2 types of furnaces that can be used for this process fuel-heated and electrically-heater furnaces. The fuel-heated ones are more common and work with worse scrap quality while electrically heated furnaces are preferred for higher quality recycling since they do not produce flue gas and limit oxidation. Further, there is more separation in types of furnaces which dictate the amount of material loss for each batch.

Interestingly, in the process of aluminum recycling salt fluxes are added to take up contaminants contained in the scrap like oxides, nitrides, carbides etc. These salts might also eliminate an ANM if one with a similar composition is added. This in turn creates a so-called salt slag, which still contains some aluminum. The Al can continue to react with air and produce its oxide in an exothermic reaction. To stop this there are presses that can be used for the slag to recover more of the Al.

There is usually a side process to clean the salt slag since it can't be landfilled due to pollution of ground water. The slag reacts with water and produces gaseous emissions which can be explosive and poisonous. Therefore, the slag is reduced in size, sieved and water is added, which achieved a leaching effect paired with gas neutralization. The composition then goes through Bruin filtration and finally the water is evaporated to be left with crystalizing salt.

Other products include gaseous emissions, filter dust and contaminated water. Results from slag treatment are Al, salt and oxides (impurities).

### 8.5.2 Steel

Steel from this application follows a similar route to Al, however no salts are added to create slag. Still, this material contains other metals that require further removal. Steel scrap primarily comes from ELV's, and other transport vehicles and it will thus be discussed in further detail in those sections.

## 8.6 Wood, paper & plastic

Carbon-based materials like wood, cardboard and paper tend to not be recycled when coming form CDW and are rather used for energy recovery. If recycled, there is a possibility for them to be formed into composites and used in the construction industry again.

Wood fibers from construction and demolition waste are used as reinforcement in wood-plastic composites (WPCs). They are ground and added to a polymer resin. These composites are typically used in decking, wall panels, and other building products. The primary challenge with using recycled wood fibers is their hydrophilic nature, which can weaken the bond with the thermoplastic matrix.

Recycled paper fibers are also incorporated into composites for applications like particle boards and acoustic panels. However, the mechanical properties of these composites are often inferior compared to those made with wood fibers, due to issues like fiber property loss during recycling and poor bonding with the matrix.

Recycled thermoplastics, like PVC, are used as matrix materials in composite manufacturing. They are processed through extrusion, molding, or casting. However, the properties of recycled thermoplastics can be degraded due to prior exposure to environmental conditions and contaminants. Despite this, they are often used in products like plastic lumber and molded items.

Less frequently they are also recycled in their proper streams. Paper as well as plastic, as its more interesting for packaging waste, will be further discussed in that section.

## 8.7 Packaging waste

Packaging waste has been ruled through Council Directive 94/62 since 1994, also referred to as the Packaging and Packaging Waste (P&PW) Directive. The directive prioritizes waste prevention while recycling, recovery, and reuse follow. Directive follow ups state that, among other rules, by end of 2024, EU countries should ensure that producer responsibility<sup>[1]</sup> schemes are established for all packaging wastes. Presently, the EU has set targets for the most common materials, as presented in Table 5. The materials have also been clearly branded according to their composition when a single material is used. Each category will be talked about separately, as represented in the table.

Table 5. Targets for packaging waste collection (Source:)

	Current targets (%)	By 2025 (%)	By 2030 (%)
All packaging	55	65	70
Plastic	25	50	55
Wood	15	25	30
Ferrous metals	50 (incl. Al)	70	80
Aluminum	-	50	60
Glass	60	70	75
Paper and cardboard	60	75	85

### 8.8 Ferrous metals and non-ferrous metals

The recycling of ferrous and non-ferrous metals, including sorting, has already been discussed in other chapters, such as WEEE, ELV, and CWD. The process of packaging waste has little to no difference with those as well. Metals in packaging, mainly aluminum and steel, are used to make food and beverage cans for storage. They are easily separated from the rest of the rest even if mixed waste is delivered, especially the steel cans. Further, as there are reported magnesium losses in ELV, the same pattern repeats here as Mg melt losses associated with Al packaging recycling are 1/3. Loss of materials is greatly dependent on the type of furnace, for all metals.

### 8.9 Plastic

Often, the plastic received from municipal disposal spots is mixed. Due to the different processing properties, each plastic type must be sorted first before recycling based on shape, density, size, color, or chemical composition. Therefore, in addition to the general sorting and separation methods mentioned in the WEEE chapter, there are multiple other choices, like air sorting, flotation and froth flotation, melt filtration, NIR, and X-ray sorting, as suggested by Ding Q. and Heping Z., 2023). Sorting is almost always correlated to losses, which typically arise due to impurities in the input waste streams and limitations in the sorting technologies used. These processes sometimes fail to adequately separate target materials from contaminants, rejecting both target and non-target materials from the recycling stream. In some cases, technical limitations like insufficient sorting precision or narrow conveyor belts can lead to significant losses. Specific numbers have been reported by Antonopoulos I. et al., 2021 as:

- PET sorting loss of 3-55%
- HDPE sorting loss of 5-25%
- PP sorting loss of 20-69%

- LDPE/PE sorting loss of 11-45%

Air sorting involves feeding mixed plastic flakes vertically into an air stream, where light and heavy fragments are separated based on specific gravity. Froth floatation utilizes differences in plastic densities by placing a gradient of liquids, gradually increasing the density. Melt filtration removes non-melting contaminants by filtering the molten polymer at mild temperatures through a mesh. Critical parameters include filter mesh size and melt pressure, which must be controlled to prevent clogging. Lastly, NIR identifies plastics based on their spectral reflection, while X-rays detect specific elements like chlorine in PVC.

After sorting, a vast number of treatments are available for plastic recycling. However, they can mainly be divided into 4 main ways to recycle plastics recovered from packaging:

1. Primary –physical recycling
2. Secondary –mechanical recycling
3. Tertiary – chemical recycling
4. Quarterly – energy recovery

All of these have subcategories of methods that can be used for polymer recycling, most of which are shown in Figure 10, along with other flows related to packaging waste.

Primary recycling processes focus on recovering and reprocessing pre-consumer or pure polymers, allowing them to be reused for the same purpose. Secondary recycling processes involve post-consumer polymeric waste, which is sorted, cleaned, and re-extruded. However, this results in a product with diminished physical and mechanical properties compared to the original polymer, often making it unsuitable for the same application. Both primary and secondary recycling are physical processes that can be repeated multiple times. Tertiary recycling involves chemical processes applied to polymers that can no longer be recycled mechanically, while quaternary recycling is used for energy recovery. When polymers and plastics are sent to landfill, they lose their value and become waste, marking the end of their lifecycle.

Primary recycling, as the most common, cheapest, and simplest technology for plastic recycling, mechanical recycling includes collection and sorting, washing and drying, grinding, melting, and extrusion or other types of forming and modelling of thermoplastics. This is done mostly for the marked and distinguishable polymer, such as PET, PP, HDPE, LDPE, PVC, and PS. For Polyethylene Terephthalate (PET), the recycling temperature typically ranges from 250-280°C. Compatibilizers, stabilizers and chain-extenders are often needed when PET is blended with other polymers to maintain quality. Polypropylene (PP) is recycled at temperatures between 230-250°C, with the addition of antioxidants to prevent degradation. High-Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE) are recycled at temperatures ranging from 180-230°C. Antioxidants are added to prevent oxidative degradation, and these polymers are often recycled into bags and pipes. Polyvinyl Chloride (PVC) is recycled at 160-210°C, with heat stabilizers being essential due to its sensitivity to thermal degradation. Recycled PVC is used in films, trays, and piping, but its recycling process is complicated by releasing hazardous HCl gas, necessitating strict process controls. This is also why PVC is highly spurned when it comes to chemical recycling. It is possible to recycle only if a dehydrochlorination or dichlorination step is included. These can be performed via thermal degradation or wet treatments. Lastly, Polystyrene (PS) is recycled at temperatures between 190-240°C, often requiring compatibilizers or stabilizers to maintain mechanical

integrity. Much like the others, PS also has limited amounts of recyclable cycles it can take before the quality drastically deteriorates.

One division of secondary mechanical recycling separates filling modification, blending modification, and compatibilization, depending on the types of additives that need to be included in the process to make the plastic in the best shape possible and mitigate degrading mechanisms which leads to the direct use of recycled materials.

The tertiary group of methods, also known as chemical or resource recovery, hold significant promise in the circular economy of plastics by potentially closing the loop through the production of starting monomers from polymers, which can then be reprocessed to create high-value-added chemicals. This process can yield four different products: refined feedstock, fuel, monomers, and value-added chemicals. Projections suggest that by 2050, nearly 60% of plastic production could be based on recycled materials. To achieve this, millions of euros are being invested in enhancing chemical recycling and other advanced technological solutions, with the goal of producing 1.2 million tonnes of recycled plastic in the EU by 2025 and 3.4 million tonnes by 2030. However, currently many chemical processes are still related to high costs.

Chemical recycling methods are categorized based on reaction conditions into solvolysis (including hydrolysis, methanolysis, and glycolysis), catalytic depolymerization, and enzymatic depolymerization. Among these, hydrolysis reactions are environmentally preferable but demand higher energy consumption compared to other solvolysis techniques. Hydrolysis can be performed under neutral, acidic, or alkaline conditions; however, acid and alkaline solvolysis currently require an excessive amount of chemicals, making them less environmentally sustainable.

Plastic depolymerization can also be catalyzed by various substances, such as strong mineral acids, bases, organocatalysts, enzymes, and metal catalysts, which can operate in either homogeneous (e.g., hydrogenolysis) or heterogeneous phases. Another technique is hydrosilylation, which involves the use of silanes like tetramethyldisiloxane and polymethylhydrosiloxane, alongside borane or iridium catalysts.

Additionally, tertiary recycling methods such as pyrolysis, incineration, and other previously reviewed processes are employed. Another important method is hydrocracking, a catalytic refining process used to selectively recover valuable chemical fractions ranging from heavy diesel to light naphtha. Hydrocracking requires a bifunctional catalyst with an acidic function, which enhances cracking activity, typically provided by a high-surface-area support like zeolite.

The overall recycling rate loss (after sorting and processing) is estimated to be around 20% to 30% for PET and HDPE. For PP and PS, the losses can be even higher, reaching up to 50% (a loss).

Finally, it should be said that waste polymers are also a good feed material for graphene and hydrogen production by flash recycling which is the rapid heating and cooling of the material in the absence of oxygen. However, the polymers coming from packaging are already mostly recyclable, and this technology might find itself more useful with plastics from other sources.

## 8.10 Wood

Recycling of packaging wood involves several processes that aim to recover materials and repurpose them for new uses, thereby reducing waste and conserving resources. Wood waste, as mentioned in CWD, is mainly recycled for energy. However, it is also possible to recover material through cascading recycling, forming composites with plastics, and hydrothermal recycling. The latter holds great potential to damage the wood, which is why it isn't utilized. Wood cascading as explained by Szichta P. et al., 2022 refers to the practice of using wood materials in multiple, sequential applications to maximize their value before they are ultimately discarded or used for energy recovery. In a typical cascading sequence, wood might first be used in a high-value product, such as furniture or construction materials. After the product reaches the end of its useful life, the wood is then recycled into lower-value products, such as particleboard or paper. Finally, when the wood can no longer be reused or recycled, it may be used as a source of bioenergy.

## 8.11 Paper and cardboard

Paper comes from various sources, including households, offices, and industries, all of which differ from each other and might require different recycling. There are multiple methods to classify collected waste paper products. In Europe, recovered paper is primarily classified according to the European List of Standard Grades of Recovered Paper and Board (EN 643), which includes 67 grades divided into five classes. The most significant grades, in terms of quantity, are sorted mixed papers and boards, supermarket corrugated paper and board, and lastly, sorted graphic paper for deinking. Additionally, for statistical and commercial purposes, recovered paper is often categorized into four main groups - mixed grades (mixed paper and boards), OCC (old, corrugated containers), ONP & OMG (old newspapers and magazines), and HG & PS (high-grade deinking and pulp substitutes). For simplicity the paper products that can be recycled or obtained from recycling can be divided into:

1. Packaging paper (case materials, carton board, wrapping papers, and other packaging papers),
2. Graphic paper (newsprint and other graphic papers),
3. Tissue paper (household and sanitary),
4. Paper for technical and other purposes.

Out of these, the most fibrous materials and, therefore, the best to recycle are the first two categories. Both packaging and graphic paper can be used to make packaging paper again; however, recycled graphic or tissue paper can only be acquired from virgin graphic paper or higher grades. The product most often obtained from recycled paper is graphic paper. These paper grades often have less demanding optical requirements and shorter product lifespans. High strength and brightness levels, or low ash content, cannot be achieved with recovered paper, limiting its use in hygiene paper. Further, when high brightness, strength, or softness is required, the use of recovered paper is limited. Packaging paper is often made entirely from recovered paper, because it has the lowest feedstock requirements. Additionally, other sources can be used to make paper, such as the above-mentioned waste wood source.

The production of paper from recovered fibers is largely the same as producing virgin cellulose fibers and includes the main steps of pulping, de-inking and refining. The main difference lies in the pre-treatment or preparation of the material to remove impurities. Cleaning can be done

via pulping, mechanical processes like washing, screening, and suspension, some chemical and thermal treatments, and de-inking.

### 8.11.1 Pulping

"Re-pulping" refers to processing recovered fibers, which involves dissolving recovered paper in water for further treatment. The paper is fed into a pulping machine, where it is mixed with water and chemicals to break it down into fibers. This mixture, known as pulp, resembles a thick slurry. The process is conducted under alkaline conditions with a pH of 8–10, using reactors (pulpers) of various sizes and capacities aimed at defiberizing and achieving a specific pulp consistency. The pulping process also helps separate non-fibrous materials like staples and adhesives from the paper. The fibrous raw material, recovered paper, contains various other substances introduced during the paper's production (such as printing inks, adhesives, and mineral particles) or accumulated during its use and collection (such as scraps, sand, and glass). As a result, when producing new paper from recovered paper, the pulp must undergo a thorough cleaning, regardless of the final product it will become. The use of recovered paper for graphic paper production is more costly than for packaging paper because it requires more intensive treatment of the raw material. Cardboard requires a more intense pulping process due to its thicker and more robust structure, often using high-consistency pulping.

### 8.11.2 Screening and Cleaning

Mechanical cleaning is further enhanced through washing, screening, and suspension processes, which utilize differences in size, density, and surface properties. Screening means passing the pulp through screens to remove larger contaminants such as plastic pieces, glue, and other non-fibrous materials. The screens can be perforated or slotted to filter out particles based on size and shape. Following screening, the pulp undergoes centrifugal cleaning. This process uses centrifugal forces to separate heavier contaminants like metal, sand, and glass from the lighter pulp fibers. The combination of screening and cleaning ensures that the pulp is free from impurities that could affect the quality of the final product.

During this step, a fraction of useful pulp is either rejected because of its lower quality or removed unintentionally with other fractions. This is estimated to be about 25% of the input material. There have been efforts to salvage that fraction by converting it into other natural products, such as levulinic acid, fermenting it into biohydrogen or anaerobic digestion for conversion into bioethanol. Otherwise, this fraction will be used for energy recovery.

### 8.11.3 Deinking

Deinking is not a necessary step, other than for graphic papers. This step removes ink from the paper fibers to improve the brightness and quality of the recycled paper but is mainly done for esthetic purposes. It must be noted that although de-inking doesn't whiten unbleached fibers, and if a whiter product is desired then a bleaching step will take place.

Flotation deinking is the most common method used, where air bubbles are introduced into the pulp. In this process, air is introduced into the paper pulp in the presence of surface-active agents, creating "flotation bubbles" that trap ink and pigment particles ranging from 20–100  $\mu\text{m}$ , along with fragments of fibers and other additives. The resulting foam is then skimmed off. However, this technique is less effective for very fine ink particles, around 1  $\mu\text{m}$ , which are produced when inks containing alkaline-soluble components break down. In such cases, an additional washing cycle may be needed. Conversely, coarse particles from cross-linked inks

or varnishes, such as those used in ultraviolet cross-linking technology, may be too heavy to float, requiring dispersion before re-submission to the flotation process.

Washing involves passing the pulp through multiple stages to achieve the desired cleanliness and brightness. It effectively removes fillers, fine ink particles, and other colloidal materials. Although it offers high cleaning efficiency, it requires significant water use, which increases costs and leads to considerable fiber loss due to the mechanical action of the water. Not all inks can be well removed. Older types of inks are easily dealt with; however, no proper process has been found for newer water-based flexography or non-impact printing inks (inkjet or toner-based inks). Preferably, papers containing these substances should be treated separately than the rest so as not to lower the quality and because different deinking mediums should be used. Packaging paper and cardboard may skip this step since they contain a lot less ink or because of more lenient requirements.

#### 8.11.4 Refining and Blending

Once the pulp is clean, it may undergo refining to improve the quality of the fibers. Refining enhances the fibers' bonding ability, which is crucial for producing strong and durable paper products. In some cases, the recycled pulp is blended with virgin pulp (new fibers) to achieve the required quality for the final product. After multiple recycling cycles, the bonding potential of the fibers is significantly reduced compared to virgin fibers. While refining can largely restore this bonding capacity, repeated recycling eventually shortens the fiber length, leading to a decline in paper strength. Top of Form Bottom of Form Cardboard typically requires less refining than higher-grade paper, as it is primarily used for packaging and does not need to meet high brightness or smoothness standards.

Technologies for refining include, in-situ precipitated calcium carbonate, dry paper recycling. The effects of recycling differ between mechanical and chemical pulp. Chemical pulp's bonding potential significantly decreases due to repeated drying and rewetting, while mechanical pulp shows less deterioration and even a slight improvement in bonding potential.

Among the leading recycling technologies is in situ precipitated calcium carbonate (PCC), which uses CO<sub>2</sub> from other industries and natural limestone to produce calcium carbonate for paper production. This method enhances paper strength and opacity, reduces wastewater and energy use, lowers costs, and minimizes environmental impact.

Another technology is dry paper recycling, used in offices to recycle paper without sending it to a facility. It involves separating paper fibers, forming new sheets, and binding them with powdered binders and heat. However, this process is energy-intensive and environmentally burdensome due to the use of bonding agent cartridges.

Additional processes for cleaning include thermal and chemical treatments.

#### 8.11.5 Thermal Treatment

Also known as "hot dispersion," this process involves treating high-consistency material with mechanical forces while heating with vapor or steam at 60–100°C, depending on the specific process. Thermal treatment is sometimes combined with chemical treatment and is primarily used to reduce chemical and microbiological contamination, especially in processes that recycle water during cleaning and de-inking steps.



### 8.11.6 Chemical Treatment

Chemical treatment, also referred to as "bleaching," involves using biocides, slimicides, whitening agents, enzymes, ozone, hydrogen peroxide, oxygen, and other chemicals to increase brightness and reduce contamination. This step is crucial for improving the overall quality of the recycled paper.

### 8.11.7 Papermaking

The refined pulp is diluted with water to form a thin slurry, which is then spread onto a moving screen to form a continuous sheet of paper. As the water drains away, the fibers begin to bond together, creating a wet paper sheet. The sheet is then passed through a series of press rollers to remove excess water, increasing its density and strength. The pressing process is essential for creating a uniform and smooth paper sheet that can be further processed into finished products. The sheet formation process for cardboard involves creating thicker sheets, often combining multiple layers for corrugated cardboard to provide strength and durability. After pressing, the paper sheet is dried using heated rollers or drying cylinders. The drying process removes the remaining water, reducing the moisture content to the desired level. For certain types of paper, a coating may be applied during the drying process to enhance surface properties like smoothness, brightness, and printability.

## 8.12 Glass

While glass is often touted as fully recyclable, only the container glass industry effectively implements closed-loop recycling. In the EU, container glass represents about 62% of total glass production, with an average recycling rate of 76%. This success is attributed to the purity of glass used in packaging, which, when properly cleaned and sorted by color, can be melted and reformed into new containers without losing quality.

Glass obtained from packaging waste is usually pure glass fit for a closed-loop recycling process. The only requirement is that the glass has been cleaned from other impurities and sorted by color. A process similar to the one described in WEEE is used to rid the glass of any impurities. A washing step is included to remove any adhesives and labeling that can be found on it. Usually, glass recyclers don't accept mixed waste but receive already sorted glass, but the process still has to include almost all removal steps because of additions like metal bottle caps, bottle cork, plastic caps, etc. Metals can then be sent to their stream of recycling, and depending on the non-metallic fraction, excluding glass, it can be landfilled, incinerated, or even recycled. The latter is less practiced.

Once shredded, washed, and sorted, the glass is sieved, and several fractions can be sold. The coarser fractions are sold for glass manufacturing in closed-loop recycling. Finer fractions can be used as filters for pools and other water treatment stations. The clean glass cullet is then melted in furnaces at temperatures between 1,400-1,600°C, where it is transformed into new glass containers. The process is energy-efficient, with recycled cullet requiring about 40% less energy to melt compared to raw materials. However, even within container glass recycling, challenges exist. The closed-loop recycling rate varies by glass color; green glass can incorporate up to 90-95% recycled content, brown glass around 70%, and clear glass only 60% due to the critical impact of color contamination.

In contrast, other types of glass, such as flat glass, automotive glass, and special glass, often face significant challenges in recycling. These challenges arise from differences in composition, the presence of coatings or additives, and higher levels of contamination.

Consequently, these glass types are frequently down-cycled into lower-quality products or end up as waste. C&D glass, automotive, and WEEE glass are generally used as filler in concrete, roadside illumination, sodium silicate formation, water filtration media, and decoration. However, should the need arise, container glass is also a contender for these processes. The need for it could be a batch of glass that doesn't comply with purity standards, for example. That excludes the option of sodium silicate production since that might require higher purity. Sodium silicate, widely used in detergents, paper manufacturing, adhesives, and more, can be produced from waste glass through hydrothermal or fusion methods. Waste glass of various colors (transparent, green, and brown) is utilized. The optimal fusion process involves using waste bottle glass with 90 wt% NaOH at 650°C for 60 minutes. Additionally, hydrothermal reactions in high pH conditions can convert cullet glass into silicate compounds like zeolite. It's curious to note that some glass fractions are suitable to be made into abrasives directly. Abrasives can also be cleaned and reused multiple times. Presently, glass wool manufacturers also prefer container glass cullets rather than other types from other sources since they are easier to work with and of a higher quality.

Additionally, there is a stream of waste glass of less than stemming from flat glass recycling that is then made into container glass as identified by Bristogianni, T. and Oikonomopoulou, F. (2023) and other sources. This occurs in the Netherlands, which has a unique system operated by the company Vlakglas Recycling Nederland (VRN), which collects all kinds of sheet glass, including float, laminated, and combination glass, which is a mix of all kinds of glass. This group can also be referred to as white glass. This excludes glass for car windscreens, special types of heat-resistant glass, and ceramic glass. Other recyclers also treat this type of glass; however, it is used in furniture and files, while only container glass cullet is sent for packaging production. Far back in 2013, the company reported the following numbers as weight percentages of recycled sheet glass cullet being sent out to the following manufacturers: 13% into the flat glass industry, 32% into the glass wool industry, and 55% to the packaging industry (to make clear glass bottles) and nothing to the glass bead industry or any other industry. That being said, the specific process used by the company wasn't disclosed.

### 8.13 Composite

The main types of composites found in packaging waste are the following:

- Paper-plastic composites
- Plastic-plastic composites
- Aluminium-plastic composites
- Paper-aluminium-plastic (tetra pak) composites
- Glass-plastic composites

#### 8.13.1 Mixed Composites and Multilayer Packaging

The recycling challenge for mixed composites and multilayer packaging is the immiscibility of different polymers if the two products are to be recycled together. The immiscibility occurs because the Gibbs free energy of mixing different polymers typically disfavors blending, resulting in phase-separated morphologies such as spheres, cylinders, or lamellae. These structures create weak points within the material, reducing its overall strength and usability. A promising approach is the use of compatibilizers, which are added to improve the miscibility of polymer blends during recycling. Other than compatibilizers, fillers, and virgin polymers can be added to improve the resulting material's characteristics. Techniques such as dissolution-reprecipitation are also explored to separate the polymers in multilayer structures selectively. Additionally, microfibrillar composites are another

method, where one polymer acts as a reinforcing element within another during the recycling process, enhancing mechanical properties.

On the other hand, it is possible to only recover one of the two or try to separate the two. Recovering one component includes transition can be done using a dissolution and precipitation method or transitioning one material into a different state (liquid or gas). If the method doesn't enforce chemical change, then it could also be named a physical delamination method. Separating the two components requires delamination, which can be done physically as mentioned and also via mechanical or chemical methods. The mechanical methods are explained in the thermoplastic segment. The chemical methods include the decomposition of the interlayer or reactions at the surface to remove the top layer. Most of the methods mentioned in thermosetting composites are the best contenders to perform chemical delamination.

### 8.13.2 Sorting and Recycling of Thermosetting Composites

Thermosetting composites like epoxy resin are challenging to recycle due to their cross-linked polymer structure, which makes them infusible and insoluble. The common recycling approaches include grinding the composite into powder for use as a filler or adopting chemical recycling techniques to break down the polymer matrix. Chemical recycling methods include supercritical water treatment, acid degradation, oxidative degradation, and electrochemical degradation. For instance, supercritical water or supercritical CO<sub>2</sub> treatment can decompose up to 99.5% of epoxy resin, recovering high-quality carbon fibers that can be reused in new composites. It also uses no chemicals to achieve the process, however its very energy intensive. This method is also applicable when metals are present since it will selectively recycle only the organic parts leaving the inorganics intact. Additionally, if the other material used is paper, then a simple pulping process will recover the paper segment leaving the plastic intact.

### 8.13.3 Sorting and Recycling of Thermoplastics Composites

Thermoplastic composites are easier to recycle compared to thermosets, as they can be remelted and remoulded as a whole, without separation of composite segments. Naturally, this also depends on what the other materials are and the compatibility of melting temperatures. Mechanical recycling is the primary method, where materials are sorted based on their polymer type, shredded, and then reprocessed by extrusion or injection molding. For sorting, technologies like Near-Infrared (NIR) sorting are used to identify polymer types, while air classification separates materials based on density. The key challenge is maintaining material properties across recycling cycles, which often requires the addition of compatibilizers. If the other material is glass or a polymer that is easily separable through mechanic abrasion alone, it is also possible to separate the composites in this way and reprocess them separately.

For more information on **Tetra Pak** is included into the annex.

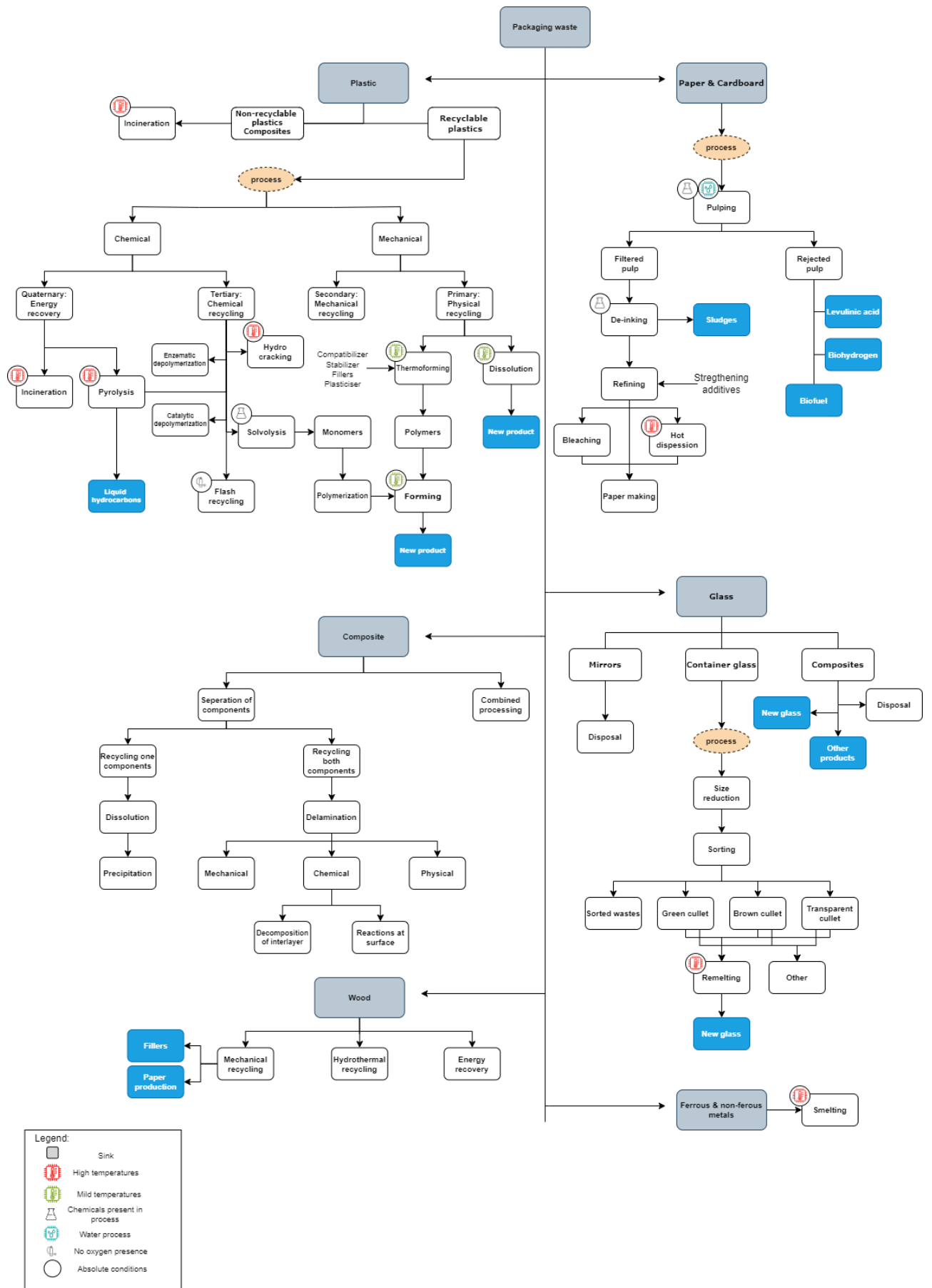


Figure 10. Packaging waste flows in recycling streams

## 8.14 Batteries & Accumulators

Batteries have been recognized as one of the main driving forces to achieve a carbon-neutral economy by 2050. The legislation that governs the flow of batteries is The Batteries Directive 2006/66/EC is the primary EU legislation concerning batteries. It includes requirements for labelling batteries and their removability from equipment, requiring manufacturers to enable that option. The last revised and updated version is Regulation (EU) 2023/1542, which has introduced these types of batteries, out of which only the first two have collection targets (refer to Table 1):

- Portable Batteries: These include batteries that consumers typically use in household devices, such as AA batteries.
- Light Means of Transport (LMT) Batteries: Used in electric bikes, e-mopeds, and e-scooters.
- Electric Vehicle (EV) Batteries: Batteries used in electric cars and other electric vehicles.
- Industrial Batteries: Used in industrial applications, including energy storage systems.
- Starting, Lighting, and Ignition (SLI) Batteries: Primarily used in vehicles for starting, lighting, and ignition purposes.

The rest of the categories are left to producer responsibility with regulations and guidelines for how to collect their batteries.

However, these directives have also added targets for recycling efficiency<sup>[1]</sup> for separate metals, forcing the recovery of critical and strategic raw metals (CRM and SRM) like cobalt, nickel, copper and lithium. So far, the first three have been the main target metals in the recycling of batteries, while lithium is more often than not disregarded. Even though lithium is a CRM it is hardly recovered in the EU because no satisfactory cost-efficient has been found. (European Parliamentary Research Service, 2022) Therefore, there is immense research being done on the topic, especially because of the use of lithium-ion batteries in electric vehicles, which play a big role in the envisioned 2050 carbon-neutral society.

On the other hand, Tan, W. C. et. al. (2022) argues that in fact lithium-ion batteries exhibit technological limitations and that their advancement is limited also. Further, they proclaim that the EoL disposal remains an unsolved issue and therefore propose an alternative battery - metal-air.<sup>[2]</sup> Metal-air batteries, despite not being completely ready for the market, are less complex to recycle, since the already existing technologies can recover most of the materials in a cost-effective manner. Moreover, solid-state batteries, containing a solid electrolyte are also considered fully recyclable, with options to regenerate both the cathode and solvent (Tan DHS et al. 2020). The study by Tan, W. C. et. al. (2022) also stressed the importance of exploring the recycling scenarios and technologies before they reach the market, so as not to repeat the unpreparedness of the recycling sector like it was for the case of lithium-ion batteries.

Although there are many different types of batteries, their internal structure is essentially the same, consisting of a cathode, an anode, a diaphragm, and electrolyte. Depending on the value and amount of the metals present in the battery or the toxicity of the substances there are a couple of routes the batteries could take after the consumer is done with them.

Very recently, in a separate regulation on mercury, the EU's commission prohibits the last intentional remaining uses of mercury in the EU and contributes to the Zero Pollution objective (Directorate-General for Environment, July 2024), including batteries, lamps and dental care.

There are very specific uses where mercury products will still be allowed, but in general mercury containing products won't be considered further in the study as they have little chance of containing an ANM.

#### 8.14.1 Extending the life of a battery

There exist two types of batteries on the market, primary and secondary. The latter have the option of being recharged while the first can't. Primary batteries include alkaline, zinc-carbon and lithium batteries. The first step of primary battery recycling is usually discharge (refer to section below), with very little talk of any type of life extension.

The secondary ones, however, stand a chance at a second life. These batteries include lithium-ion (Li-ion), lead-acid, nickel-cadmium (NiCd) and nickel metal hydride (NiMH) batteries. To maximize the value of an end-of-life (EOL) battery and reduce its environmental impact, it is essential to consider various methods of extending its lifespan before it is regarded as waste.

The most promising and researched types for a second life are electric vehicle batteries (EVB), especially the Li-ion type. Li-ion battery reuse is viable as these batteries still retain about 80% of their initial capacity after their first life in EVs ((Milojević et al., 2022). . Consequently, the battery lifetime can be prolonged by 5-10 years, mitigating the demand for raw materials needed to manufacture new batteries (Bobba et al., 2019; ).

It has to be noted that the EU doesn't currently possess any regulation regarding this possibility, falling back behind the USA and Canada which have already set in motion legislations regarding the procedure.

There are multiple ways to achieve a second life for a battery, including:

1. Repurpose – use of whole product or parts in a different function
2. Remanufacture – use parts in a new product with the same function
3. Refurbish – to restore and update the old product
4. Repair – repair and maintenance of defects and use in the original function
5. Reuse – reuse of a functioning discarded product by another consumer

Currently, the options of reuse and repurposing are most viable and require the least amount of additional investment to implement. However, an EOL EVB should first be remanufactured, for automotive applications, ensuring circularity of the product. Only then, the second-best option is to repurpose the battery for less demanding applications, such as stationary energy storage systems (SESS), storage for domestic purposes or uses in micro or urban electromobility (street-lighting, refrigerated vehicles and forklifts). According to a study by Tao et al. (2021), repurposing an EVB before recycling can reduce its carbon footprint and energy use by 8-17% and 2-6%, respectively.

#### 8.14.2 Discharge

Once it is affirmed that a battery's life can't be extended anymore, it is sent to a recycling facility where the first step is the discharge of the battery, due to safety reasons. The techniques usually used to discharge are resistive discharge or thermal discharge, and salt solution discharging. Resistive discharge is done by connecting the anode and cathode with high-power resistors. Thermal discharging is done by heating the battery in the range of 100–500°C for a time, inducing degradation and self-discharge. Last and most often used method, salt solution discharge involves water electrolysis starting an ionic process of discharge. Further, there is an

option to by-pass this operation and do it simultaneously during shredding by the addition of an inert atmosphere or simply by sprinkling water throughout the process. There is a possibility that a battery won't go to any discharge technique if it was evaluated that there is no charge left. Following discharge, a battery would go to size reduction, usually a shredder or end up directly in a smelter, skipping the discharge step.

#### 8.14.3 Recycling processes

The main recycling techniques for batteries were pointed out by Toro L. et al (2023) There are 4 main ways that are used to recycle batteries and accumulators:

1. Pyrometallurgical
2. Mechanical
3. Hydrometallurgical
4. Bio leaching

Often, they are paired amongst each other to obtain maximum recovery. The current EU regulatory framework requires only 50% of the average weight of an EVB to be recycled, after which the remains can be disposed of in landfills or by incineration. For example, in Finland, at least 50% of an EVB is recycled, after which the remains, such as plastics, are incinerated to recover energy. The ashes and other unburnable residues are disposed of in landfills. Among the things that are rarely recovered are the electrolyte and any carbon-based materials, such as graphite. Recyclers strategies on graphite will have to be changed because battery-grade graphite has been placed on the list of EU's strategic materials (SRM), as part of European Commission's Critical Raw Materials Act (CRMA), deemed vital for the Energy transition goals. Consequently, as the EU's targets keep growing so will have to the recycling technologies regarding both total mass recovery and that of specific materials.

Moreover, the main recycling value in a battery comes from its cathode. According to the price that could be recovered from it the technologies further were assessed by Lander et al. (2021), who found that for LIBs specifically, pyrometallurgical methods weren't profitable, hydrometallurgical methods differed according to the cathode chemistry and metal content and lastly direct recycling was found to always be profitable. This study hints at the path industries will undoubtedly take in the future and altering the flow of contained ANM with them.

#### 8.14.4 Pyrometallurgy

Pyrometallurgy refers to the recovery of metal resources from battery active materials using elevated temperatures, followed by purification or refining through physical or chemical transformation.

These processes typically include roasting, incineration, calcination smelting, and thermal desorption.

In roasting, batteries are subjected to temperatures between 500–800°C to remove moisture and decompose metal compounds into oxides or reduced species using oxidants or in the excess of oxygen. The aim is to obtain oxides to facilitate the next step of smelting. For example, carbothermic reduction roasting at 700–1000°C reduces  $\text{LiCoO}_2$  cathode material to recover cobalt, lithium carbonate, and graphite. Vacuum pyrolysis, chlorination, and nitration roasting with  $\text{NH}_4\text{Cl}$ ,  $\text{NaCl}$ , or  $\text{HNO}_3$  have been investigated to obtain cobalt and lithium as chlorides, carbonates, or oxides.

Calcination is a thermal treatment process operating at similar temperatures to roasting in which materials are heated to high temperatures in the absence or limited supply of air or oxygen. This process causes thermal decomposition, phase transition, or the removal of volatile fractions.

Incineration typically refers to the combustion of organic materials to reduce volume and remove volatile substances, often serving as a pretreatment step for batteries, but mainly used other types of waste. The process converts waste into ash, flue gas, and heat.

Thermal desorption at 300–500°C can selectively vaporize and recover metals such as mercury by breaking the bonds between contaminants and target materials via the energy input, achieving desorption and release from the adsorption site without extensive heating.

Roasting, incineration, calcination and thermal desorption are used as pretreatments to smelting or other methods of refining.

Smelting is a common pyrometallurgical process where battery materials are heated in a furnace to separate metals from other components. Metals melt and are collected while other materials form a slag or waste product, slag formers can be added to help slag formation and reducing agents are also an input to separate metal in metallic form. Further refining can achieve higher purity levels. During smelting metals in the battery electrodes and current collectors liquefy to form an alloy phase that separates from a top slag layer. This alloy can contain iron, nickel, cobalt, copper, manganese, and other transition metals, which are usually sent to electrolytic or other chemical processing to obtain each metal separately. However, lithium and manganese are commonly lost to the slag during direct smelting.

It is possible to pair smelting in furnaces with other processes, in order to recover the vapor fraction. For instance, Ni-Cd battery recycling employs high-temperature processes above 1000°C, including vacuum distillation, which can recover 99.95% purity cadmium metal by heating to 850–900°C in a closed system, leaving a nickel-iron alloy residue. Major industrial processes like SNAM, SAB-NIFE, and INMETCO utilize closed furnace distillation at 900°C or reduction with carbon, condensing cadmium vapor.

Direct smelting involves heating above 1000°C (usually 1300–1500°C) to separate metals from other less valuable components like zinc and manganese from slag, though it can result in zinc losses. Direct smelting, as the name suggests, is done without a thermal pretreatment, unlike smelting which requires one of pyrometallurgical pretreatments like incineration, roasting or calcination.

The formed slag, from both direct and pretreated smelting can be applied in the construction industry as a filler in materials or soil, it can be stored or could be included in innovative products depending on what the slag is rich in. Some part of the slag is kept at the smelters to be brought back into the furnace to help the new input material reach the wanted temperature faster. This also ensures maximum metals extraction.

Pyrometallurgy is more suitable if large amounts of metal are present in the gathered waste. As the critical metals such as REE (found in NiMH) in batteries aren't in such a position, they are usually insufficient to extract marketable REEs as they result in a mixture of REEs in slag form. Similarly, until now, for lithium-ion batteries copper, cobalt, and nickel were recovered, while lithium and manganese are often lost to slag or emissions.



For lithium-ion battery recycling, pyrometallurgical treatment goals include decomposing and burning off volatile organic compounds like electrolytes, binders, and plastics to prepare materials for high-temperature smelting, removing moisture, passivating reactive components like lithium salts, and pre-concentrating metals by converting compounds to metals through pyrolysis and reduction reactions at elevated temperatures. Pretreatment methods like incineration, pyrolysis, or calcination remove organic components and enrich the metal fraction, facilitating subsequent pyrometallurgical steps.

Companies like Umicore, Glencore, Accurec, and Retrie Technologies all operate pyrometallurgical recycling processes with capacities of up to 20,000 tons per year. These processes might differ in feed pretreatment, furnace types, slag design, and gas treatment depending on optimization.

#### 8.14.5 Mechanical Recycling

Mechanical separation techniques are commonly used as the initial step in battery recycling processes. These techniques involve the physical separation of battery components based on their size, shape, and density. The main goal is to separate the metallic components, such as electrodes and current collectors, from non-metallic components, like plastic casings and electrolytes. Mechanical separation techniques have the flexibility to handle a wide range of battery types. Mechanical separation processes are designed to handle significant volumes of spent batteries. For instance, one described process is designed to handle 1 metric ton per hour of spent batteries, offering a rate of 98% diversion from landfills with a recovery rate of 87% for battery materials.

Mechanical recycling starts at size reduction, after which there is material sorting going on just like for other types of waste. Commonly, batteries are broken down via shredding into smaller pieces to facilitate subsequent separation processes. If there are hazardous substances involved, like with Li-ion batteries, then cryogenic shredding is applied. After shredding, sieving uses screens with different mesh sizes to separate materials based on particle size. Magnetic separation extracts ferrous components, while eddy current separation recovers non-ferrous metals based on conductivity.

Once the casings and bigger parts of the battery or accumulator are removed then the rest is sent to hydrometallurgical refining as well, in order to guarantee purity. For some types of batteries, such as the alkaline-ion or zinc type, the metals might not show enough economic worth to be exploited and are therefore either sent to landfill or, since the metallic ions present are considered nutrients, as fertilizer. However, recently there has been a movement to recover some of those metals as well.

An example of a specialized mechanical process for the recovery of alkaline batteries involves first shredding the batteries to uniform small sizes and then drying them at 425°C in a rotary oven to remove moisture and evaporate any mercury present and capture it in a scrubber. After shredding and screening, the coarse and fine fractions are obtained. The coarse fraction usually consists of scrap metals and is sold as such while the finer fraction contains the electrode and electrolyte materials. To recover the materials from the fine fraction it could go through gravity separation, even if this isn't usually the case. The coarse fraction undergoes sorting techniques and a washing step to obtain ferrous and non-ferrous metals as well as plastics and papers which are used for energy recovery.

Industrial shredding and mechanical recycling in general, in addition to problems with reactivity, it introduces contamination and material losses. Problems with reactivity occur due to hazardous substances being exposed and the possibility of combustion. Material losses occur due to the finest of fractions being easily airborne and it generally being a messy process. It can be said that 10-30% of material can be lost with this technique.

#### 8.14.6 Hydrometallurgy

Hydrometallurgical recycling involves the use of aqueous chemistry to selectively dissolve and recover metals from spent batteries. It can be done, or rather most often done after mechanical or after pyrometallurgical pretreatment. This typically includes steps in the following order:

1. Leaching
2. Solid liquid separation
3. Solution purification

Leaching can be done using alkaline, acid, salt solutions or water. In acid leaching, strong acids such as sulfuric acid at low pH (1-2 pH range) dissolve metals like lithium, cobalt, nickel, manganese, and copper from battery materials. This is one of the most common approaches. Alkaline leaching utilizes alkaline solutions at high pH (9-11pH range) such as ammonia to selectively dissolve high-purity lithium, nickel, and cobalt. The choice of lixiviant (leaching agent) and operating conditions, including acid concentration, temperature, and oxygen levels, can be tailored to target specific metals based on their chemical properties.

After leaching, the resulting metal-rich solution undergoes purification to separate the dissolved metals from impurities. Techniques such as chemical precipitation, cementation, ion exchange, solvent extraction, adsorption and membrane separations are commonly used.

Selective solvent extraction utilizes immiscible organic extractants to transfer targeted metals from the aqueous phase. For instance, dimethylglyoxime (DMG) can be used to selectively precipitate nickel, while D2EHPA is effective for extracting manganese. Cobalt and lithium can be sequentially precipitated using ammonium oxalate and sodium carbonate solutions.

Recent research focuses on advanced selective solvent extraction methods, including the use of tailored nanosorbents, ionic liquids and deep eutectic solvents, which offer improved stability, recyclability, and efficiency. New approaches such as the simultaneous synthesis of reduced graphene oxide (rGO) and lithium–manganese-rich cathode materials directly from electrode powder have been explored, demonstrating the potential for effective upcycling of waste lithium-ion batteries (LIBs).

During leaching valuable metals as well as impurities (Fe, Al) dissolve into the pregnant leach solution (PLS). What's more, unlike pyrometallurgical pretreatments where these substances would not be a threat, in mechanical pretreatments organic chemicals and fluoride may end up in the PLS if not properly removed. Therefore, a purification step is applied, to make sure to remove as many impurities of the product as possible. Solution purification also consists of processes such as precipitation, cementation, gas reduction or electrowinning. It is worth noting that the alloys obtained from pyrometallurgy, or the fine fraction obtained from shredding usually sustain multiple hydrometallurgical reactions at different conditions depending on what is the target metal in each.

Hydrometallurgical processes offer high selectivity and the potential to produce high-purity products, including battery-grade precursors. They can be tailored to different battery chemistries and can directly recover valuable metals from mixed waste streams. However, these processes are often complex and involve multiple stages, leading to high reagent consumption and the generation of large volumes of corrosive effluents, which require proper treatment to avoid environmental contamination. Optimization is needed to make these processes more efficient and economically viable on a commercial scale.

Several industrial-scale recycling technologies incorporate hydrometallurgical steps. Examples include the Umicore Valéas process, Retrie Technologies, and Recupyl Valibat, which utilize combinations of mechanical, pyrometallurgical, and hydrometallurgical methods to recover various metals from LIBs.

#### *8.14.6.1 Waste solvents*

The management of waste from bleeding acids or bases in leaching processes is crucial for minimizing environmental impact and ensuring sustainable practices.

Options to mitigate environmental damage from waste acids is to wither recycle the acid and neutralize the contaminants. In fact, this is common practice for many processes thanks to it also being a cost-effective method. For instance, sulfuric acid from copper tank house electrolyte bleeds can be recovered through solvent extraction, reducing both neutralization and acid makeup costs (Gottlieb et al., 2000). This process involves using a branched long chain aliphatic tertiary amine as the extractant, which allows the acid to be reused in the leaching circuit. Nonetheless, for sulfuric acids the evaporation of water and crystalizing of the acid into reusable crystals is also a potential solution.

Other than that, neutralization of the acid or base through addition of the opposite results in water and salts. The water can be reused in the process again. Another option is electrodialysis which utilizes ion-exchange membranes, recovering concentrated acids. Acid washing is a good option. It can remove a lot of left over materials, particularly metals, which can then be stabilized through solidification processes. (Sun & Yi, 2020)

Solidifying the waste solvent acids and bases using materials such as cement helps stop their toxic impact on the environment. Cement can stabilize heavy metals and reduce their leaching potential. For example, incorporating ordinary Portland cement and pulverized fly ash into waste sludge has been shown to stabilize heavy metals, preventing them from leaching into the environment (Li et al., 2001). Moreover, cement has shown excellent adsorbent properties and is often discussed for this utilization.

When it comes to bases there also a few known processes -some similar to the acid ones such as crystallization and membrane filtration (ultra- and nanofiltration). Other options include ion exchange resins which adsorb the base ions and after washing with a regenerative solution the base is recovered. Finally, carbonation is also a choice. It works by reacting bases like sodium hydroxide with carbon dioxide to form carbonated. These carbonates can then be thermally decomposed to obtain the base again.

#### *8.14.7 Biohydrometallurgy*

Bio-hydrometallurgy employs microorganisms to selectively extract and concentrate metals from spent batteries. The microbe-assisted bioleaching process converts the insoluble metal composition into water-soluble metals by bio-oxidation, and the microbe gains energy by

rupturing the wastes into their component metals (Rohwerder et al., 2003; Mishra et al., 2008). Organic acids produced by fungi, such as citric acid, can also mobilize metals through complexation leaching. In hindsight, bacteria or fungi can mobilize metals through various metabolisms. Both bacterial and fungal bioleaching have been explored mostly for spent LIBs, with fungal bioleaching appearing more effective due to higher metal tolerance and the production of multiple organic acids as leaching agents.

Bioleaching processes can operate at moderate temperatures around 30–40°C, which eliminates the need for high temperatures or concentrated inorganic acids typically required in traditional chemical leaching processes. Leaching occurs mostly in range from 1 to 3.3pH as presented by Roy J.J. et. Al. (2021). However, while bioleaching shows promise for recycling, its application at an industrial scale is still in the preliminary phases. Challenges include optimizing the kinetics and efficiency of metal recovery, managing the growth and activity of the microorganisms, and ensuring the consistency and reliability of the bioleaching processes.

Another example of bio-leaching utilization is its successful application to extract cadmium and nickel from battery paste. By optimizing parameters such as pulp density, which refers to the concentration of solid particles in the leaching solution, the efficiency of bioleaching can be improved.

Bioleaching is considered a good but slow alternative. The process exhibits slow kinetics and a long processing time, as well as it being a batch process Roy J.J. et. Al. (2021). Moreover, it is hard to optimize and a lot of factors like metal, electrolyte or binder toxicity, pulp density etc. Roy J.J. et. Al. (2021). On the other hand, the critical advantage of LIB bioleaching over the conventional recycling processes is that it generates mild acid waste and emits low levels of harmful gases, eliminating the need for additional treatment thus reducing the treatment costs (Bahaloo-Horeh et al., 2019; Yu et al., 2020a).

It might be more appropriate for elements in traces such as REEs than major mass capture, since it's a slow process. Such has been its usage in the mining sector, where REEs are rarely the main product.

The before and after processes of bio-leaching are the same ones as leaching. Beforehand there needs to be treatment to reduce its size and increase metal concentration and after there needs to be a step to purify the metal captured.

Recovering material from bio-leaching is a good candidate for regenerative recycling such as direct recycling. Both the cathode and anode would be sent to a separate calcination process. In LiBs the graphite can be regenerated from the bioleaching residue by cleaning it with acid and then calcining it at high temperatures. (Ma et al., 2019; Yang et al., 2019; Natarajan and Aravindan, 2020).

#### 8.14.8 Direct recycling

Instead of hydrometallurgical degradative recovery of metals in spent batteries to prepare electrode materials recent efforts have focused on the direct utilization of recycled active materials to prepare electrode materials, mostly the crystalline structure of cathodes, without losing the energy embedded in the battery particles. In this way, the cathode materials are regenerated and can be used directly in new batteries. The relithiation step involves a stoichiometric adjustment of the cathode material, commonly given by a reductant coupled to a Li salt, which may be followed by a sintering step (Marchese D. el al. (2024)). Lithium salts

or sources that can be used are lithium hydroxide (LiOH), lithium carbonate (Li<sub>2</sub>CO<sub>3</sub>), or lithium metal. The choice of lithium source depends on the specific chemistry of the cathode material and the desired outcome. The process is usually in the range of from 400°C to 800°C and in an inert atmosphere.

This approach mainly refers to LIB recycling. Since it was found that the lithium cathode exhibits a behavior of aging, instead of undergoing hydrometallurgical processes to obtain metallic lithium, it was found that with a process called relithiation the cathode can be healed via selectively adding lithium.

#### *8.14.8.1 Graphite recycling*

The primary waste output from the metallurgical recycling process, known as leach residue, mainly comprises battery-grade graphite, binder, plastic, and residual undissolved metals. Typically, this leach residue is disposed of through incineration or landfilling. Recent studies have explored graphite recovery, including separation by flotation, for direct use or as a reductant in high-temperature (pyrometallurgical) LIB metals recycling. However, this process consumes the graphite chemically, removing it from circulation rather than utilizing it as a high-value product.

Conversely, several studies have examined the use of recycled graphite from pre-metallurgical treatment as a raw material for graphene-like materials. These materials can be used as electrode materials for batteries and capacitors or as carbon support materials for sensors and catalysts.

Innovative processes, such as those using supercritical CO<sub>2</sub>, aim to extract and recover electrolyte components more effectively. This method can recover up to 90% of the graphite from the anode, including the removal of electrolyte residues, demonstrating promise for more environmentally friendly recycling practices.

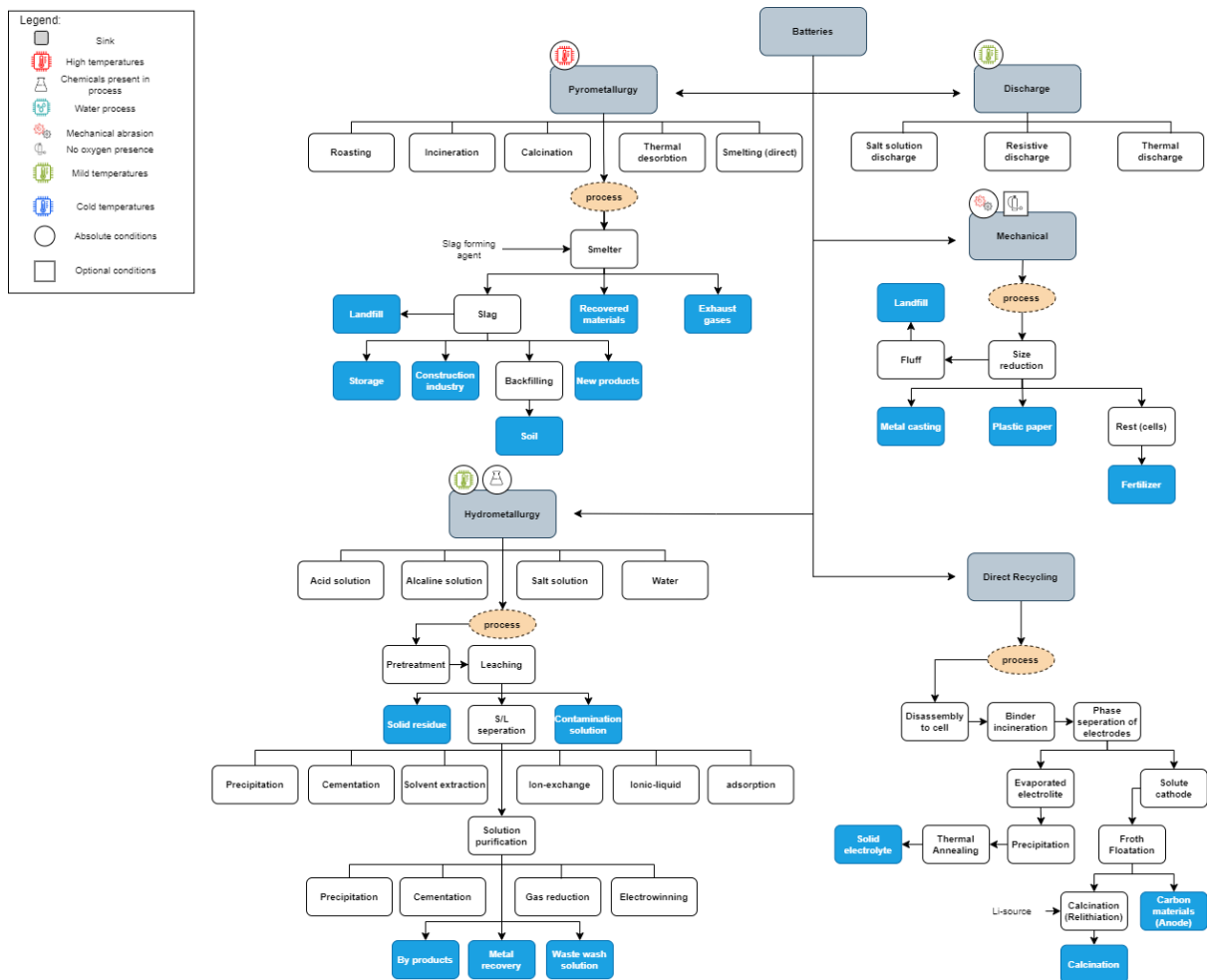


Figure 11. Batteries and accumulators material flows through recycling streams

### 8.15 Biodegradable waste & Municipal waste

Municipal solid waste (MSW) consists of waste collected from private households and similar waste from other establishments. Although the exact composition of MSW varies by municipality and across Member States, a significant portion of MSW typically contains biological material. In many countries, kitchen waste and green waste from gardens and parks make up 30–50% of the total mass of MSW. Additionally, the paper fraction in MSW often includes processed biological material, as does a portion of textile waste from non-synthetic fibers, which is why municipal and biodegradable wastes will be considered together, as they will be subjected to the same processes. Further, some of the biodegradable waste have the option of containing ANM and some wastes that end up in the municipal waste – due to lack of better waste management or lack of education, could also contain ANM. One example of this is sporting products which are most often disposed of in mixed waste streams.

Since biodegradable waste is the biggest mass found in MSW, most of the processes that are made for MSW center around it. Sometimes selection is not done by the consumer, but by the MSW collectors due to the calculation that the selection is done better by machines than by consumers. One such case of municipal waste management is the one in Utrecht, the Netherlands. Furthermore, the usage of these machines puts requirements on the amounts able

to be processes. Not all places have enough waste to utilize such machines or some places would require huge investments because of too much waste.

Generally, biological wastes are biodegradable in the presence of oxygen (aerobic conditions), and most can also degrade without oxygen (anaerobic conditions). However, an exception is lignin, found in woody materials, which does not readily degrade anaerobically unless pretreated by thermal hydrolysis, which increases its anaerobic digestibility. The rate of degradation depends on environmental factors such as moisture, temperature, pH, and the physical structure of the materials.

## 8.16 Waste Treatment Options

### 8.16.1 Landfilling

Historically, landfilling of mixed MSW without pre-treatment or separating the biological fraction was common practice in many Member States. However, this practice is now considered environmentally unsound due to the risks it poses, including the production of landfill gas (methane) with a high greenhouse gas potential, leachate, and the use of valuable land space. The European Union's Landfill Directive has set strict requirements to prevent and minimize these negative environmental effects with its new target setting that less than 10% of waste should be landfilled.

### 8.16.2 Incineration and Other Thermal Treatments

Incineration of waste reduces the volume of waste by converting it into inorganic ash residue, with organic carbon and hydrogen oxidized to CO<sub>2</sub> and H<sub>2</sub>O, which are released into the atmosphere. Large-scale mass burn incineration, where waste is combusted with little or no sorting or pre-treatment, is the most common method. However, due to the low calorific value and high-water content of many biodegradable wastes (excluding paper and wood), source separation of biodegradable materials is generally preferred for incineration. In most modern incinerators, energy is recovered to produce electricity and/or heat.

An alternative to mass burn incineration is to preprocess the waste to produce refuse-derived fuels (RDF). This preprocessing allows for the removal of recyclable materials, including biodegradable wastes, which can receive separate treatment. The remaining combustible residue, with a higher calorific value than mixed waste, can then be incinerated or co-incinerated, such as in cement kilns. Emerging technologies like pyrolysis and gasification break down organic matter into gaseous or liquid products, which are used as secondary fuels, though these technologies are still in development.

### 8.16.3 Mechanical Biological Treatment (MBT) and Mechanical Biological Stabilization (MBS)

In MBT and MBS plants, mixed MSW undergoes mechanical sorting to separate biodegradable materials from non-biodegradable ones. The biodegradable fraction is then composted or anaerobically digested. The non-biodegradable fraction may be further separated to recycle metals and other materials, with the remaining waste either landfilled or incinerated. This is very important when considering transfer coefficients, since wastes that were wrongfully placed in MSW could still end up in the correct recycling stream.

Mechanical biological stabilization (MBS) is designed to reduce the volume and degradability of the biodegradable fraction. This stabilized residual waste, when landfilled, produces less

landfill gas and leachate, and can be used to cover or restore land. For use in agriculture or horticulture, the material must meet strict quality standards regarding pollutants

- Composting

Composting is the aerobic degradation of waste to produce compost, a method with a long history in Europe. Composting systems vary from simple open-air windrows to sophisticated systems with controlled aeration and temperature. Open-air windrow composting is the simplest and relies on natural aeration, whereas systems with forced aeration often include waste gas treatment using scrubbers and biofilters. The composting process can take from a week to several months, depending on the technique and desired compost maturity. High temperatures during composting (up to 70°C) kill pathogens and weed seeds, making the compost hygienically safe.

- Anaerobic Digestion

Anaerobic digestion decomposes biodegradable waste in the absence of oxygen within airtight vessels, producing methane-rich biogas and a sludge-like digestate. The biogas can be used to generate electricity and heat, or upgraded to methane for injection into the gas grid or as vehicle fuel. The digestate can be used as a liquid organic fertilizer or further processed by aerobic composting.

Anaerobic digestion systems vary widely, with innovations in reactor design leading to diverse proprietary systems. These systems can operate as either wet or dry, single-phase or two-phase, with different modes of feed introduction, mixing, and temperature control. High solids digesters, or dry anaerobic fermenters, operate at higher solids concentrations and are increasingly common due to their efficiency and reduced need for water.

- Fermentation for Biofuel Production

Apart from biogas production, certain biodegradable wastes can be used for biofuel production through fermentation. While first-generation biofuels were derived from energy crops, second-generation biofuels utilize waste materials like lignocellulose, often requiring pretreatment to break down the material for fermentation.

- Home and Industrial Composting

Home composting, unlike industrial composting, occurs at lower temperatures and with less frequent mixing, leading to slower degradation. Industrial composting involves higher temperatures (50–60°C) and frequent mixing, ensuring faster degradation and more homogenous biomass. Both composting methods have varying impacts on greenhouse gas emissions, with industrial composting being more controlled and efficient.

### 8.17 End of Life Vehicles (ELV) & other means of transport

The ELV directive from the Directive 2000/53/EC covers mostly passenger cars of the category M1 (no more than 8 seats) and light commercial vehicles of the category N1 (mass not over 3.5 tons), and other additions such as motorhomes. The directive demands a reuse/recycling rate of 85% and a reuse/recovery rate of 95%, per average weight of the vehicle. These rates include energy recovery but limit it to a maximum of 10% of the total weight of the vehicle. Other modes of transport like motorcycles, tractors and mobile machinery aren't covered in this or any other directive specifically, although some regulations could influence them. For



example, the CO<sub>2</sub> emissions standards for vehicles as part of the Regulation (EU) 2019/631 includes heavy-duty vehicles also. Tractors and similar agricultural and forestry vehicles do have a directive of their own, Regulation (EU) No 167/2013, however it only encompasses its production and use, while emitting the end-of-life strategy. Moreover, some parts of the vehicle itself or small electrically-powered vehicles are governed by other directives such as the one for WEEE, the one for waste batteries and even the one for hazardous waste, for specific parts.

Interestingly, the EU has specified very little when it comes to modes of transport that aren't automotive or electric vehicles. Modes of transport like airplanes, trains and smaller vehicles like bicycles are mostly governed by either broader waste management or industry-specific guidelines. However, this excludes ships. There is a specific regulation Regulation (EU) No 1257/2013 for the safe and environmentally sound recycling of ships, which follows the requirements of the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (2009). This includes the regulations regarding disposing of ships in dedicated ship recycling yards and labelling all hazardous substances on board.

As a lot of the transportation vehicles always strive to achieve a lighter mass and as a result ANM has very high chances of finding itself within these vehicles. The EU has some major sites for full or partial recycling or repair of all means of transport, and they will therefore be relevant to the study.

The EU has also re-defined some concepts in the end-of-life sector from the Waste Framework Directive (WFD) and tailored them explicitly for ELVs. They are as follows:

- **Reuse** refers to the reconditioning and use of spare parts from dismantled cars for the same purpose as originally intended.
- **Backfilling** involves using non-hazardous materials, like car glass, from dismantling or shredding for engineering purposes such as landscaping. It differs from reuse, as the materials serve a different purpose than originally designed.
- **Energy recovery** is the incineration of combustible waste to generate energy, aligning with the WFD.
- **Recycling** includes reprocessing waste materials for their original or other uses, excluding energy recovery, and, unlike the WFD, includes backfilling.
- **Recovery** encompasses both recycling (including backfilling) and energy recovery.

The key difference between the ELV Directive and the WFD is the classification of backfilling. In the ELV Directive, backfilling is considered recycling, while in the WFD, it is classified only as recovery. These definitions are crucial for calculating target rates under the ELV Directive.

#### 8.17.1 Recycling techniques

When it comes to material recovery, as part of the European Green Deal, new targets have been set for specific materials, namely for both steel and aluminum there is a proposed target of 20% recycled metal or low emission virgin materials to be used in each new vehicle produced. Further, in the Directive 2000/53/EC the EU has also established four materials (Valentini F and Pegoretti A. (2022)) that need to be recovered from ELVs:

1. Removal of catalysts
2. Removal of metal components containing copper, aluminum and magnesium
3. Removal of tires

#### 4. Removal of glass

Out of those, catalysts are out of scope for this study, tires will be talked about in their own segment and the other two have been explained under different segments, like WEEE and CDW., however recycling of specific parts and metals like steel and magnesium will be covered here. It can be said that the other means of transport follow a similar procedure to the automotive sector up until now.

##### 8.17.2 Pretreatment

The uniform initial treatment stage of any type of vehicle recycling involves draining the vehicle and removing hazardous waste and liquids. Operating fluids such as oils, brake fluids, and antifreeze are extracted and stored in separate containers before being sent to specialized facilities for either material recycling or energy recovery (in the case of oils). Next, waste such as batteries, capacitors, fire extinguishers, braking and anything that has the capacity to be explosive is removed and handled separately.

Following the removal of hazardous substances, dismantling is performed. During the dismantling process, parts and subcomponents that can be reused or recycled are removed. Priority is given to parts that are reusable, such as bogies, bogie frames, wheel sets, couplings, buffers, springs, control valves, brake systems, and doors. Some of these parts can be directly reused in other vehicles, while others may require refurbishment to restore their original operating conditions. These parts must be removed carefully to prevent damage and undergo inspection to determine the necessary refurbishment and potential for reuse. They also need to undergo thorough inspection and obtain a certificate of refurbishment. Afterwards, other elements are dismantled for material recycling, including seats, glazing, wire harnesses, electronic parts, flooring, and HVAC units. These are split between reuse, recycling and disposal. It should be pointed out that dismantlers follow these general guidelines for vehicles:

- Parts and materials without available recycling technology or where the technology is locally unavailable are not dismantled.
- Only elements with identifiable material composition are dismantled.
- Parts requiring excessive time to dismantle are not removed.
- Only easily accessible parts and subcomponents are dismantled, except for high-value items.

After dismantling, the leftover material called hulk is sent to an industrial shredder for scrapping. Before shredding, the waste is pressed to reduce transport space and costs. The packed materials are then ground into small pieces for further treatment. The primary function of an industrial shredder is to recover the metal fraction. After shredding, the waste is sorted into the following fractions:

- Ferrous metals: steel and iron
- Non-ferrous metals: primarily aluminum, copper, zinc, and magnesium
- SLF: a mixture of various materials, including plastics (foams and textiles), fibers (wood and textiles), glass, ceramics, elastomers, remaining minerals (soil and sand), and residue (rust, dust, and paint coatings).

Ferrous and non-ferrous metals are almost fully treated and recycled. Shredder residue may be further separated for reuse or partially combusted for energy recovery due to its high calorific

value. Approximately 50% of the light shredder residue contains combustible material suitable for thermal treatment. Although technologies exist that can sort and utilize up to two-thirds of the shredder residue mass, in practice, 67% of the remains after shredding are landfilled. In some countries, such as Poland, shredder residue is not treated and is entirely landfilled, which causes big amount of waste to be discarded. Not only that but the overall recovery rate of vehicles decreases and SLF also contains high amounts of ash and heavy metals and fine particles, which are problematic to dispose of. To make more efficient recycling of the SLF there are two ways to go about it, the first of which is intensive dismantling which prevents the formation of SLF in the first stage or post-shredder treatment (PST) which focuses on separation and sorting. Although intensive dismantling offers environmental benefits, its economic viability is questionable due to rising labor costs and declining prices for recovered materials. As a result, PSTs are increasingly necessary to comply with EU regulations and to achieve economic sustainability especially in the automotive recycling sector. A study done in 2014 by Sakai, Si., Yoshida, H., Hiratsuka, J. *et al.*, prior to the new recycling targets set for 2015, found that Japan landfills a much smaller fraction of the waste from automobile vehicles due to better sorting in the beginning as well as additional separation happening to the automotive shredder residue (ASR), as seen in Figure 12.

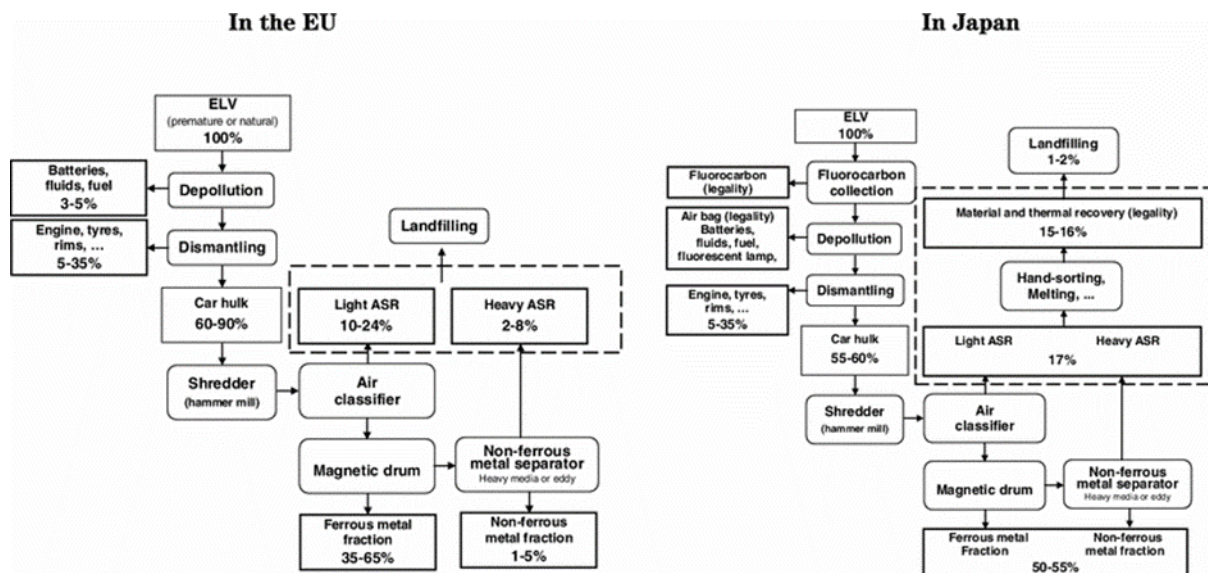


Figure 12. Comparison of typical processing of an ELV in the EU and Japan (Source: Sakai, Si., Yoshida, H., Hiratsuka, J. *et al* (2014))

Otherwise, all dismantled elements and components from the initial or intensive dismantling stages (except those suitable for direct reuse) are sent to specialized recycling facilities where they undergo treatment using available technologies, for example plastics obtained in this way can be reprocessed for material recycling. Similarly, materials separated during the shredding process are sent to steelworks or non-ferrous metal recycling facilities. The separated fractions of shredder residue are directly used in industry, such as polymer granulate in blast furnaces and fibers and foams in sewage sludge conditioning, as well as waste glass being used in backfilling.

### 8.17.3 Ships

Ships contain enormous amount of metal, particularly steel, and using recycled steel requires just one third of the energy needed to produce that same amount from raw materials. Ships

follow the EU and Hong-Kong Convention regulative, which states that before any ship is dismantled a Ship Recycling Plan is made for each specific vessel, in line with the manufacturer's instructions for the ship assembly. Unsurprisingly, this leads to somewhat different working practices in different recycling yards. Ship recycling commonly takes place in developing countries which tend to have a competitive advantage as they provide a pool of low-cost labour, may have weaker environmental protection / worker health and safety regulations, and have national demand for the outputs of the activity (predominantly scrap steel). That being said, there are also dedicated yards within the EU, most of which are situated in the north of the continent.

What's more, ship recycling principally follows the same steps as the one explained above, however due to the size, instead of shredders, large cutting tools are used, which have to be handled properly due to a possible fire hazard that could occur. This holds up for all large vehicles like planes as well.

#### 8.17.4 Airplanes

An airplane's useful lifetime varies from 15 to 25 years. To extend an aircraft's operational life, "extended service goal" upgrades can increase flight hours or cycles. It is estimated that by 2038 there will be 1.100 units of airplanes sent for recycling each year (KPMG-Circularity in flight, March 2024). When retirement is unavoidable, reusing parts and recycling materials yield significant financial returns, as many components and metals retain substantial value. Additionally, aircraft can be repurposed for training or museum exhibits. A big chunk of the parts dismantled can be reconditioned and re-certified for resale. Interestingly, a lot of airplane parts find a second-life thanks to interior design, from designing fireplaces to a roof from an old airplane wing. Companies like Wilco Design create exclusive items from these components. Depending on the type of waste the products aren't a standardized line of production but rather multiple designer pieces. Up to 60% of the weight of an aircraft can be re-used at given costs (Scheelhaase J. et al. (2022)).

During dismantling, engines, landing gear, and avionics systems are thoroughly assessed and often more valuable than the airframe. Once certified, these parts re-enter the market, supporting ongoing aircraft maintenance. Fluids, lubricants, and gases are also reclaimed, ensuring minimal waste. Everything else is split into four categories of recyclable materials or waste. First is metal (whether that's steel, stainless steel, titanium, aluminum or something else). Then there are recyclables such as flight deck glass, tires and so on, then hazardous components such as fire extinguishers and batteries, then composite materials such as the interiors and seats.

When it comes to material recovery it is possible to recycle up to 92% of an aircraft's total weight, including 99% of its engine components. Metals like aluminum, steel, and titanium, are recycled into non-aeronautical applications. Superalloys like the ones made of titanium and nickel are also of high interest. Further, composites such as carbon-fiber reinforced polymers (CFRPs), are either recovered for energy or disposed of. This is a problem for almost all types of vehicles including aerospace vessels and even wind turbines. This composite is used more and more, while no specific recycling technology has been developed yet. That being said, there are Lab groups working to tackle that specific problem, such as the one in the Fraunhofer ICT. A lot of them are looking into pyrolysis as an answer for epoxy resin, while thermoplastics are shredded and reshaped. Further, funding for such research has been provided within the EU with projects like HELACS project in 2022. Challenges remain with materials like nickel alloys

and flame-retardant composites, but technological advancements continue to improve recycling efficiency.

#### 8.17.5 Trains

Unified recycling guidelines for rolling stock were established in 2008 by the Association of the European Rail Industry (UNIFE), which developed Product Category Rules (PCR) for rail vehicles. These guidelines are based on the ISO 22628 standard from the automotive sector, with specific methods for calculating recovery and recycling rates detailed in a document issued by UNIFE in January 2013.

Train carriages are predominantly composed of aluminum, steel, or stainless steel—metals that are relatively straightforward to recycle. Steel, in particular, is easily recoverable due to magnetic separation. Cargo railcars, with 60 to 80% of their mass made of steel and cast iron, are the simplest to recycle. Passenger railcars, especially multiple units, present more challenges due to their varied material composition. A significant issue is the increasing use of composite materials like Carbon Fiber Reinforced Polymer (CFRP) and glass fiber reinforced polymer, which currently lack easy and cost-effective recycling technologies.

The typical life cycle of rail vehicles spans 30–40 years, with European railway carriers decommissioning rolling stock according to their internal regulations, informed by experience and environmental laws. Similar to end-of-life vehicles, decommissioned rolling stock is classified as hazardous waste.

The standards for trains introduce a category of modified organic natural materials or MONM such as leather, wood, cardboard and cotton fleece. All materials other than leather have been discussed so far. Leather will be discussed in this section

#### 8.17.6 Separate treatment

##### 8.17.6.1 Leather

ANM is definitely connected to leather, because of its use as flame retardance, shielding, tanning antimicrobial properties, and enhanced durability (Wang et al. (2021)). The material itself, however, presents a problem at its end of life. While a lot of it can go to reuse final disposal is undefined.

Leather recycling has a list of obstacles as outlined by Pringle et al. (2016), primarily centered around achieving commercial viability, developing efficient recycling processes, and finding suitable markets for recycled materials. Innovative techniques have emerged to address some of these challenges, particularly through the integration of leather waste into composite materials. Notably, leather waste has been successfully combined with natural rubber to produce eco-friendly composites that are suitable for manufacturing products such as shoes and upholstery (Santos et al., 2015). This approach exemplifies how recycling can transform waste into valuable resources. Upcycling represents another promising avenue for leather waste management. By converting discarded leather into new, marketable items, either in clothing or reupholstering, upcycling not only reduces waste volume but also contributes significantly to sustainability efforts (Kushwaha S. and Swami C. (2016)). The adoption of circular economy principles further enhances the potential of leather recycling by focusing on waste valorization. This approach involves converting leather waste into useful by-products, such as collagen and chromium, or even generating energy through waste processing. Such practices are crucial for the sustainable development of the leather industry (Chojnacka et al., 2021).

#### 8.17.6.2 Magnesium

The recycling of magnesium, particularly from automobiles, is an intricate process due to the various steps involved in the treatment of end-of-life vehicles (ELVs). As mentioned, the vehicle body is shredded, and the resulting materials are separated using techniques like air separation, electro-magnetic separation, and sink-float separation. Magnesium is part of the nonferrous metal fraction, which also includes aluminum and heavy metals. Depending on the technology available at treatment facilities and the economic viability, these metals can either be separated further or sold as a combined fraction. Typically, the removal of light metals, including aluminum and magnesium (30% Mg), is standard practice and is often achieved through sink-float separation, or similar methods. While it is possible to separate magnesium from aluminum, magnesium generally ends up mixed with aluminum in the light metal fraction due to economic reasons, as aluminum is more abundant in vehicles than magnesium. In the European Union, magnesium is primarily imported for aluminum alloy production, accounting for 66% of the flow. The processing of aluminum scrap involves either refining, where most magnesium is removed, or remelting, where magnesium loss is minimized. The refining process, known as "demagging," typically reduces magnesium content from 0.5% to 0.1%, with the removed magnesium ending up in salt slag. This slag is recycled to recover aluminum and salt, leaving an oxide residue containing magnesium, which is used in cement production, aggregates, and mineral wool—forms of non-functional magnesium recycling.

Secondary magnesium can be used in steel desulfurization, aluminum alloying, and the production of new, nonstructural magnesium products. However, due to a lack of economic incentives, magnesium often remains in the aluminum scrap and is utilized as an additive in aluminum alloys.

An alternative recycling pathway involves the direct recovery of magnesium for use in secondary magnesium alloys or in the steel industry. In this path, magnesium and aluminum are separated using x-ray fluorescence technology. The magnesium scrap is then treated in a dedicated recycling plant where it is cleaned and remelted. While there are various approaches to producing high-quality secondary magnesium alloys, the current market for such alloys is limited. However, this pathway could become more viable as magnesium prices rise or as the availability of magnesium increases, since it has been named a critical raw material by the EU.

#### 8.17.6.3 Steel

Major steel scrap is recycled in electric arc furnaces (EAF), using electricity as a energy source for smelting. The working principle is encompasses material of different grades like shred, heavy melt, DRI and pig iron is loaded into baskets with layering to achieve uniformity. After heating, oxygen is blown to commence combusting and extra chemical heat is provided by fuel-oxygen burners on the walls to compensate for cold spot areas . Once the scrap is completely melted and a flat bath is reached, another bucket of scrap can be added in the furnace and refining takes place. The previous fraction helps melt the new one. Slag formers (calcium oxide and magnesium oxide) and more oxygen are introduced to the system which takes out the impurities such as silicon, phosphorus, aluminum, manganese and calcium. Their oxides are now in the slag. The slag is important because it acts as a thermal blanket and stops excessive heat loss and reduces erosion of the vessel. In the slag there is also iron oxide. Carbon (in the form of coke or coal) is injected into this slag layer, reacting with the iron oxide to form metallic iron and carbon monoxide gas, which then causes the slag to foam, allowing greater thermal efficiency, and better arc stability and electrical efficiency. The slag blanket also covers

the arcs. Removal of carbon from the steel happens after the slag has been formed because the impurities have a higher oxygen affinity. Metals that have a poorer affinity for oxygen than iron, such as nickel and copper can't be removed so they must be controlled, which is why temperature and chemical sampling must take place. With the process being done the steel is tapped out in a preheated ladle by tilting the furnace. Some alloy additions are placed here as well as lime on top of the ladle to make a new slag. When the slag layer is about to go into the ladle the furnace is placed straight again and then the slag is removed. A few tons of steel and slag are often left in the furnace to help the next batch. To control carbon content more oxygen is added or degassing treatment is done in the secondary metallurgy phase. Carbon is not used for reduction in scrap recycling like it is in primary steel production for iron. Instead, its usages are to carburized the iron or to induce foaming of slag in EAF. Several sources of carbon could replace coal like plastics and tires. After the EAF, comes the ladle metallurgy or secondary metallurgy used for refining. The scrap can also be pretreated before entering the EAF but temperatures shouldn't exceed 800C, this temperature is optimal for energy spendings and won't cause actual melting and over-oxidation. This approach might result in dioxin issues. Other problems that are hard to control are the fine particles are hard to recover due to carry-over, inert materials might find their way in and embedded water that can cause explosions.

The Electric Arc Furnace (EAF) is efficient for smelting but less effective for refining or adding large amounts of nonmetallic materials, necessitating further refining for high-quality steel. Steel production involves various alloy compositions with elements like chromium (Cr), manganese (Mn), and vanadium (V), and the rise in coated steel production is leading to more complex scrap materials. In the final product the steel may be provided with a coating of zinc, pigments etc. These are also referred to as residuals or tramp elements. In traditional melting processes, impurities either evaporate and are captured in gas cleaning systems or oxidize into the slag or steel. When stainless steel is recycled, ferritic stainless steel, being magnetic, often ends up mixed with carbon steel scrap, while austenitic stainless steel is largely recovered. This influences which impurities end up in the recycled steel, like for example chromium staying with the recycled product.

Scrap can contain impurities which influence the product in hardness, embrittlement, weldability etc. For low and ultra-low carbon steels the properties are strongly influenced by tramp elements, among which Cu, Sn and Mo. The EU has set standards for quality about it. To avoid it scrap sorting, O<sub>2</sub> blowing, limit transition of slag into ladle and do sample analysis can be done. Desulphurization and deoxidation should also be done at the ladle furnace.

Other elements that are inseparable and hinder the recycling are phosphorus, nitrogen and hydrogen. To avoid local concentrations of phosphorus, working at lower temperatures is advised. To prevent the latter two elements coming from air and moisture respectively degassing and stirring the dry charge of metal is advised.

- Alloying elements

The current ELV recycling process, which predominantly uses electric arc furnaces (EAF), often leads to the loss of alloying elements because their presence is not adequately accounted for. Studies evaluating alternative ELV recycling schemes suggest that sorting ELV-derived steel scrap (ELV-dSS) by specific parts could lead to more efficient recovery of these elements. For example, in Japan, sorting exhaust parts alone can result in a tenfold increase in the recovery of alloying elements, representing 8.2% of the annual consumption of these elements

in EAF steelmaking. This approach highlights the potential for significant conservation of alloying element resources through improved sorting practices.

Another study examined the input of 25 scarce metals into the Swedish ELV recycling system, assessing how effectively these metals are functionally recycled—i.e., recovered in a way that their material properties are utilized in new applications. The study found that, among the scarce metals, only platinum is consistently functionally recycled in its primary application. Metals like cobalt, gold, manganese, molybdenum, palladium, rhodium, and silver may be functionally recycled depending on their specific applications and the recycling pathways they follow. However, for the remaining 17 metals, functional recycling is largely absent. This suggests that despite high overall recycling rates for ELVs, there is a significant risk of losing these scarce metals to other materials or landfills. Given the differences in how metals are used and the pathways they follow, there is considerable potential for improving the functional recycling of these valuable resources. The results of the study are presented in Figure 14.

To Bath			To Slag		To Gases	
Sb	Cr	B	Al	B	Zn	Pb
As	Pb	Cd	Be	Cr		
Bi		P	Ca	Cd		
Co		Se	Hf	P		
Cu		S	Mg	Se		
Mo		Te	Si	S		
Ni		V	Ti	Te		
Ta		Zn	Zr	V		
Sn						
W						

■ Totally   
 ■ Mostly   
 ■ Partially

Figure 13. Distribution of Some Common Alloying, Impurity and Tramp (Source: Björkman B. and Samuelsson C. (2014))



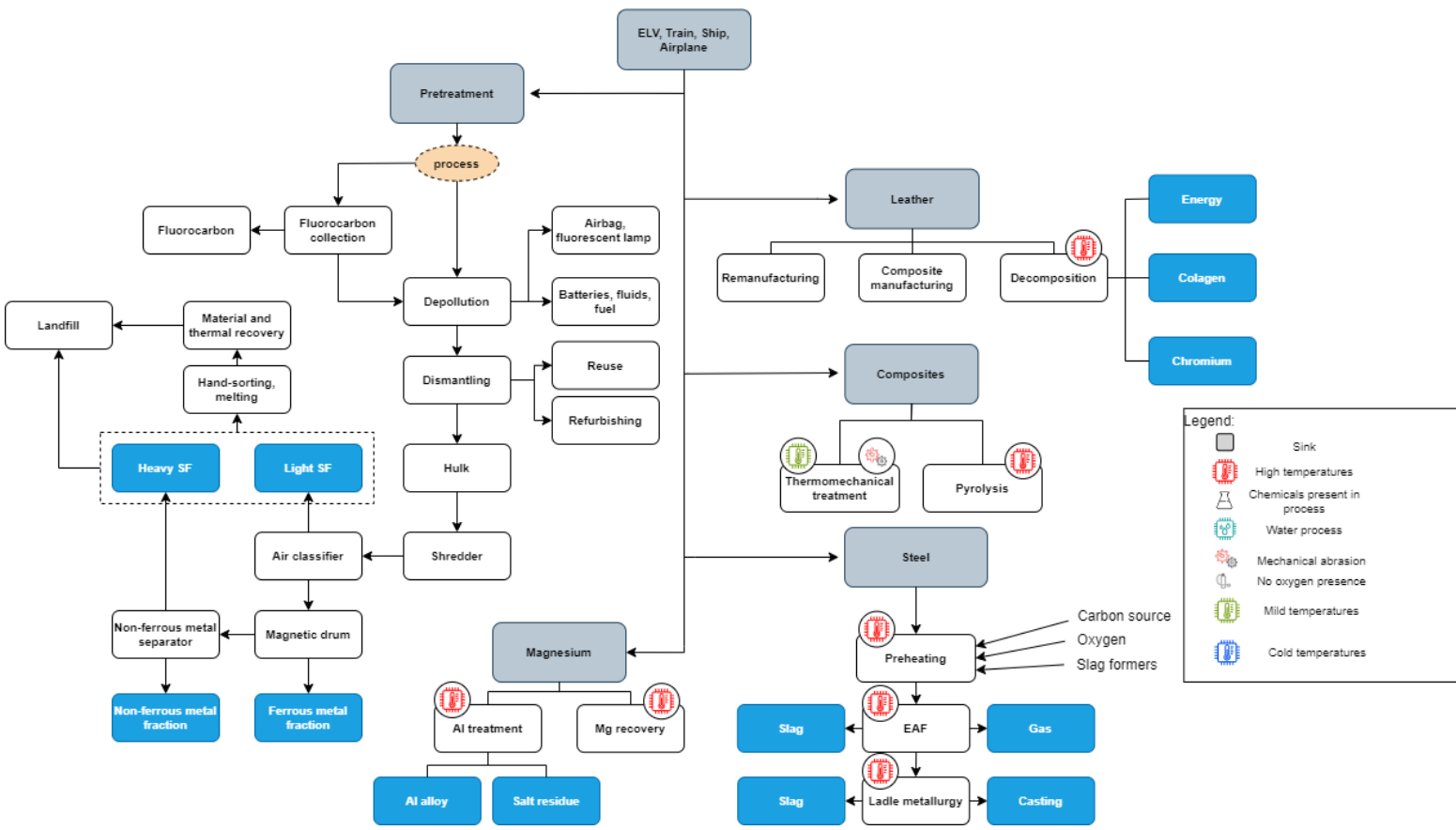


Figure 14. ELV material flows in recycling streams

## 9 Tires

Tires don't have a specific category with their own targets and regulative just yet. Currently, they still fall under ELV (End-of-Life Vehicles) where the collected waste is calculated by mass percentage from an average mass of the vehicles. Further, many associations of recyclers and involved parties urge for a separate regulative concerning tires and possibly rubber also.

In the past, the way to deal with waste tires was largely focused on either incineration or export, however with the implementation of the EU goal for minimizing the export of waste and increasing the recycling material demands, tires stand a growing chance to stay within the EU. Additionally, the new targets for the automotive industry state that new vehicles need to evidence 95% of the mass of the vehicle to be recoverable and 85% reusable or recyclable. Tires play a role in this percentage as they amount for 2-3% of an average 4-passenger car.

On top of that, the Landfill Directive (1999/31/EC) has banned the landfilling of end-of-life tyres (ELT) since July 2006. Subsequently, several management systems under the scheme of producers' responsibility have been created in the EU for collecting, recycling and recovering end-of-life tyres. The systems are governed with either the tax payer system, tyre industry responsibility or the free market system. There also exists a second-hand market for used tires, where no technique is utilized and tires are sold as is. This a good opportunity to extend a tire's life span and also represents a cheaper option for buyers. Generally, tires are said to have a life span of 3 to 5 years. That being said, in the upcoming period of major electric vehicle employment by 2050 it could be argued that tires will gravitate towards the lower end of that range, due to the vehicles being heavier and perform faster acceleration. (DNV GL. 2024)

Other than the reselling of the whole tyre on the second-hand market there are some processes that are done to extend tire-life. The options are summed up as:

1. Second-hand market
2. Retreading
3. Regrooving

Refurbishing or rethreading of tires is a possibility, where the procedure involves stripping away the top rubber part of the tire and placing a new one. However, that still means that some of the rubber part has to go to further processing or another EoL, like being used as TDR. Mostly medium- and heavy-duty truck tires, off-the-road vehicles, and aircraft tires are retreaded (Fu, P., et al. 2016).

Moreover, regrooving, is also a reuse method where less material is replaced than in retreading. This implies that a new tread pattern is cut in the already existing rubber. This is a cost-efficient method mostly performed manually to larger tires rather than automotive ones. Regrooving has been found to increase tread life by 25%. (Wilcox, 2006).

### 9.1 Tire treatment

Tires consist of three basic types of materials which are easily separable once the size is reduced:

1. Rubber
2. Steel
3. Textile fibres

The first part of any sorting process, as mentioned so far is size reduction. Once the size is reduced to chips with dimensions of around  $2.5 \times 2.5 \text{ cm}^2$  (Isayev, A. I. (2005)), the materials undergo simple separation techniques such as magnet separation and density or gravity separation. From there the steel is usually sent to pyrometallurgical recycling plants (smelters), the textile is usually incinerated and the rubber can be turned into a plethora of new products.

Some plants only shred the tires and, without further processing, send them to high-temperature processes as a fuel source. This is welcomed by industries because tire-derived fuel (TDR) produced twice as much energy compared to coal. (Duo W. et al. 2002) Sometimes not even shredding is required since it's possible to incinerate the whole tire. In this way the rubber and textile part will be eliminated and the metal part will stay clean in the residue, making it easy to separate without employing any extra steps.

Tires also stand to be utilized in co-combustion, alluding to mixing tires as an energy source as well as other waste such as wood or combined with standard energy sources like coal. Some studies have been looking through the efficiency of such mixtures and have found that when combined with coal the interaction effects between coal and tire powders were slight, but a synergy existed. The addition of tire powders improved the ignition characteristics, reduced the burnout temperature and increased the burnout rate of coal to a certain extent. (Carmano-Calado et. al. 2020) However, when mixed with plastic waste, Dan-lu et. al. (2021) found that co-combustion is a suitable technology for the recovery of waste tires, but operational problems arise with high levels of residues in the mixture. Increasing pollutant emissions and the need for pre-treatments are other limiting factors. (Dan-lu Pan et. al. 2021).

## 9.2 Rubber from Tires

It has been brought to attention that rubber from waste tires is never treated together with other rubbers, such as rubbers from cables and the like. They are treated by plants that only focus on tires. These are the most probable ways that EoL tires are treated in the EU:

1. Energy recycling
  - 1.1. Pyrolysis
  - 1.2. Gasification
2. Material recycling
  - 2.1. Mechanical treatment
  - 2.2. Devulcanisation and revulcanisation

### 9.2.1 Energy recovery

Generally, in the past, for many collectors of tire waste it was easier to export the waste due to expenses and strict regulations set by the EU regarding the incineration or combustion of tire rubber. However, with the recent push to keep the materials within the EU, the processes available to recycle the rubber have been perfected to make less CO<sub>2</sub> emissions and to valorize the waste to the maximum. Moreover, as the value of fuel keeps increasing coupled with a high energy demand, tires become an exploitable choice to source it from. Processes that stand to be used in this regard are pyrolysis and gasification.

#### 9.2.1.1 Pyrolysis

Pyrolysis is a high temperature process, done at temperatures between 300°C to 900°C, which aims to convert the starting material, in this case waste tires, into oil and fuel (hydrocarbons) in the absence of oxygen. The residue is char, and when cleaned it is converted to a substance

called carbon black, categorized under “Wastes from thermal processes” which is then used as filler in new products, as activated carbon (Martínez et al., 2019) or sent to further cleaning of metals, since some get left inside. Once the metals are taken out there are multiple possibilities that could occur, such as using it as a fertilizer, using it as a heat source or newer studies suggest the possibility of making graphene. This pathway is the one with the most material recovery. The process and its transfer coefficients of general material are given in Figure 15.

Other than this one, possibilities include combustion to produce electricity which results in steam, landfilling the pyrolysis waste or coupling pyrolysis with gasification.

#### *9.2.1.2 Gasification*

Gasification is the chemical transformation of waste including but not limited to tires and directly into a gas. A limited amount of oxygen reacts with the carbon-based matter (but does not burn) and breaks it down into simpler molecules called syngas, which is a mixture of hydrogen (H<sub>2</sub>) and carbon monoxide (CO). Temperatures range in 900°C–1100°C for air and 1000°C–1400°C for oxygen, which is typical for gasification reactors. (Singh D. et al. 2023).

Further, gasification can be used on its own or in combination with pyrolysis, as mentioned and shown in Figure 15. In both cases, with the addition of simple side processes the wastes can also be recovered in the form of metals & minerals, sulfur, zinc concentrate, mineral salts and water.

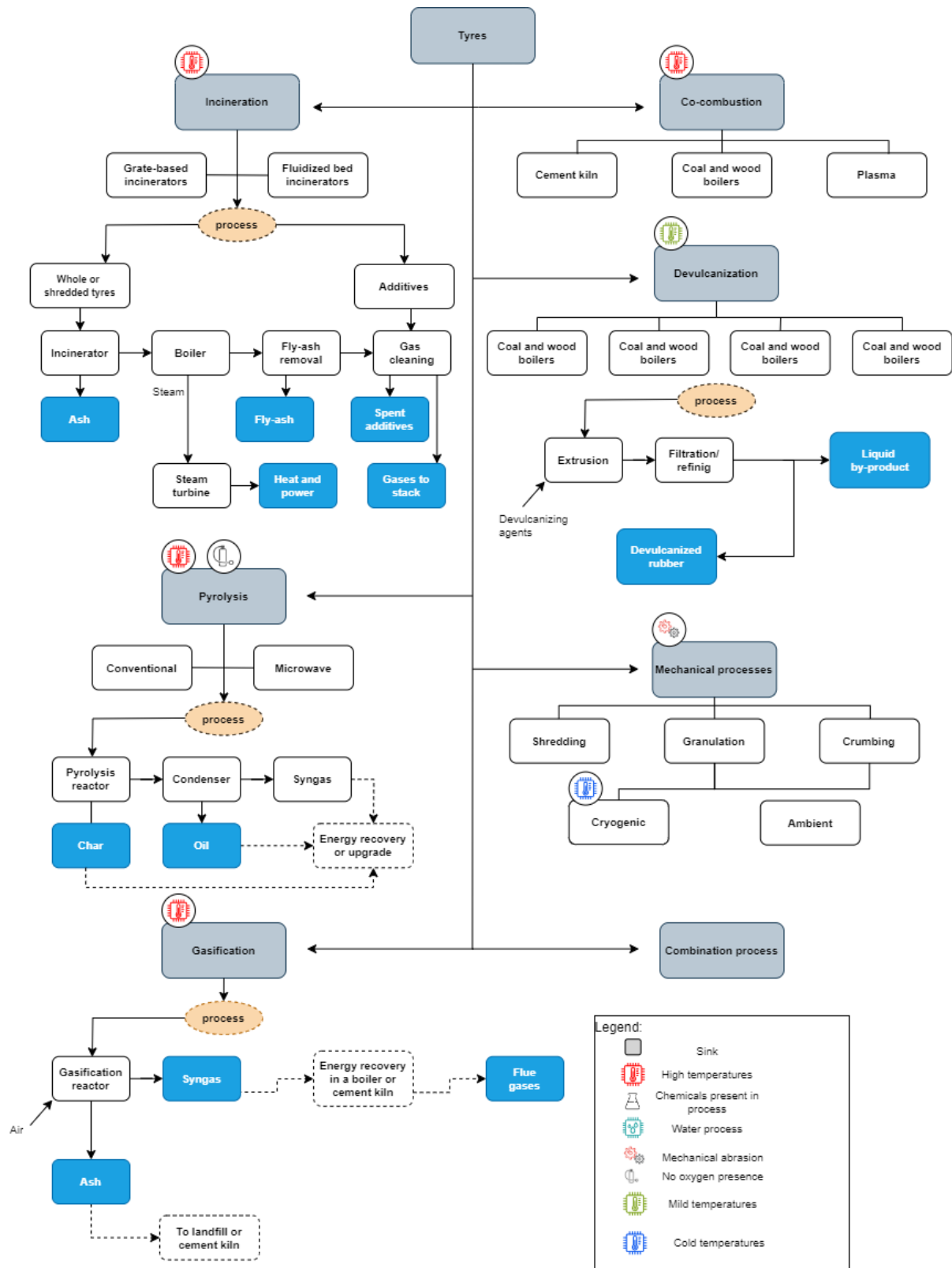


Figure 15. Tire material flows in recycling streams

### 9.2.2 Material recycling

Material recovery methods in tire recycling are generally considered as the more cost effective and easiest to implement option. What's more, the materials obtained in this way can produce or be used in a wide variety of products. Depending on the quality of the treatment, the quality of the obtained product can vary as well.

When material recovery is brought up, it usually refers to mechanical recycling of waste tires. However, this segment also encompasses a widely less use technique, namely devulcanization.

#### 9.2.2.1 Mechanical recycling

Other than the size reduction explained before and after material separation, mechanical recycling of waste tire rubber can go one of three ways, as seen in Figure 15 below:

1. Shredding
2. Granulation (cryogenic, wet or ambient)
3. Crumbing (cryogenic, wet or ambient)

The difference between the three is generally in the size of the size reduced products. Either way, the particles acquired can be split in to the coarser fraction or crumb rubber with a size of 400 microns and finer fraction or rubber powder with a size of approximately 149 microns. Crumb rubber is most often used as an additive in asphalt, concrete, playground surfaces, athletic tracks, molded products and new tires where it provides enhanced durability and flexibility (Fazli & Rodrigue, 2020), while the powder can also be used in modifying asphalt but also as filler in polymeric matrices (Yehia, 2004), other construction materials, new rubbers and in pigments.

Regarding the temperatures of each of these processes other than the obvious ambient one, the cryogenic reduction occurs at temperatures near  $-196^{\circ}\text{C}$ , which is below rubber's glass point and ensures easy breakage of bonds. Wet processes on the other hand, do not use temperature but water is used to control the release of fine particles. This in return means that a technique like this produces large amounts of waste water and there is probability of water contamination. Further regulations and processes should be looked under Chapter 19.

Since there is little chance of a chemical change within this process, the thing that could change the recycling pathway the most would be the so-called Shredder Light Fraction (SLF), though sometimes the same fraction uses different names. SLF, consisting of very fine dust-sized particles, is in most cases either landfilled or incinerated since the particles aren't big enough to be used in a different way. This is true for all subsequent times a size separation is mentioned, and it is a loss of material that has to be considered in every MFA study. The questionnaire and interview of experts shone light on this number saying that in most cases, this waste now classified under Chapter 12 of the EWL, amounts to 10 to 30% of material can be lost in this way. However, in the case of tires this dust can also be used as filler if a wet process is used. It has been commonly used as filler to reduce the price of products such as floor mats, microcellular sheets etc.

Another subsequent mechanical method of recycling introduced is extrusion pulverisation. This can be applied after size reduction and it is a form of extrusion in order to obtain new moulded products. By using a twin-screw extruder to impose compressive shear on the rubber at temperatures typically around  $120^{\circ}\text{C}$ , it then pushes them through a pump to obtain the desired

shape. This method originally made for plastics, is beneficial to be used when the properties of the material need greater control than the rest.

#### 9.2.2.2 Devulcanisation

Devulcanization is a process where it is assumed that the cleavage of intermolecular bonds of the chemical network of rubbers, such as carbon-sulphur and/or sulphur-sulphur bonds, takes place, with further shortening of the chains occur. The purpose if the process is to make to make the material also referred to as reclaimed rubber, vulcanisable once more. (Isayev, A. I. (2005))

Key methods of devulcanization include the following options, showcased in Figure 15:

1. Mechanical methods
2. Thermal methods
3. Chemical methods

Mechanical methods use shear forces to break down the rubber structure, often involving high-pressure or ultrasonic equipment. This can produce rubber particles ranging from approximately 250 microns to 1700 microns.

Thermal methods involve heating the rubber to high temperatures to degrade the cross-links. Commonly used temperatures range from 150°C to 300°C. Microwave and ultrasonic devulcanization are notable techniques, where controlled energy application breaks down the sulfur bonds without significant degradation of the rubber.

Chemical methods use chemicals to cleave the sulfur bonds. Agents like diphenyldisulphide and other disulfides are used to selectively target sulfur-sulfur and sulfur-carbon bonds. The rubber is typically processed at temperatures between 200°C to 225°C.

Additionally, devulcanization methods can be split into total and surface devulcanization methods depending on the target. Surface devulcanization, as the name suggests, only targets the top layer of the material leaving the inside intact. It is usually performed in a temperature range between 150°C and 300°C and uses different chemical agents to achieve its goal, some of them being alcohols and ketones; desulfurization agents like toluene, naphtha and benzene, natural rubber and the ethylene-co-acrylic acid copolymer.

Devulcanized rubber can be blended with virgin rubber and reused in various products, as well as new tires. The challenge lies in achieving efficient and cost-effective devulcanization without compromising the mechanical properties of the recycled material. Advanced methods like ultrasonic, a technique that uses mechanical vibrations and cavitation bubbles that break sulfur bonds at around 120°C, and microwave devulcanization, using microwave radiation to generate heat within the rubber, breaking sulfur bonds through thermal degradation at temperatures between 150°C to 300°C, show promise for their efficiency and minimal environmental footprint, nonetheless each with advantages and disadvantages for their usage. Surprisingly, this technology doesn't hold a big market share in the recycling sphere, however some increase is expected in the near future.

## 10 WEEE

WEEE is a complex, heterogeneous waste stream containing over 1000 different substances (Ye et al., 2009) and is primarily composed of plastics (34.6 wt.%), electronic components (23.5 wt.%) and ferrous metals (15.6 wt.%) (Dimitrakakis, Janz, Bilitewski, & Gidarakos, 2009). Waste electric and electronic equipment (WEEE) comes in 6 categories divided according to the function of the products that require different treatments. Namely:

1. Temperature exchange equipment

2. Screens and monitors and equipment containing screens having a surface greater than 100 cm<sup>2</sup>
  3. Lamps
  4. Large equipment with an external dimension of more than 50 cm (excluding the equipment that falls under categories 1 to 3)
  5. Small equipment with external dimensions not surpassing 50 cm (excluding the equipment that falls under categories 1 to 3 and 6)
  6. Small IT and telecommunication equipment with no external dimensions surpassing 50 cm
- Each of them is handled differently in the beginning depending on hazardous materials and parts which have to be removed before any machinery is used. This means that for most WEEEs the beginning of the procedure is largely manual. Those segments will be explained for each category separately. However, once the hazardous or problematic materials are removed the following procedure is very similar for all types, as shown in Figure 16.

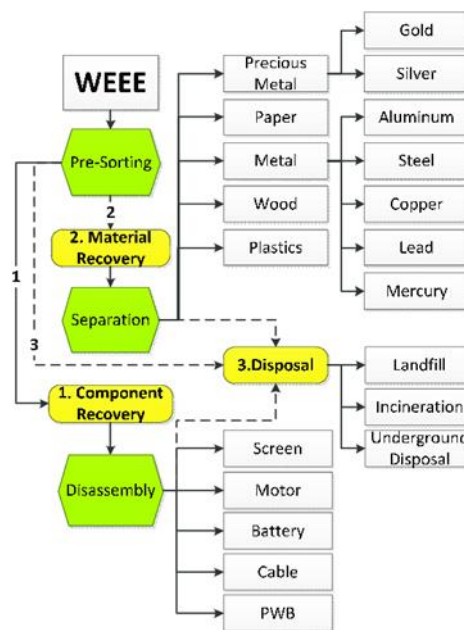


Figure 16. General WEEE treatment diagram (Source: WRCloud: A novel WEEE remanufacturing cloud system)

Undoubtedly, the main aim of WEEE recycling is to recover the metals. The biggest variety of metals that end up at recycling come from WEEE and batteries, but not necessarily the biggest mass. Up until now, many of the metals found in traces other than precious metals, weren't recovered because of their low economic worth in those amounts. Nonetheless, with the current situation of the EU which keeps adding metals to the CRM list every couple of years, their exploitability keeps growing.

On the other hand, there is a lot of metals coming from C&D waste or automotive and other transport vehicles, however these are a lot simpler to recycle. Since most of them contain predominantly one metal it usually ends up in a smelter. Generally speaking, all metals that come in bigger quantities and need to be recovered faster end up being recycled in pyrometallurgical ways, while metals which are found in traces are usually recovered in a hydrometallurgical way or with the use of new bio-techniques, such as bioleaching or biosorption. More on this topic is discussed in the battery section.



## 10.1 Sorting, separation and pretreatment

The first step in the diagram represents the selection by type so that they would follow the correct procedure. Firstly, the "Disassembly" step alludes to the manual work done to remove hazardous substances or others that have to be dealt with separately. These will be discussed later on per category. Everything that isn't removed on the side undergoes a very similar separation stage. What's more, most mixed streams of materials undergo the same procedure, it will only be explained once.

The separation stage always begins with a size reduction step. This includes shredders, grinders or different mills, the first one being the most common. One thing to note is that on one treatment plant there might be a couple of shredders with different sizes or specialized for a specific category. This in turn means that not all materials will be mixed from the 6 categories even if they seem like they undergo the same procedure.

After size reduction comes a step where ferrous metals are removed. This is simply done with a magnetic separator or an electrostatic one. An electrostatic separator removes both the ferrous and non-ferrous fractions, leaving a mix of glass, paper, wood and plastics.

If only a magnetic separator is used then the following stage is to include an eddy-current separator which tries to temporarily magnetize the non-ferrous metals and remove them via magnets, leaving behind the same fraction as the electrostatic separator.

The ferrous and base metals are usually sent to smelters where they melted at different temperatures to remove the specific target metals, while precious metals are treated hydrometallurgical, possibly with a pyrometallurgical technology employed as pretreatment. Such metal recycling will be looked into in the section for batteries. So far, most of the target metals have included gold and silver from the precious metals and aluminum, steel, copper, lead and mercury from the base metals, as suggested in Figure 16. However, currently there is a new directive put in place by the EU stating that for all critical raw materials (CRMs), mostly consisting of metals, 15% must come from recycling. This changes a lot since it would mean that other metals will become the targets of recycling, even if their quantities are very or relatively low. One example is the recovery of indium from ITO plates used in screens or gallium from LEDs, which will be discussed further in the text. For the case of ANM, this means that a lot of the ANM that could end up in landfills or incinerators will go through more processes and stand a higher chance of being chemically changed.

That being said, ANM so far stands very little chances of being chemically altered, however the transfer coefficients do. Separation techniques do not work perfectly and there is always a fraction that is wrongly distributed. Moreover, the size reduction step produces a mass called the shredder light fraction (SLF) consisting of materials whose mass was reduced too much for it to undergo further separation. Companies and experts have reported that 10 to 30% of the mass may end up in this fraction, however most experiments have reported numbers in the lower range (Evangelopoulos, P. et al 2018). This mass is usually sent to incineration or concrete plants as filler. It usually isn't used as RDF [\[1\]](#) (Refuse Derived Fuel) also because of its fleeting particle mass and could contain flame retardants or other unwanted substances. There could even be slight air emissions depending on the machine installation and how well the plant stores and transports this SLF fraction.

Nevertheless, the amount of material ending up in the SLF and dust fractions is large, which rounds up to 2.5 billion tons yearly in Europe, from all sources (WEE, ELV etc.). Some desirable materials like metals (Cu, Pb, Sn, Zn, Au, Ag) are stuck within this mass. If the SLF comes from a hazardous waste category it can't be disposed of in a landfill and has to be incinerated. There is the option of using pyrolysis to at least gain energy recovery and Diaz F., Latacz D. & Friedlich B. (2023) have also succeeded in making this process continuous, which has majorly preferred in industrial applications. They further argue that pyrolysis to this waste, as well as others, concentrated the metals in the left-over solid fraction and it is then more susceptible to other metal extraction treatments. Other uses of thermal treatments have also been mentioned and used by companies such as cement kilns, reducing furnaces, combustion, gasification-vitrification and even dissolution-distillation methods. Many companies are putting in effort to valorize this type of waste and minimize loss both materialistically and economically (SIGRAUTO - "Best practices on EVLs management").

Another point for the change in transfer coefficients is the possibility to introduce newer and better separation techniques, especially with the rise of AI and starter computer systems to aid the selection. This segment can also vastly improve the municipal waste treatment, as discussed in its own segment, by returning materials improperly disposed of in their rightful streams.

Further down the line, the light non-metallic fraction gets separated to its components such as glass, different plastics and paper/wood. Paper and wood can be recycled together to obtain new paper, as discussed in the packaging waste section, or if their masses are too low then they are simply used as a fuel source. Plastics are usually separated only by color and are then further processed in a specialized plastic recycling facility. This might change in future if products have the indefinable QR code or digital passport on their products which will make distinguishing which plastic it is just by scanning. This type of identification methods will be used for hazardous substances also- such as mercury and cadmium in batteries It can also be argued that this technology would help a lot more for municipal waste, whilst here most of the products are shredded and therefore unscannable unless removed manually.

The techniques used in this sector vary vastly. These could include density separation/froth floatation, optical separation, air centrifuges, gravity separators etc. These also shouldn't affect the ANM by much however in some of these processes there are some none-abrasive liquids, including water, present that could potentially affect an ANM if it's a coating. Further, this fraction doesn't always include a washing step. The only reason it would is to lower the amount of dust collected on top of the appliances if it was kept outside for too long (because it could affect the total mass and therefore the price), but it isn't a necessity like it is for example for packaging waste which has been in touch with food.

This non-metallic fraction, shredded or not, is sent to recycling facilities that specialize in this type of waste, and they usually have some separation machinery of their own, similar to the one mentioned above. This means that transfer coefficients have to be taken into account again since there could be further loss of material, as well as some getting back on the right track.

Lastly, it is important to note that depending on how automatic and manual a facility is, there should be different transfer coefficients. It could be said that manual work results in less mistakes, especially if it is not work on a moving lane. Wang et al. (2016) suggest that the accuracy of manual disassembly and sorting is typically less than 90%, which means that error

rates could be around 10% or higher depending on the complexity of the disassembly task and the working condition.

There is also the possibility of a thermal pretreatment depending on the input. Depending on the target material, this process could promote some reactions, degradations or volatilization, especially of metals.

Lastly, it should be emphasized that there is no specific way to arrange the process structure, and all plants utilize a combination well suited to them, which has the best output and optimal spending.

## 10.2 Temperature exchange equipment

Temperature exchange equipment, which includes items like refrigerators, freezers, air conditioning units, and heat pumps, requires careful handling due to the presence of hazardous refrigerants (freons) and oils. Components containing these and possibly mercury are manually removed from the machine. Non-hazardous parts are sent to the shredder or further manual dismantling. Hazardous parts are treated with specialized tools like "piercing pliers" or "drilling heads," which safely puncture the circuit to release and capture gases (such as R-12 and R-134a) and oils. These extracted materials are then securely stored in tanks for further processing or disposal. The compressors, containing oil, are drained and then sent to size reduction as well.

### 10.2.1 Refrigerants

essentially, there are two ways to deal with refrigerants, either they are destroyed or recovered. Park J. et al. (2019) and Niza S. et al. (2009) explain that destruction of refrigerants is done via an incineration process or using plasma technology, while recovery can be split between storage, recycling or reclamation. Recycling is easier to achieve than reclamation. It includes passing the refrigerant through filter-driers to remove or reduce moisture, oil, chloride acidity, non-condensable contaminants and particle matter. A refrigerant recycled in this way is viable to be used only in the same system from which they were extracted, and it doesn't get the certification as a new refrigerant would, therefore it is mostly practiced for maintenance. On the other hand, reclamation strives to clean the refrigerants enough for any use, on par with new ones. This process involves filtration (similar as in recycling), dehydration and distillation. Beforehand, a phase separation is done with the oil. After the filtration process, dehydration is done at mild temperatures (40°C to 60°C). Distillation however is done at temperatures below 0°C (-26.3°C for R-13a and -40.8°C for R-22).

### 10.2.2 Blowing agents

Based on research done by Keri C. (2019), blowing agents like CFCs, HCFCs and HFCs are used in the insulation (polyurethane) foam in fridges. The foam is shredded and grinded in order to release the blowing agents. The ozone-depleting gases are then captured. The gases are then either subjected to thermal cracking, to break down the harmful gases or they can be reused.

## 10.3 Screens and monitors

This category includes Cathode Ray Tube (CRT) monitors and flat-screen televisions, both of which contain hazardous materials like leaded glass and mercury. As CRTs aren't being produced anymore, their chances of containing an ANM are nonexistent and therefore excluded from this study. That leaves mostly Light emitting diode (LED) technologies. This category is first handled manually to remove the LED panel, screen and other internal parts, as seen in

Figure 17. As a greater fraction of LCD-containing devices with LED backlights reach end-of-life management operations, automated device characterization equipment will become increasingly economical to separate devices that require CCFL removal from those that do not.

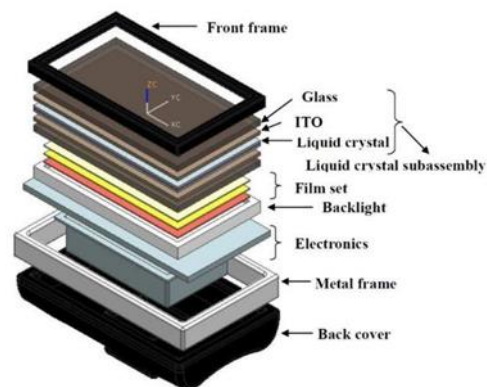


Figure 17. Structure of an LCD-LED monitor (Source: Boundy R. and Taylor P. (2018))

Of the components identified in the figure, the ones containing only plastic, such as the back cover and only metals such as the frame are directly sent to recycling. The film set also consists of three plastics which are recyclable and are sold separately. Electronics are taken apart and send to their respective streams – PCBs and cables are sold separately to different facilities for further treatment. This holds true for the two products regardless of what type of equipment they originate from, and their detailed recycling is discussed later in the text. That then leaves the Liquid crystal display (LCD) sandwich structure front screen and the backlight where the LEDs are placed.

#### 10.4 Lamps

Lamps, including fluorescent tubes and compact fluorescent lamps (CFLs), contain hazardous materials such as mercury and require a fully automated treatment process. The lamps are first crushed in a controlled environment to minimize the release of hazardous substances. The crushed materials are then separated into different fractions: glass, fluorescent powder, and metals like aluminum and steel. The fluorescent powder, which contains mercury, is captured by vacuum systems and collected in barrels for further treatment, usually involving distillation to remove the mercury. The separated glass can be recycled into new products, while the metals are recovered through additional shredding and electrostatic separation processes.

Lamps have the potential to contain phosphorus, and its recovery can be made using ionic liquids. Ionic liquids are said to be highly selective and purifying for this section as well as for batteries. Schaeffer N. et al. (2018) even suggests the use of ionic liquids in the selection and sorting stage as well as the hydrometallurgical one. They also proclaim the importance of better efficiency in the sorting stage if ionic liquids are to be utilized later on.

#### 10.5 Large equipment

Large equipment, such as washing machines, dishwashers, and other large kitchen appliances, is processed using fully automatic shredding and separation systems. The equipment is first fed into large shredders that break it down into smaller pieces.

Before shredding, older equipment that contains metallic capacitors filled with hazardous materials like polychlorinated biphenyls (PCBs) must be manually removed.

## 10.6 Small equipment

Small equipment, which includes household appliances like toasters, microwaves, and irons, undergoes a combination of manual and mechanical processes. Before the equipment is shredded, certain hazardous and non-hazardous components, such as batteries, toner cartridges, and glass parts, are manually removed.

## 10.7 Small IT and telecommunication equipment

Small IT and telecommunication equipment, such as mobile phones, routers, and small computers, contain valuable components that require meticulous manual dismantling, given the high value of the components found. Essential constituents of many EEE products, in particular IT and communication equipment, are base metals (Fe, Cu, Al, etc.), precious metals (Au, Ag, Pd) and speciality metals (In, Sb, Te, Ta, rare earth elements (REEs), etc.) (Schaeffer N. et al. (2018)). However, screens and plastics which contain a lot of additives (like flame retardants) are rarely made into pellets and are mostly used for energy recovery. Moreover, the small size and weight makes it difficult to make a profit out of them.

Small case studies with an outlook for recycling of these specific WEEEs can be found in the Annex: LCD, LED, Wind Turbines, Photovoltaics, Toners, Printed Circuit Boards and Cables/Power Supply.

For more information on **PCBs** and **Cable and power** supplies look in to supplementary information, sections 5 and 6.

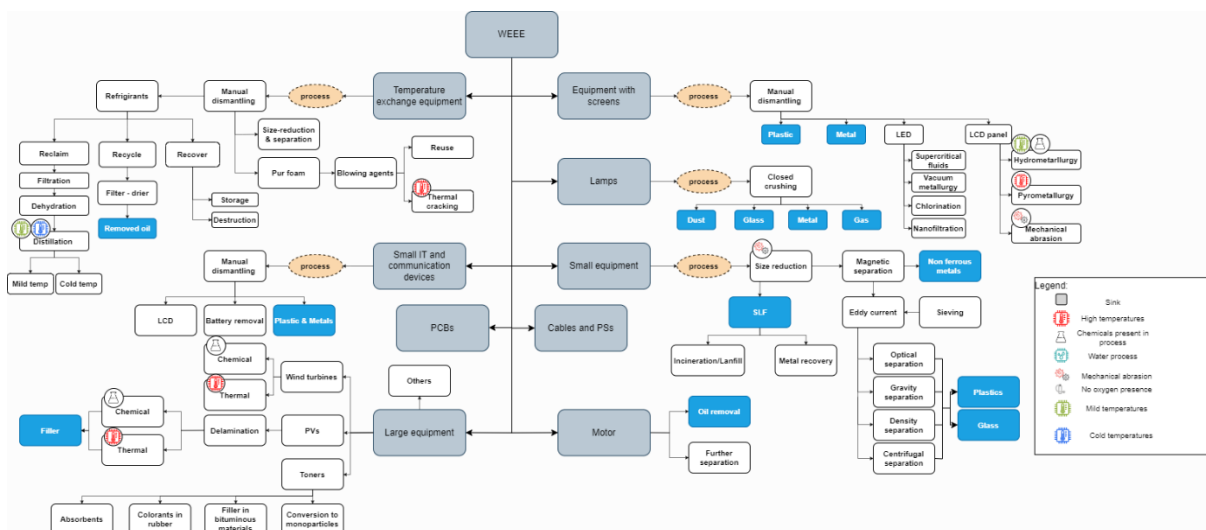


Figure 18. WEEE material flows in recycling streams

## 11 Textiles

Discarded textiles can be primarily divided into pre- and post-consumer goods. The first are by-products, also known as “clean waste”, coming out of manufacturing including offcuts, scraps and defective items, which are a lot simpler to recycle because of their uniformity of material. If an ANM is present in the system, there is also a possibility for them to be contained in the pre-consumer offshoot. On the other hand, post-consumer goods, which make up 85% of textile waste (McKinsey, 2022), consist of discarded garments and textiles after their use and are more complex because of their fiber content, varying degrees of wear, and contamination with dirt, dyes, and other substances. Fiber content can be explained as the nature of the material as divided between natural fibers (ex. Cotton, silk, wool), synthetic (ex. Polyester, nylon) and blended fibers, each of which requires different handling. A study done by Damayanti D. et al. (2021) also added another group in here called regenerative fibers also called semi-synthetic and defined as produced by natural polymers through processing, which includes materials like rayon, viscose, cuprammonium and acetate. Other segregations place this category within the synthetic fiber group.

Additionally, some studies have also added a third category within the primary segregation, isolating industrial textile waste as a separate category which includes waste generated from commercial applications, such as upholstery, carpeting, and other industrial uses. As these will probably be swept up into the same textile management systems as the others they will not be discussed in the later text. That being said, it is important to note that if a material falls within this category its possible to change its transfer coefficients with tendencies such as – waste from industry being more recycled or more being sent to energy recovery.

Regardless of the type, technological treatments are available for most textiles. However, at this stage a lot of them are either exported, incinerated or landfilled due to inadequate waste management systems (Sandberg E. and Pal R. (2024)). According to the McKinsey report, of the textile waste generated in the EU only 22% is recycled or reused. If the geographical scope is extended to all of Europe that number decreases to just 12%, as reported by the European Environment Agency (EEA). McKinsey also estimates that if the materials are properly selected and recycling centers are established, about 70% of the textile waste is eligible for closed loop recycling also known as fiber-to-fiber recycling, while the remaining 30% can be recycled in an open loop. Another source, GFA & BCG – 2017, claims that Across the European countries, only 18% of clothing is reused and recycled, while 30% is incinerated and a significant fraction of 70% goes to landfills.

To achieve these numbers the EU has placed an obligation for all the textile waste to be collected separately starting 2025. The EU member states’ reuse and recycling targets for municipal waste have been set at 55% by 2025, 60% by 2030, and 65% by 2035. EEA reports that half of the current EU-27 member states already have textile management systems, with an average collection rate of 30-35% for post-consumer textiles in charge of collection, however their main goal is reuse. From the collected waste just above 50% is considered as reusable. However, this collected waste, even ones deemed reusable is largely exported to African countries, like Kenya and Ghana, and some countries in Asia also has led to some environmental problems arising due to an improper infrastructure to handle the landfills. The current data from the McKinsey report suggests that 50% of the collected waste goes to international second-hand markets and only 10% goes to intra-EU recycling markets. Data continues to say that 30% of the collected waste undergoes downcycling or open-loop recycling

and the rest is split to incineration and landfill. Incineration of textiles is practical for energy recovery since most textiles have high-energy contents.

As the collection goal still doesn't cover recycling, it could be said that until proper investments are made, the trend of export of textiles will remain well until 2030. Further, as the market of fast fashion is rapidly growing in the EU, from both domestic production and import, a recent article written by expert Andreas Bartl working for the International Solid Waste Association (ISWA)'s Waste Management World magazine did a cover story on textile recycling highlighting that, considering the growth of the textile market, even if 50% recycling rate of the fiber-to-fiber type is achieved by 2035, the demand for primary raw materials would remain nearly unchanged.

Still, McKinsey predicts that closed-loop recycling can reach between 18% and 26% by 2030, because textile recycling could be an independent and profitable industry by then, generating potential profit of 1.5 to 2.2 billion euros, yearly. They have also outlined that to achieve this an initial investment of 6 to 7 billion euros has to be made.

### 11.1 Sorting and separation

As mentioned, the first step of separation is done between garments for reuse and the ones for recycling or disposal. So far, this is mostly done manually, weather by companies or help organizations. There isn't much that can be done to automatize this process, which is why it represents a big problem for recycling textiles, especially post-consumer. The process is long, ineffective for large-scale operations and labor-intensive. After this sorting is done the next thing to look out for is to remove all other materials that are mixed up in the fibers, like buttons, zippers, labels and other additions to the garments. This type of sorting may require mechanical methods for size reduction like cutting, shredding and disintegrating to break down garments before they can be separated.

Additionally, where EWL is concerned, chapter 4 describing wastes from the leather, fur and textile industries, also includes shoes and possible accessories in their definitions. As shoes can be treated as composites between rubber and fibers, they have to be sent for either pretreatment, as discussed below, or to disposal. There are also methods like supercritical carbon dioxide treatment which can dissolve the adhesives between the composite material and in this way the rubber and textile parts can be separated.

Lastly, the separation between fiber types occurs. Currently, there exist emerging technologies relying on near-infrared (NIR) spectroscopy and other optical sensors based on reflected light from the materials. NIR spectroscopy can quickly and accurately distinguish between various textile fibers, such as cotton, polyester, and nylon, even in mixed fabric compositions. According to Damayanti D. et al. (2021) this achieves a recognition rate of 98%. However, recognition doesn't mean effective separation just yet. Efforts are being made to include robotics and AI to enhance the speed and accuracy of sorting. It is worth noting that if municipal solid waste centers do include sorting mechanisms it is possible to retrieve the waste that was wrongly discarded there. Grading can be done to the materials obtained based on the quality, color and fiber content.

### 11.2 Pretreatment

It is common for post-consumer textiles to be heavily soiled by contaminants like dirt, oils and other impurities, for which washing is practiced. When washing is applied, filters have to be

used to limit the amount of possible micro, bigger and smaller fiber particles contaminating the waste water stream.

After that comes a process of dye or finish removal. Currently, only 1% of clothes end up in proper recycling in the EU, and those are mostly white garments. Colored ones are usually looked over because of the complexity, their need for more pretreatments and the unpredictability of the products' coloring at the end. Dyes can either be organic compounds or based on heavy metals as well as the possibility of them being ANM. The papers by Määttänen M., et al (2019) and Tayyaba N, Younas T and Ali S. (2019) provide several dye-removing techniques that can be used in textile recycling, focusing particularly on cotton waste. The primary techniques discussed for dye removal include chemical refining sequences. For most of the pretreatment techniques the temperatures don't exceed 150°C, so as to not damage the fibers, especially synthetic ones. The processes are usually lengthy and highly corrosive.

- Reductive Color Stripping

Reductive color stripping is a chemical process that involves breaking down dye molecules using reducing agents. The reducing agents, such as sodium hydrosulfite and caustic soda, are used to strip dyes from cellulose fabrics dyed with reactive dyes. This method targets the chromophoric groups within the dye molecules, effectively breaking the covalent bonds between the dye and the fiber. The process is influenced by various factors, including the concentration of the stripping agents, temperature, and the type of fabric. However, this method can cause significant damage to the fabric due to the harsh chemicals involved, leading to strength and weight loss of the treated textiles.

- Hot Alkaline Extraction (HCE)

Hot alkaline extraction (HCE) is a process used to remove silicate and polyester residues from recycled textiles, which also effectively strips dyes from the fibers. This process involves treating the textile waste with sodium hydroxide at elevated temperatures (around 110-120°C). The high temperature and alkaline conditions help break down the chemical bonds between the dye molecules and the fiber, effectively removing dyes, especially reactive and direct dyes. HCE is particularly effective in degrading reactive dyes, which form covalent bonds with cellulose. The alkaline environment disrupts these bonds, causing the dye to lose its color. This method is often the first step in dye removal before applying other refining processes.

- Ozone Treatment (HCE-Z)

Ozone treatment is another technique employed to degrade dye molecules in textile recycling. Ozone, a powerful oxidizing agent forms hydroxyl radicals, which break down the chemical structure of specifically organic dyes, especially those with azo chromophores, which are common in reactive and vat dyes. The process is typically conducted in a medium consistency reactor, where the textile waste is exposed to ozone gas in the presence of an acidic medium (adjusted with sulfuric acid) at mild temperatures and achieves high efficiency. The ozone attacks the chromophore groups within the dye molecules, leading to the loss of color. This method is particularly effective for removing stubborn dyes that are resistant to alkaline treatments otherwise called reductive stripping, such as vat dyes.



- Peroxide-Based Treatments (HCE-P)

Hydrogen peroxide is used in textile recycling as a bleaching agent that can also remove dyes. After initial treatments like HCE and ozone, hydrogen peroxide is applied to further increase the brightness of the fabric. The oxidative nature of hydrogen peroxide helps break down any remaining dye molecules that survived previous treatments, ensuring that the textile waste reaches a high level of brightness. This step is crucial for producing a white or near-white material that can be easily redyed in subsequent processes. Hydrogen peroxide is often used in conjunction with other chemical treatments to maximize dye removal effectiveness.

- Dithionite Treatment (HCE-Y)

Dithionite is used as a reducing agent in the dye removal process. This method is especially effective for vat dyes, which are known for their high colorfastness. Dithionite reduces the vat dyes, converting them back into a soluble form, which can then be washed out of the textile fibers. The reducing environment prevents the reattachment of the dye to the fiber, thus ensuring thorough dye removal. This technique is particularly important for managing textiles dyed with vat dyes, which are otherwise difficult to decolorize due to their strong attachment to the fiber

- Photo-Catalytic Color Stripping

Photo-catalytic color stripping is an advanced technique that uses light and a catalyst, typically titanium dioxide (TiO<sub>2</sub>), to generate reactive species capable of breaking down dyes. The paper emphasizes that this method is particularly effective due to the generation of hydroxyl radicals and superoxide ions under UV light, which can degrade even the most stubborn dye molecules. This technique is noted for its high efficiency, low environmental impact, and energy savings. It is considered superior to both reductive and oxidative stripping because it avoids the use of harsh chemicals and operates under mild conditions. The photo-catalytic method is presented as an innovative solution for the textile industry, offering a sustainable approach to dye removal and fabric recycling.

The stripping methods presented is how the bonds between the dye and fabric are broken, however to remove the dye from the solution absorbents have to be added. Reports include the use of nitric acid-modified activated carbon (AC-HNO<sub>3</sub>), tin-doped ZnO nanoparticles and even ethyl acetate. These absorbents can be added during the main treatments also, especially the solvolysis types.

Other pretreatments are done to reduce the complexity of the fibers. So far, alkali, acidic or ionic liquid pretreatment are available. Alkali pretreatment, using bases like sodium hydroxide, is effective for lignin solubilization and reducing cellulose crystallinity, thereby enhancing the digestibility of cellulose for subsequent processes like enzymatic hydrolysis. Acid pretreatment, utilizing sulfuric or phosphoric acid, breaks down polymeric structures in hemicellulose, increasing cellulose availability and improving biodegradability. However, acid pretreatment often requires corrosion-resistant equipment due to the harsh nature of the chemicals involved. Ionic liquid pretreatment offers an environmentally friendly alternative, using solvents that dissolve cellulose at moderate temperatures without degradation. This method is particularly effective for cotton waste, providing high glucose yields for bioethanol production. These treatments occur at mildly elevated temperatures, according to the feed of

material. Only one process developed by Li S. et al. (2014) requires temperatures to be at – 20°C.

### 11.3 Natural fibers

Natural fibers make up 29% of all fabrics produced and use natural resources to be produced. They can further be separated by origin types such as plant origin (cotton, linen hemp), animal origin (wool, silk) and mineral origin (asbestos). They also require large amounts of resources and cultivation, in comparison with synthetic fibers. (Li S. et al. (2014)

Some natural fibers like cotton are also treated as biodegradable materials and are easily dealt with as described in the section for Biodegradable waste. Simply explained, they are degraded by living organisms into water, carbon dioxide, methane and other non-toxic residues, however the dyes and additives can contaminate groundwater or release undesired gases. As part of the exhibition in the Basel Paper Mill it is explained how in the past, since most clothes came from natural fibers, the wastes were left to rot and turned into pulp which would then be turned into printing paper. The practice was stopped because they had issues securing enough waste clothes from the citizens to supply the printing demand, which is why they turned to wood, which was found in abundance. Interestingly, in the past clothes were recycled more than they are today. However, some natural materials like wool are not good biodegradable materials. Generally natural fibers are hard to recycle with currently available techniques so they end up getting downcycled.

### 11.4 Synthetic fibers

Conversely, synthetic fibers which make up the other 71% are easier to recycle with available technologies but are persistent environmental pollutants who also cause huge microplastic release, if they find themselves improperly discarded. Another, disadvantage is that they are petrochemical-based and energy-intensive to produce. They can be divided by material type including natural polymers (manmade cellulosic fibers previously discussed as regenerative or semi-synthetic), synthetic polymers (PET, PA) and inorganic materials (glass). The latter are only used for other reinforcements or disposed of. The first two however stand a chance at recycling, especially the synthetic polymers.

### 11.5 Fiber blends

Fiber blends are the biggest hurdle in the recycling of textiles. There are some methods to divide the two used materials from each other, as will be explained below, however some materials remain untreatable. Such is the case of elastane which is a polyurethane material and no methods work. Therefore, a lot of these blends are used as feedstock or in energy recovery.

### 11.6 Recycling technologies

Recycling products can enter back into the process chain at multiple steps and as multiple types of materials, which requires at least some of the steps of production to be transversed again. Depending on how much the waste is degraded, or how far back it goes in the process chain the technologies can be divided as:

1. Production of cleaning and wiping rags (CWR) aka downcycling
2. Recycling where the fiber structure is kept aka mechanical recycling
3. Recycling down to the polymer aka thermal recycling
4. Recycling down to the monomer aka chemical or biochemical recycling

CWR is a downcycling method which only uses a size reducing mechanical treatment – cutting. The material is cut in specific dimensions and after it has been used it is sent to energy recovery facilities. This process is done to extend the life of the product with minimal efforts.

### 11.6.1 Mechanical recycling

Other than treatments fit for biodegradable materials, natural fibers are usually treated mechanically, while this process is decidedly unfit for blended textiles because the drop of quality is too drastic. Various size reduction methods are used, such as chopping, shredding or grinding, which are utilized post-cut. One example is the Grett machine, which is often used for mechanical recycling for textiles, shown in Figure 19. Sometimes the textile is moistened to enhance the tearing process.



*Figure 19. Garnett textile recycling machine (Source: <https://www.indiamart.com/proddetail/garnett-machine-14013596412.html>)*

The textile waste is first dismantled and cut into smaller pieces, typically 4-6 cm in size. Accessories like buttons, zippers, and labels are removed, either manually or automatically. Coatings and prints are generally avoided as they can lower the quality of the output or cause issues in further processing. The pre-treated textiles are fed into tearing machines, which consist of high-speed rotating cylinders with saw or steel pins that tear the textiles apart, releasing individual fibers. The process typically involves several stages, starting with coarse spikes and gradually using finer spikes to achieve the desired fiber opening. The torn fibers are then carded to disentangle, clean, and align them, producing a continuous web or sliver. Additional steps might include fine-opening, blending, and cleaning to remove remaining contaminants and ensure consistent output quality.

While this keeps the fiber texture intact, it also significantly shortens fiber length, which usually means decreased quality. The resulting textiles are either spun into new yarn to make clothes or sent to non-woven fabric manufacturing, like for example carpet padding or mattress stuffing. Non-woven manufacturing includes garnering, carding, or air laying webs, which are subsequently mechanically, thermally, or chemically bonded. Else, one of the options is also making a flock<sup>4</sup>, which can then be used as additives in construction materials such as bricks. What's more, if the recycled fabric is spun into new yarn (re-woven or knitted) it has to be

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<sup>4</sup> flock - the art of enhancing textiles by applying minuscule fiber dust particles to their surfaces, creating a velvety texture and intricate patterns that engage both the sense of touch and sight

mixed with virgin materials precisely because of the length. That being said, efforts should be made to limit the creation of short fibers by optimizing the mechanical processing. What's more, there is a difference depending on which material it is. Depending on how pure the cotton is it is sent to different facilities. Cottons composites are sent to brick kiln factories because the addition of cotton enhances tensile strength. Else, clean cotton is used to produce medical textiles or absorbents for heavy metals and the waste can be additionally treated to increase adsorption efficacy. Wool, however, is usually spun into new yarn and used back in the textile industry.

### 11.6.2 Thermal recycling

Thermal recycling can sometimes use mechanical methods as pretreatments for the procedure. It is only suitable for synthetic fibers made of thermoplastic polymers like polyester (PET) or polyamide (PA 6,6). The process begins with shredding and then melting to obtain pellets for re-extrusion. More often than not, the waste flakes of fibers obtained are mixed with virgin materials. During extrusion the material is also melted via heating elements and internal friction generated from the moving screw. During melting, volatile substances might be produced as by-products, which can be extracted using a degassing system. The melt is then cooled with water to prepare it for the next stage of processing. Most contaminants need to be removed for this process to be utilized. Therefore, some of the pretreatments like sanitation steps or drying have to be done beforehand.

Presently, this process is used more for PET bottles rather than waste textiles. The PET bottle waste is spun into fibres and used to create garments. Most fast fashion companies who have decided on a green approach have in fact been using this method to produce “greener” products.

Other than extrusion, which is the easiest process to employ other processes such as gasification and pyrolysis are applicable, but their processes are mainly discussed in the Tire section. The outcomes of these processes are very reliant on the input as they are suitable for most textile types, including composites.

Thermal methods can only be used on natural fibres like cotton to produce lyocell (modified cellulose) fibres in a fibre spinning process, thus substituting wood. This fabric can also be used as an absorbent.

### 11.6.3 Chemical recycling

Chemical recycling of textiles involves breaking down polymers in the fibers into their constituent monomers, which can then be re-polymerized to create new fibers. This method is particularly effective for recycling synthetic fibers like polyester, as well as some natural fibers and natural polymers. One common chemical recycling process is glycolysis, where polyesters are treated with glycols at high temperatures, breaking the ester bonds and producing oligomers that can be further processed into new polyester fibers. Other processes include hydrolysis, methanolysis, and alcoholysis. In this way monomers are obtained that need to undergo polymerization before they can be re-spun, for example, mono-ethylene glycol [MEG] and purified terephthalic acid [TPA] have to be brought back to the polymer level, such as PET. The process may require post-treatment procedures such as purification, separation of contaminants, distillation, and drying. Depending on which solvolysis method is chosen, the products will differ. From PET when using hydrolysis TPA is obtained, for alcoholysis dimethyl terephthalate (DMT) is recovered and from glycolysis PU or resins (epoxy, polyester) and Bis(2-hydroxyethyl) terephthalate (BHET) is produced. (Juanga-Labayen, J. P et al.. 2022).

Another process for chemical recycling is the well-established pulping process, which is an upgrade of the process mentioned in the Basel Paper Mill. The cellulose is suspended in a chemical solution, partially depolymerized to a slurry or pulp. The process may include steps for decolorization and bleaching to remove dyes and finishes. The resulting pulp is then processed into regenerated cellulose fibers using techniques like viscose or Lyocell spinning. Pulping can also be done for blended fabrics, where the natural fiber will enter a pulp while the other will be left pure and then purified.

There are other options for blended fabrics using chemical recycling. As seen before, different types of fibers can't be extracted at the same time so one is usually converted into another product or lost. Segregation can be solvent-based or hydrothermal. A synthetic fiber obtained in this way can be spun into a new textile in this way.

The hydrothermal method uses high temperatures and pressures in an aqueous environment to decompose textiles into their constituent phases: liquid, solid, and gas. The textiles are treated with hot, pressurized water (subcritical water) and green acids. Cotton is decomposed into cellulose powder, while polyester fibers are separated via filtration. In some processes, PET is depolymerized into monomers like TPA and EG, which can be repolymerized, while some groups have also reported complete degradation of polymers such as PA 6,6. This method does not require extensive pretreatment, making it a versatile option for textile recycling. Hydrothermal recycling can be classified into five groups based on the temperature range that is used:

1. hot water extraction,
2. pressurized hot water extraction,
3. hot liquid water treatment,
4. hydrothermal carbonization, and
5. hydrothermal liquefaction.

Depending on the method and desired product temperatures range between 150 up to 700°C. The latter has the capacity to produce nanomaterials and activated carbon. Moreover, if blends are used for the process temperatures used do not exceed 140°C. Cotton or other natural fibers have to be dissolved first here also using acidic solutions. Interestingly, alkaline solutions don't show any effect on these fibers. The process can produce valuable chemicals or fuel from textile waste, although it requires substantial energy input and specialized equipment to manage the high-pressure conditions.

Solvent-based recycling or solvolysis is different for different materials. Cellulosic fibers like cotton are dissolved in solvents like N-methylmorpholine N-oxide (NMMO) or ionic liquids to regenerate cellulose fibers. Processes like the Lyocell process are used, though these methods are costly and energy intensive. Synthetic fibers are usually treated via depolymerization, for example PET is transformed into terephthalic acid (TPA) and ethylene glycol (EG). This process requires higher temperatures and pressures, even though it can produce high quality fibers.

#### 11.6.4 Biochemical recycling

The most interesting process for fiber blends is enzymatic hydrolysis. This is used for blends of cellulose-based materials and petrochemical-based materials but can also be used for purely cellulose-based materials.

Enzymatic separation occurs when specific enzymes are used to selectively degrade one type of fiber in a blended fabric, mostly the natural fibers, leaving the synthetic part intact and thus facilitating the separation of different fiber types. The cellulose is broken down into glucose which is then used to make bioethanol or in other industrial applications. Various enzymes, such as cellulases and  $\beta$ -glucosidases, are employed depending on the textile material. It typically follows pretreatment to improve the yield. Pretreatment methods such as alkali or acid are often used to enhance the efficiency of enzymatic hydrolysis. The process operates under mild conditions, reducing energy consumption and minimizing the use of harsh chemicals. However, the current limitations the relatively slow reaction rates and the high cost of enzymes.

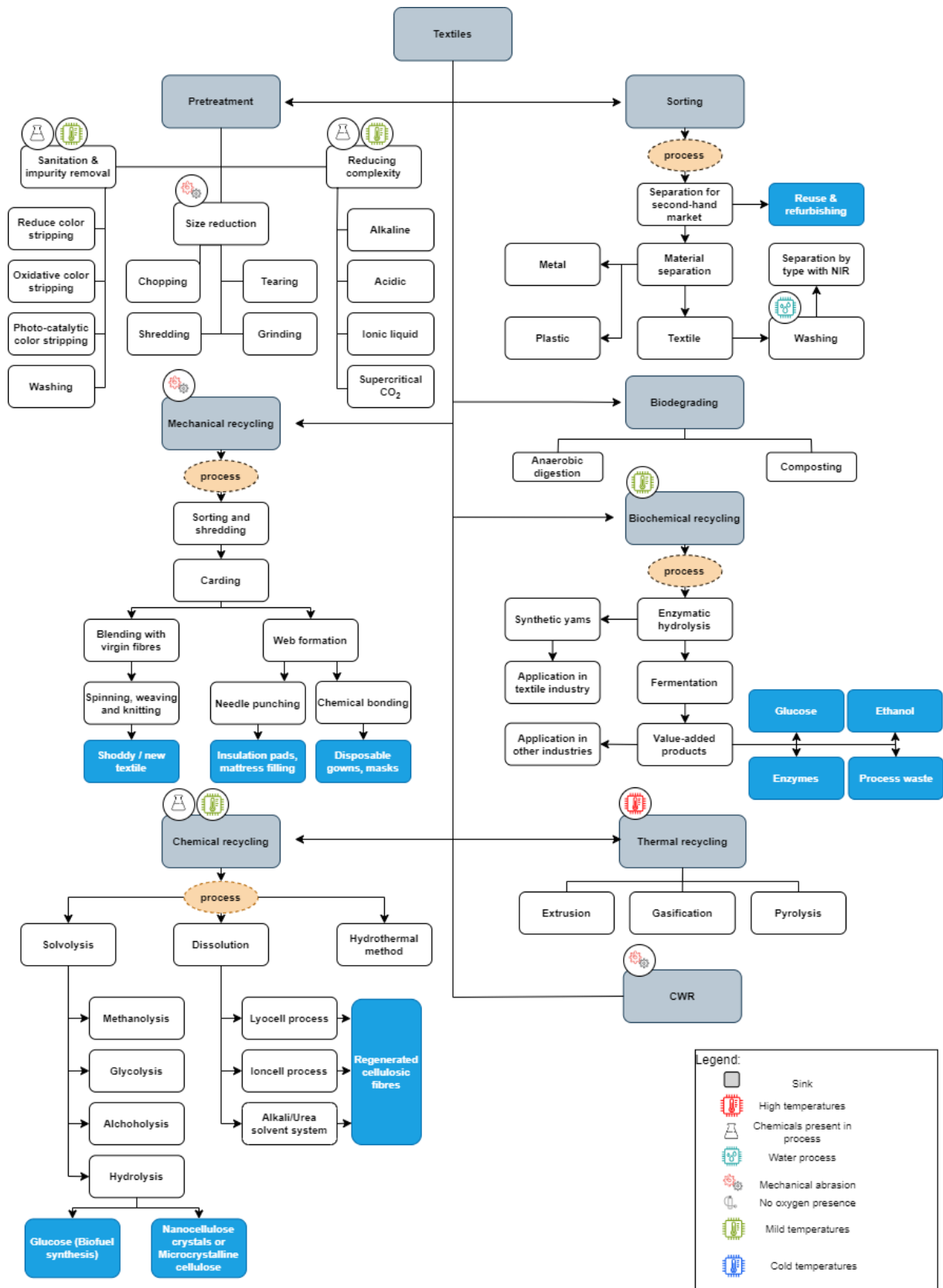


Figure 20. Textile material flows in recycling streams

## 12 Medicinal waste

Medicinal waste, often referred to as healthcare waste or medical waste, encompasses a wide variety of by-products generated by hospitals, healthcare facilities, veterinary institutions, and research laboratories involved in medical, diagnostic, treatment, and preventive care. There are multiple ways to divide medicinal waste.

The first segregation is between hazardous or non-hazardous waste, with a small percentage of about 15% classified as hazardous due to its infectious, toxic, or radioactive properties. Non-hazardous does not pose a risk to health and the environment and is treated as other municipal waste. However, hazardous medicinal waste must undergo special treatment, with classification occurring at the place of origin to ensure proper handling. Another typical categorization is based on the waste's physical characteristics, such as color, shape, and size. According to the World Health Organization (WHO) and the European Union (EU), medicinal waste is classified into several categories depending on the type of hazard it poses such as sharp waste, pathological, infectious, chemical, pharmaceutical, cytotoxic and radioactive. Sharps, such as needles, scalpels, and broken glass, pose a risk of injury. Pathological waste includes human tissues, organs, blood, and body fluids. Infectious waste consists of materials contaminated with blood, bodily fluids, cultures, and swabs. Pharmaceutical waste includes expired, unused, and contaminated drugs and vaccines. Chemical waste involves discarded chemical substances used in medical processes, while radioactive waste contains radioactive substances like unused radiotherapy materials.

Once treated, medicinal waste is either disposed of in landfills—particularly the ash produced from incineration—or repurposed when possible, such as through the recycling of treated sharps or plastics. Although not all types of medicinal waste are suitable for recycling, several categories can be processed for material recovery. A significant portion of non-hazardous waste, such as packaging, plastic containers, and disposable medical instruments made from materials like polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), can be recycled. After proper segregation and decontamination, these plastics can be processed and reused, reducing the volume of waste that requires incineration or landfill disposal. Metals from surgical instruments, prosthetic devices, and other medical equipment can also be recovered and recycled. This process typically involves sterilization and melting down the metal for reuse in manufacturing. Non-contaminated glass from vials, bottles, and laboratory equipment is another recyclable material, provided it is carefully segregated to avoid contamination with hazardous waste. Additionally, electronic medical devices, such as diagnostic machines, can be dismantled to separate and recover valuable components like metals, plastics, and circuit boards for recycling.

However, some types of medicinal waste, particularly those contaminated with hazardous chemicals or biological agents, are not suitable for recycling. These waste types may require advanced pretreatment technologies, which are often not readily available or cost-effective.

As with other waste, the handling procedure can be divided in pretreatment and treatment techniques. Pretreatment processes primarily involve mechanical techniques such as shredding, grinding, mixing, liquid-solid separation, agitation, palletization, and crushing. It's important to note that pretreatment does not eliminate infectious pathogens or fully disinfect the waste; rather, it prepares the waste for further chemical or thermal treatment by increasing the specific surface area of the solid pieces. Shredding is the most common pretreatment process, often



used before or after the main treatment. Another pretreatment of importance here is pelletization, which compacts medicinal waste into regular particles, typically in the form of pellets or briquettes. This process increases the waste's density, lowers its moisture content, raises its calorific value, homogenizes its physical and chemical properties, and simplifies handling, transportation, and storage. Pelletization is often used after thermal operations, preparing the waste for further energy recovery or disposal. Other mechanical pretreatments include agitation, filtration, and solid-liquid separation, depending on the type of waste and the requirements of the subsequent treatment. Treatment processes focus on disinfecting the waste, where some seek to avoid chemical change and some welcome it.

Incineration is one of the oldest and most common methods for treating medical waste. Over 50% of hospitals part of a questionnaire done by Health Care Without Harm Europe reported that national legislation requires incineration of hospital waste. This high-temperature process (typically 800–1200°C) effectively destroys all organic material, reducing waste volume by up to 90%. It is particularly useful for treating infectious, pathological, and pharmaceutical waste. However, incineration releases toxic emissions, including dioxins, furans, and heavy metals, requiring advanced filtration systems to mitigate environmental impact.

Pyrolysis is a thermochemical process that decomposes organic material in the absence of oxygen at 400-800°C, converting medical waste into valuable byproducts like syngas, bio-oil, and char. Pyrolysis generates energy with fewer pollutants than incineration but requires high capital costs and careful waste segregation.

Plasma Gasification uses a plasma torch to ionize gas and convert medical waste into syngas and glassy slag. Operating at up to 3,000°C, it can break down even hazardous waste with minimal emissions. However, its high cost and energy requirements limit its economic viability.

#### Autoclaving

Autoclaving or steam sterilization is second most commonly used method for treating medicinal waste, following incineration and its particularly favorable for infectious waste. It uses steam under high pressure at 121-134°C to disinfect waste without burning it, thus avoiding harmful air pollutants. This method uses steam to denature the proteins in pathogenic organisms and is widely applied for the disinfection of infectious waste, including laboratory and medical waste. Autoclaving operates on a low-temperature treatment technology that utilizes increased temperature, pressure, and time to deactivate microorganisms. Various types of autoclaves are available, including gravity-fed, pulse, and multi-vacuum cycle systems, with advanced methods incorporating features like vacuuming, internal mixing, fragmentation, drying, and compaction. Unlike incineration, autoclaving heats the waste to levels that disinfect without burning, thus avoiding the creation of harmful air pollutants. However, this method is unsuitable for the treatment of pharmaceuticals, radioactive materials, and pathological waste, and it is ineffective for large quantities of hazardous waste.

Variants of the autoclave system include the hydroclave, which heats waste indirectly through steam in an external jacket, and the chemiclave, which uses a chemical vapor for sterilizing surgical instruments. Despite requiring significant energy and producing some emissions, autoclaving is environmentally preferable to incineration, as it does not generate carcinogenic dioxins.

Microwave treatment is a relatively new method of sterilizing medical waste, utilizing high-frequency short waves that cause particle vibration, generating heat up to 200°C. This heat, produced by the oscillation of liquid molecules within the waste, is sufficient to kill pathogens and reduce the risk of infection. The effectiveness of this method relies heavily on the moisture content of the waste, as microwaves are more effective in a damp environment. Consequently, microwave units often incorporate humidifiers to ensure adequate moisture levels and shredding for higher effect. Microwave units can be batch or semi-continuous and are suitable for on-site or mobile treatment. After treatment, the waste can be disposed of as domestic waste in a sanitary landfill, and any wastewater produced should be treated, discharged, or reused. The primary disadvantage is the high capital investment and running costs, making the process economically challenging, especially for large-scale deployment in developing countries. Additionally, microwave treatment is unsuitable for certain types of waste, such as cytotoxic materials, volatile compounds, large metal items, and hazardous chemical or pharmaceutical waste. The presence of metal in the waste can create reflection surfaces, leading to non-uniform treatment and the need for special handling.

Other methods as identified by Giakoumakis, G., (2021) include

- Reverse Polymerization

Reverse polymerization (RP) is an innovative medical waste treatment technology that decomposes organic material using microwave energy in an oxygen-depleted or nitrogen-rich environment. This process breaks down complex molecules into simpler chemical compounds, effectively sterilizing the waste without combustion. Unlike traditional thermal treatments, reverse polymerization operates at moderate temperatures, allowing for precise control over the process. The primary products of reverse polymerization are gases, liquids, and solids, which can be further processed or safely disposed of. The process is also associated with high costs.

- Nanotechnology

Nanotechnology utilizes nano photocatalysts, which harness UV or solar energy to break down microorganisms from waste. The process generates hydroxyl species and superoxide anions that oxidize toxic pollutants into harmless substances like carbon dioxide and water. This technology, however, is still not ready to operate at a full-scale facility.

- Chemical Disinfection

Chemical disinfection is a widely used method that involves mixing crushed medical waste with disinfectants to decompose and kill microorganisms. The process can be divided into chlorine-based and non-chlorine-based systems. Sodium hypochlorite and chlorine dioxide are common agents in chlorine-based systems, while hydrogen peroxide is commonly used in non-chlorine systems. Chemical disinfection is fully automated, efficient, and cost-effective, but it is not suitable for all types of medical waste, such as radioactive waste or chemotherapy agents. Additionally, wet chemical treatments may produce residual liquid pollutants.

- Alkaline Hydrolysis

Alkaline hydrolysis is a process that transforms solid medical waste into an aqueous solution through the addition of an alkaline solution, typically sodium hydroxide (NaOH) or potassium hydroxide (KOH). The process is effective for destroying all classes of infectious waste,

including anatomical parts and tissues, by breaking down organic material into basic compounds. After digestion, the resulting sterile, neutral solution, known as hydrolysate, can be safely discharged into a sanitary sewer, used as fertilizer, or dehydrated for landfill disposal. The process is environmentally friendly, producing no harmful emissions or by-products.

- Ozonation

Ozonation is a chemical treatment method that uses ozone, a strong oxidizer, to sterilize medical waste. It is effective against a wide range of pathogens and does not produce harmful residues, as ozone decomposes back into oxygen. However, ozonation requires thorough shredding and mixing of the waste to ensure exposure to the bactericidal agent. This method is suitable for treating pharmaceutical waste, as well as water and air. The high operational costs and the toxic, explosive nature of ozone require careful handling and limit its use to small-scale applications.

- Thermal Plasma

Thermal plasma technology utilizes high temperatures generated by a plasma torch to treat medical waste. The intense heat effectively dehydrates the waste and disintegrates toxic compounds into harmless elements. Plasma treatment produces minimal emissions and can convert waste into valuable by-products like syngas, which can be used for energy generation, and vitrified solid slag, which is safe for landfilling. Despite its environmental benefits, thermal plasma technology is expensive and energy-intensive, making it less accessible for widespread use.

- Immobilization

Immobilization involves transforming waste into a stable, compact form by embedding or encapsulating it in materials such as plastic foam, cement, or clay. This method is primarily used for radioactive waste, as it prevents the dispersion of harmful substances during handling, transport, and disposal. After immobilization, the waste is typically buried in landfill sites to prevent contamination of groundwater. This process is essential for managing hazardous waste but is limited by the need for specialized materials and procedures.

- Promession

Promession is a novel treatment method that involves freeze-drying medical waste, particularly body parts, using liquid nitrogen. The process reduces the waste to a brittle state that can be easily crumbled into fine powder through mechanical vibration. The powder is then dried and any remaining metals are removed using an electrical current. Promession is a hygienic, odorless process that significantly reduces the volume of waste, making it easier to handle and dispose of safely.

- Torrefaction

Torrefaction is a thermal treatment that involves the dry carbonization of medical waste in an oxygen-free environment at temperatures between 200–300°C. The process reduces the waste to char, which is highly stable, hydrophobic, and energy-dense, making it easier to store and transport. Torrefaction also produces an oily liquid by condensing volatile matter released during the process. This method is simple, well-established, and suitable for medical waste

with low moisture content. The char produced can be used for energy generation, offering a practical and efficient solution for waste management.

- Wet Carbonization

Wet carbonization, or hydrothermal carbonization (HTC), is a thermochemical process that converts organic waste into hydrochar by heating it in water at high pressure and temperatures between 180–300°C. The process generates hydrochar, liquid fractions, and a small amount of gas. Hydrochar can be used as fuel, a catalyst, or for carbon sequestration. Although suitable for high-moisture waste, HTC requires significant energy input for pressurization and heating, making it more energy-intensive. This method is effective for treating medical waste when mixed with other organic materials.

- Vitrification

Vitrification is a high-temperature treatment that converts medical waste into a stable glass-like material. This process immobilizes hazardous components, especially heavy metals, by encapsulating them within the glass matrix, reducing their leachability and environmental impact. Vitrification is commonly used for high-level radioactive waste but can also be applied to other hazardous waste types. The process requires substantial energy input and is typically used in smaller installations. The vitrified product can be safely disposed of or utilized in construction, making it an effective long-term solution for waste management.

- Irradiation

Irradiation involves exposing medical waste to ionizing radiation, such as gamma rays, electron beams, or ultraviolet light, to disinfect it. This process disrupts the DNA of pathogens, effectively sterilizing the waste. Although efficient and fast, irradiation requires specialized containment, such as a concrete bunker, and does not reduce waste volume, necessitating additional processing like shredding. It is particularly suitable for treating infectious waste but is costly and requires strict safety protocols to protect workers from radiation exposure.

- Dry Heat Treatment

Dry heat treatment uses hot air ovens to sterilize medical waste through conduction, convection, and thermal radiation. This method operates at higher temperatures and longer exposure times than steam-based processes, effectively oxidizing and destroying microorganisms. It is simple to install, has low operating costs, and is environmentally friendly, as it does not produce toxic emissions. However, dry heat treatment is less effective on materials like plastics due to its slow heat penetration and may require complementary treatments for complete waste management.

- Converter Technology

Converter technology integrates various processes, such as sterilization, grinding, dehydration, and compaction, into a single unit for treating medical waste. The compact design and ability to operate under atmospheric or negative pressure make it suitable for on-site treatment, reducing transportation costs. It is a clean, chemical-free, and reliable technology that produces no harmful emissions. The converter reduces the weight and volume of waste significantly, making it easier to manage and dispose of. This technology is particularly useful in hospitals for managing infectious waste efficiently.

- Bio Converter

The bio converter is a treatment technology that utilizes biological processes to decompose organic medical waste. This method leverages microbial activity to break down waste materials, converting them into non-hazardous substances such as compost or biogas. Bio converters are environmentally friendly, as they produce minimal emissions and can handle a wide variety of organic waste types. However, the process is slow compared to thermal treatments and may require careful control of environmental conditions, such as temperature and moisture, to optimize microbial activity.

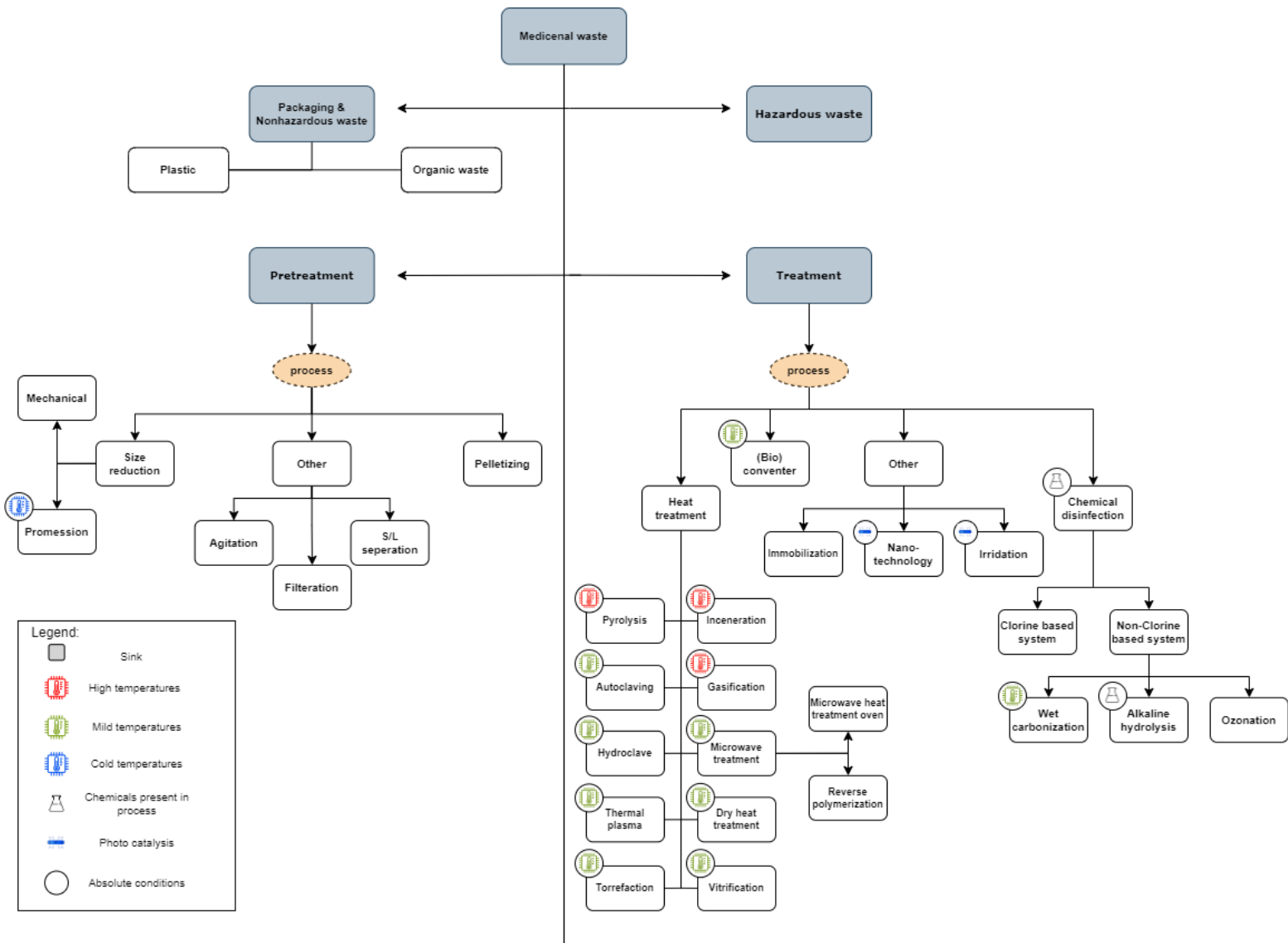


Figure 21. Medical waste material flows in recycling streams

### 13 Results from case studies

The case studies are represented by the two graphs bellow. Each flow, sink and stock are characterized by 3 numbers. The top number represents the mean of the values obtained for scenario 2. As the lower value the mean of scenario 1 is represented in the bottom left, and as the high mean value scenario 3 has the bottom right corner. More information on the results, complete with tables can be found in the Annex.







## 14 Discussion

### 14.1 Discussion on case studies

The best way to discuss the results is to analyse amounts of graphene ending up in the following sectors, as presented in Figures 25 and 26:

1. Environmental sinks
2. Technical sinks
3. Others
4. Elimination

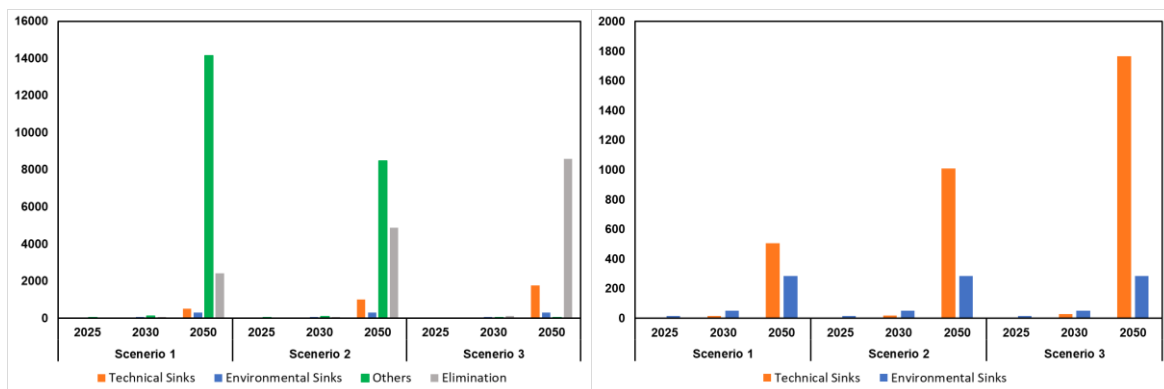


Figure 25. Accumulation of graphene in different sinks timewise and throughout scenarios for batteries a) all sinks b) environmental and technical sinks only

Production of graphene in the year 2017 was still relatively low and the market hadn't reached its full potential yet, explaining the low values entering recycling in 2025 for all scenarios. This trend is similar for 2030, when products from more recent years will enter the recycling market, considering that the average lifetime of a battery was considered to be 9 years. That being said, as the market for graphene is expected to mature by the late '20ies and early '30ies values of batteries ending up in sinks grow, and with it the amount which is improperly disposed of also grows. This should be a major concern for Scenarios 1 and 2 in the year 2050. The first graph representing batteries shows that in Scenario 1 a lot of the graphene will end up in sinks of improper disposal and export, hereby and in the graph represented under Others. Out of the two, improper disposal will have around 50% of the material yearly entering the market, leading to high accumulation values if things continue as they are now.

Improper disposal- this could be attributed to the EU not having set goals for the recovery of all types of batteries that have been listed in its directive. Moreover, improper disposal can also be attributed to the main product containing the battery rather than the battery itself.

Studying the case of e-scooters alone, currently these products fall under WEEE but don't have a proper collection strategy and are often improperly disposed of. As Trapp S. et al. (2022) have observed, with the e-scooters becoming very popular for rent in major cities like Paris, Cologne, Copenhagen and others, the vandalism on these products has also reached high levels. Moreover, the study observed that they are majorly thrown into bodies of water. It was concluded that the battery contents remain mostly protected when this happens, however action is still necessary. Not only that, but the municipality of Paris has also banned e-scooters in

2023(BBC, *Paris says au revoir to rental e-scooters*) for use in an attempt to stop this kind of vandalisms and mitigate injuries that resulted from the use of e-scooters. What's more, a lot of these products can be sent to maintenance, which can change the battery, making sure to deliver it to the proper recycling stream. However, a major problem is the cost. It turns out that the price to switch out a battery from such a device amount to about one third to half of its price, stated in an article by Epic Cycles, 2022, which is why many opt to buy a new e-scooter. Another point is the trackability of the products containing batteries. A lot of them get lost, stolen or shipped to other continents illegally because of their value. A report made in 2015 by the European Union Action to Fight Environmental Crime (EFFACE) reported that illegal shipments from the EU to China estimate to 8 million tonnes of e-waste every year (Illes A. et al. (2015)). Similar activities are taking place in other regions of Asia as well as Afrika. The case of e-scooters is just a recent example, however a lot of similar activities can be related to other WEEE and ELV products which contain batteries in them. Many case studies need to be done to affirm where battery-containing products end up in reality.

A lot smaller values are reported for other sinks such as the technical and environmental ones. On the whole, the amount ending up in environmental sinks stays almost the same throughout the years in all 3 scenarios. This suggests that the amounts ending up in environmental sinks are related to the operation of the processes themselves rather than human management of waste. With the optimization of main processes like production, manufacturing or recycling and auxiliary processes such as wastewater treatment and incineration these values stand a change of being decreased even further. Not only that but utilizing residues of these processes and fashioning new products from them can also decrease the value going to technical sinks. Moreover, technical sinks rise steadily with the increase of batteries going to recycling, suggesting a closer relation of the two. Therefore, if residues of recycling were designed into a new product, preferably an electrode material, the amount ending up in technical sinks will largely decrease as well. This of course relates to non-high temperature recycling processes.

On the other hand, when high temperature processes with the presence of oxygen are chosen for recycling, the graphene will end up being eliminated and transform into CO<sub>2</sub> emissions. Ermakov et al. (2015) and Šilhavík et al. (2022) both concluded that even though graphene has high oxidation resistance and structural stability as a stand-alone compound, however that changes when other products are present. Both studies confirmed that graphene burns rapidly and at much lower temperatures (550°C) than it normally would (1500°C) when a matrix was introduced. Not only that, but graphene might even act as a combustion catalyst of the other compounds present influencing thermal decomposition and reducing agglomeration, as researched by Lu et al. (2021). Presently, as identified by the general recycling technologies presented in this thesis, thermal methods are by and large seen as the answer to composite recycling, which is why big amounts in the Elimination sink. Unsurprisingly, as more waste is collected for recycling and this method is chosen, the mass of eliminated graphene will grow, reaching its peak in Scenario 3 with most of the collected waste going to recycling. The same trend is seen in the tire results graph as well.

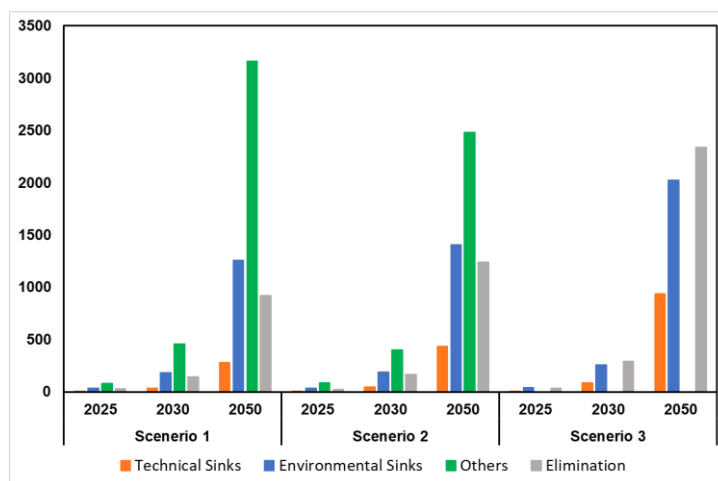


Figure 26. Accumulation of graphene in different sinks timewise and throughout scenarios for tires

The second graph representing waste tire flows shows a lot more versatility in its sinks. Scenario 1 shows the growth of material, whether its being exported or improperly disposed of, with the immense rise of the group of sinks named Others. This is in line with the trend that EU keeps exporting most of its waste tires elsewhere rather than focusing on a closed-loop market. This proves that a lot of the current situation isn't very opportunistic for tire recyclers within the EU, which is why organisations such as EuRIC have been pushing for a ban of export, for recycling or disposal, of tires and other materials. This number also shows that most of the tire waste will be untraceable, either because it's out of scope for the EU or improperly disposed of in the first place.

Scenario 2 and 3 however, show a decrease in Other values, although still high in Scenario 2. Unfortunately, for tires, with the increase of circularity, the amount ending up in Environmental sinks also increases. This is related to release that tires have during their use phase, and release during the use of the recycled products that could contain it. One such example involves the biggest market for recycled tire rubber other than energy recovery, and that is the production of soft fall surfaces. Soft fall surfaces encompass areas like sporting pitches, playgrounds, running tracks etc. It has recently been found that from such surfaces there is major leaching of microplastics into natural and urban soils. Although specific numbers on how much exactly vary depending on source, there had even been talk of banning waste rubber to be used in such places again. The tires recycling association and EuRIC stand against this, because it would be a huge blow to the recycle tire business sphere and instead suggest adding systems for control of such releases.

Another point to be made is that with the addition of graphene, the flows of microplastics might decrease. Multiple studies show, that addition of graphene into plastics and similar materials decreases their speed of degradation or aging. For example, the study by Hocker et al. (2017) found that the incorporation of graphene oxide into polyamide-11 was shown to decrease the rate of hydrolytic degradation by reducing the molecular mobility of water and the polymer chain, resulting in a higher equilibrium molecular weight compared to neat polyamide-11. Similarly, Finnis et al. (2016) found that the addition of graphene nanoplatelets to PLA slowed down the rate of degradation under elevated temperature and humidity. The graphene acted as a moisture transport barrier, reducing moisture diffusion into the polymer, although

significant degradation still occurred over time. Additionally, Patwary & Mittal, (2015) discovered that the addition of graphene to polyethylene increased its thermal oxidative stability, enhanced its mechanical properties, and delayed the degradation process by reducing oxygen permeation and UV absorption in the polymer matrix. More testing is required on the matter before certain conclusions can be made for recycled tires specifically. That being said, it is of no doubt that adding graphene to tire rubber helps the material be more stable, at least in some areas. This is also confirmed by Xingna et al., (2018), who uncovered that incorporating reduced graphene oxide into silicone rubber improved its thermal oxidative stability by increasing the initial formation temperatures of pyrolysis products and reducing the concentrations of oxidative degradation products.

Nevertheless, it can also be concluded that with the rise of circularity in tires, so rises Elimination. This means that there will be less graphene contaminating products which weren't meant to have it, nor will it end up in the environment. This result is in fact a favourable one.

Lastly, flows which weren't computed in the model but are viable future possibilities should be discussed. In both tires and batteries there lies the possibility to produce new graphene from some of the waste products of recycling. It is unclear if the existing graphene structures will stay intact during these procedures or will they be eliminated and formed again. More testing must be done on the matter to be able to discuss more. Even if graphene does persist, it will not be considered as unwanted since it is still the target material. This is an option for a second uncontaminating type of closing the loop and is a very lucrative option for recyclers because graphene holds a higher price than any of the recycled matrixes it is contained in. This could also solve the problem of using graphene in more commercial products since massive production will pose a smaller problem. Additionally, an energy modelling study and a financial study must be done for this option, before businesses can consider implementing it. Further, a comparison between the techniques should be possible. Some researchers even thought about how to recycle the graphene itself from the batteries.

Although MFA, can't give the energy and economic analysis, it can provide arguments for which technology results in least material loss and can indicate how to avoid options for disposal in sinks such as Landfill. In that sense, energy recovery techniques are the best option for graphene in tires so far, since in that way no graphene will end up in Landfill or contaminating new products. Interestingly, if the route of material recovery grows, it will require testing on how the amount of accumulated graphene can change tire or battery properties if it ends up contaminating them, and if the results turn up positive or negative.

## 14.2 Discussion on general waste recycling methods

Collection rates can greatly influence the flow of a system. The case studies on tires and batteries proved so, and also showed that a lot of improper disposal or export, legal or illegal, takes place within the geographical scope of EU27(+NO+CH+UK). Improper disposal could be done out of relatively innocent reasons of the consumers such as recoverable products being placed in mixed household waste. This can be attributed to lack of public awareness or convenience. On the other hand, export is provoked by strict regulations set by the EU (Fikru M. (2012)) which make it harder and more expensive for businesses to treat certain materials but also the labor, energy and materials costs related to recycling (Illés & Geeraerts, 2016). There is also limited domestic capacity for treating many waste types (Callao C. et al (2021)). Because costs are the main driving force of exports, newer studies aimed at developing better

recycling procedures have a segment discussing economic viability and environmental impacts, however the depths vary. This is a positive change, since this perspective is highly important to inquiring businesses. Nevertheless, many procedures explained in papers remain unexplored in this way, making it unclear of their implementation potential.

Another thing to be pointed out is that even that there is lacking standardization in reporting and law structure dedicated to waste. Although the EU has its own directives, a lot of the member states have their own regulation and therefore the reporting isn't the same. This could happen even in the same supply chain with values reported differently, for example manufacturers and recyclers reporting the same material mass under different classifications. This leads to obscured results and a bad outlook on the big picture. MFA result values are greatly influenced by these numbers and can therefore lead to wrong conclusions. Thus, the need for more uniform definitions related to end-of-life classifications and procedures are needed throughout the member states and in all supply chains.

Out of all the recycling technologies researched, one of the main problems currently seem to be composites. This is not surprising because composites change and advance rapidly and are suitable to today's every improving technology. Their utilization in many different products is also substantially rising. In fact, many of the ANM which are included in post-consumer waste also come into the recycling sector within this category. When an ANM is paired with a matrix, it is most often, (but not limited to, being paired with the plastic or organic components within the product, possibly relating to its price and abundance. (Heggelund L. et al. (2016))). In consequence to the fast rise and adjustability of composite materials, the recycling sector seems still technically unprepared for it.

In a lot of the cases researched, concrete and asphalt are viewed as an escape route. As there are flows to concrete from both the battery (assumed) and tires systems, which are two products that have very little in common, it could be said that concrete will have a higher level of contamination than most other products due to it being used as a solution to store wastes that can't achieve circularity or have exhibited hazardous behavior. This might in turn complicate future recycling of concrete as well as lead to soil contamination if the trend of backfilling concrete is proceeded with.

The forming of new composites out of waste is another way of encapsulating materials that can't be dealt with otherwise. If a composite isn't disposed of then it there is a high chance it will enter either chemical or thermal recycling. Chemical methods, although they achieve successful separation rates are generally disliked due to environmental (ex. disposal of chemicals) and economic concerns. That is why many most turn to thermal methods. Out of those, pyrolysis seems to rise above others because of its low carbon emissions within the process, as the process is conducted in the absence of oxygen. Other than the energy recoverable fraction produced via pyrolysis, there is also a gas product, which is out of the scope of the thesis, and a solid residue.

Solid residues are found in multiple processes, regardless if they have a thermal, chemical or mechanical nature and there is potential for ANM to remain in it. In the case of graphene, it was unclear if during pyrolysis it would remain as is or it would change its structure. So far many of these wastes are incinerated or landfilled, which is a loss of precious materials. Consequently, with rising recovery rate demands set by the EU, many are looking to further valorize this material. Interestingly, many of the wastes, especially ones derived from thermal

processes, are viewed as a possible graphene source. It is massively researched to add value to carbon material considered waste so far, as seen in the case studies and other materials like coal tar pitch (from products that don't contain graphene) like for example in products like:

- LiB residues can be used to make electrocatalysts in flexible Al-air batteries (Hu H. et al. (2024))
- Recycling graphene itself via wet shredding from the electrodes of supercapacitors into polymer composites (Jiang, G., et al. (2019))
- LiB residues used to make graphene based electrochemical sensors (Ribiero J. S. et al. (2021))
- LiB residue to make graphene to be used in newer LiB via plasma solution treatment (Beletskii E. V. et al. (2023))

to name a few. A paper by Raghavan N. et al. (2017) even identified precursors such as paper cups, glucose, hemp, rice husk, cockroach legs, cookies, and grass. The focus is not only on graphene, and the possibility to create other nanomaterials from waste is entertaining for many other such as metals. Metals are also contained within residues from recycling processes and can be recovered from them, especially pyrolysis residues (Singh J. & Lee B. (2016)). This has the potential to change future material flows especially those where ANM is concerned.

## 15 EIT chapter

### 15.1 Circularity and raw materials

Performing an MFA can outline the whole life of a product, whether linear or circular. It shows where the materials are at the moment and where it will end up, all while using purely computational methods. This method proves to be very important for the introduction of nanomaterials to the market. The introduction of nanomaterials should be supported in many ways because it can vastly decrease the demand for many raw materials and possibly mitigate the crisis of critical raw materials to an extent. On that note, end-of-life treatments, especially recycling play a big role in circular economy, thus estimating material loss and material flows for these processes can be very helpful in optimizing them as well as estimating their environmental impact. Furthermore, conducting this kind of research shines light on the bigger picture of the whole system of a certain product, which can pinpoint problem areas and focus attention at solving them. MFA of materials coupled with an LCA analysis give a very comprehensive overview of the ecological footprint of a material, which is fast and adjustable to changes unlike laboratory experiments. Given the circumstances, it's possible to convert this into a business entity, namely a consultancy situated in the EU.

### 15.2 Business plan

To start off, the business can be called Advanced Materials, Nanotechnology, Data and Analytics Solutions (AMANDAS). Its mission would be to provide expert services, to government, association and commercial clients and partners, related to the tracking of advanced materials, their recycling and the optimization of material usage throughout its lifecycle. The vision would consist of influencing laws, guidelines and policy on advanced material recycling in the EU and world-wide.

#### 15.2.1 Value proposition

The value proposition for the consulting agency lies in its specialized ability to track and manage advanced materials, particularly those that are hazardous or critical. This is achieved through proprietary mathematical models that follow the flow of these materials throughout the supply chain, both upstream and downstream. Clients will have the choice between having an MFA done for them or buying an updatable user-friendly software, operating similarly to Open LCA, which will allow them to do it themselves.

Furthermore, the agency adds value through the implementation of MFA for each client, tailored to their industry and the broader market. By quantifying and modeling the material's lifecycle, the agency identifies inefficiencies, loss points, and areas where intervention can optimize the recycling process. The culmination of this analysis is presented in tailored reports that highlight inefficiencies and suggest strategic key performance indicators (KPIs). These reports are designed to guide both commercial and governmental clients in refining their strategies, ultimately leading to more efficient material management and better-informed decision-making processes.

### 15.2.2 Target market

- Industries -primary industries of interest will include those that most heavily work with advanced materials including construction, aerospace, medicine, energy, electronic, and automotive sectors.
- Government Bodies - The preeminent partners of this consultancy will be the EU governmental agencies dedicated to waste management and protection of the environment, such as The European Environment Agency.
- Commercial Recycling Companies - Operational partners will include specialized private companies in the fields of graphene recycling and other such materials, in an attempt to cut down costs in the initial phases of our operation.
- Associations and NGOs – Associations who are already involved in policy making, who require further knowledge on the standing of their industry of interest. An example is EuRIC

### 15.2.3 Revenue Creation Channels

**Consulting Commissions:** This encapsulates fees for consulting on projects, and performance-based commission where we charge based on percentage of project cost if the project is successful

**Software Licensing:** This includes fees charged for licensing our proprietary software to other SME's and government agencies.

**Data Monitoring and Newsletter Subscription:** The company will publicize data collected from our mathematical models and charge a subscription fee to those that want to access and utilize this information.

**Marketing Strategies:** AMANDA will employ a multi-faceted approach to marketing that includes funding research publications in nanotechnology and advanced materials to enhance its public image and drive sector growth. Networking will be key, with the development of strategic partnerships involving industry experts, policy influencers, and environmental organizations, among others. Additionally, a robust online presence through social media, a professional website, and specialized forums will be crucial for digital marketing.

**Securing funding:** AMANDA plans to secure funding through European grants aimed at sustainability initiatives. Private investment will also be sought, including raising capital in exchange for equity. Additionally, AMANDA will establish a boutique venture capital division to invest in nanotechnology and advanced material startups, aligning these investments with the consultancy's future growth and direction.

### 15.2.4 Competition

Presently, there are several consultancies in Europe that specialize in Material Flow Analysis (MFA). For example, Except Integrated Sustainability, based in the Netherlands, uses MFA as a foundation for sustainability strategy consulting, sector roadmapping, and industrial process design. They work with clients across various scales, from companies to entire cities, to evaluate material and energy flows, helping to design more sustainable systems. Another notable firm is Milgro, also in the Netherlands, which provides customized MFA services to help organizations optimize their material flows, reduce waste, and improve sustainability. They offer detailed insights into the flow of materials within a company or region, identifying opportunities to reduce environmental impacts and enhance resource efficiency. Additionally, the German consultancy ifeu gGmbH incorporates MFA into their broader life

cycle assessment services, assisting industries and governments in understanding and managing material flows to support sustainable practices.

Lastly, there are many research institutes who perform MFA studies such as EMPA in Switzerland and they can also complete them with lab work in necessary.

However, none of them have produced a user-friendly interface for MFA yet.

## 15.3 SWOT Analysis

### 15.3.1 Strengths

AMANDA is well-positioned to leverage its specialized knowledge and advanced expertise in material and recycling technologies, giving it a competitive edge in a niche market. This expertise allows AMANDA to serve major clients focused on end-of-life materials, offering precise consultations and eliminating the need for costly lab work by accurately modeling outcomes. The development of a user-friendly software focused on Material Flow Analysis (MFA) further enhances its value, providing clients with easy access to essential information. The rising demand for advanced materials and the shift toward circular economies strengthen AMANDA's market position, while alignment with EU regulations could bring favourable conditions and regulatory benefits. High profitability is achievable due to large consulting fees and high margins, with scalability and early mover advantages positioning AMANDA for significant growth as a market leader.

### 15.3.2 Weaknesses

AMANDA faces significant challenges, mainly due to the high funding required for its consultancy, venture capital, and software development activities. The substantial capital needed for office space, marketing, and product development is a major barrier, especially in a developing market sector. Operational expenses like salaries and taxes in EU countries further strain early cash flow. Extensive brand development and client acquisition are resource-intensive. The reliance on software introduces risks, as malfunctions could disrupt operations and harm the brand. Additionally, constant technological updates add recurring costs, and navigating evolving regulations presents potential compliance challenges.

Even though MFA holds supremacy over lab experiments on time and resources consumed, it is still atheoretical approach. If there are new materials or processes to be explored, not all interactions can be foreseen, and it can't fully substitute a lab experiment. However, building databases and staying on top of relevant findings, these weaknesses can be mitigated.

### 15.3.3 Opportunities

Despite these weaknesses, AMANDA has substantial opportunities to grow. The expanding market for advanced materials across various industries presents numerous consulting opportunities. The EU's continued push for higher recycling rates increases demand for AMANDA's services. Technological advancements in AI and automation could reduce costs and enhance the software's capabilities, while innovation in material management could drive new revenue streams and strengthen the company's unique selling proposition. Partnerships with SMEs in manufacturing and recycling could expand AMANDA's market share, and securing government contracts could provide a stable and lucrative revenue source. Furthermore, international expansion offers significant growth potential, particularly in regions with emerging sustainability regulations.

### 15.3.4 Threats

Nonetheless, AMANDA must remain vigilant against potential threats. Competition from established consulting firms and new market entrants could erode market share. Economic volatility, particularly in downturns, may reduce client spending and affect revenue. Rising costs and frequent changes to the



legal landscape could also challenge profitability. Additionally, technological risks, such as cybersecurity threats and the risk of obsolescence, must be managed to protect the company's assets and maintain its competitive edge.

In conclusion, by leveraging its strengths and capitalizing on opportunities while addressing weaknesses and mitigating threats, AMANDA is well-positioned to achieve success in the consultancy sector.

### 15.4 PESTLE Analysis

This analysis will inform the strategic direction of the consultancy by taking into consideration a plethora of external factors that could determine the feasibility of the business concept by analyzing the political, economic, social, technological, legal and environmental risks associated with the inception of such a venture.

Factors	Key Considerations	Risks	Influence on Strategic Direction
Political	Elections	New leadership might have different objectives and prioritize other sustainability initiatives	AMANDA must remain diligent and informed on the latest regulatory changes and grow relationships with government entities to involve itself in policy determination. We must anticipate change and modify our compliance.
	Policy Changes	Policy change could make many of our services redundant or outdated	
	Industry Regulations	More stringent laws for advanced materials and their recycling could drive up demand for our services yet it will present many compliance complications	
	Global Trade Agreements & Restrictions	Business operations will be hindered as trade of materials will be reduced and demand for services on the open market will decrease	This could completely shut down the entire enterprise and thus diversification both geographical and across sectors is necessary to minimize this risk
	Political Stability	Although political stability is generally high among EU states, however, in consideration of the worst-case scenario this could jeopardize the existence of the project	
Economic	Growth/Stagnation	Depending on the economic condition of our home market AMANDA could experience increases or drops in demand for its services as overall investment in the sector is directly correlated to economic growth.	AMANDA will reevaluate its pricing model in times of economic growth or stagnation based on cost fluctuations and inflation
	Interest Rate & Inflation	Cost of operations and investment and tied to inflation rates and AMANDA pricing will be affected as a result	
	Exchange Rates	Dealing with foreign direct investment or clientele abroad will be affected as	Volatility in this sector would impact revenues from global markets.

		overseas business transactions and operation will become more costly	
	Unemployment & Labor Costs	Access and cost of quality labor will be diminished increasing costs	AMANDA will automate where possible, increase employee efficiency through more rigorous training and tighter knit teams, and guarantee that it is staffing accurately
	Globalization & Consumer Spending	Worldwide trends and consumer preferences trending in the direction of sustainable processes will rise demand	AMANDA will expand its services and offerings
Social	Demographic Fluctuations	Demand will fluctuate in direct correlation with demographic changes	Target social groups increasingly concerned sustainability and environmental impacts
	Health Statuses	The health awareness of the population could influence many toward sustainable behavior and practice.	Tailor offerings to coordinate with shifts in social attitudes
	Education Levels and Social Mobility	A more specialized and educated client base requires more expert, niche and specific service provision	Increase costs to maintain alignment to social expectations to provide services relevant to the current client and maintain higher price for more expert consultations
	Cultural Norms	Shifting/fluctuation in public opinion about environmental distress correlates with AMANDA's growth opportunities.	Different cultures and their perspectives on environmental concerns vary depending on region, country and culture, affecting AMANDA's strategic approach to each part of the EU.
Technological	Access to and Price of New Technologies	Technological advancement is the most influential aspect in improving sediment tracking and recycling, however, is also a large capital expenditure	Investment in high powered IT technology and infrastructure will aid efficiency
	Technological Infrastructure:	Costly data analytics systems updates are needed constantly.	
	Data Storage and Security	Data security and storage is a key consideration for a consulting firm in the age of automation and online services, breaches of which could undermine the entire operation and trust of customers	Invest in good data security
Legal	Labor Laws	Compliance is mandatory for smooth operation	Stay updated on new requirements and comply to decrease risks of legal prosecution.
	Health & Safety Laws	Compliance is required for a healthy work environment and employee satisfaction	

	Relevant Court Cases:	Familiarity with precedents can inform industry practices and be important in day-to-day business practices and decisions	Adjustments in legal standards could mandate operational changes, awareness of which is needed to mitigate legal risk.
Environmental	Weather Conditions	Conditions can affect operations and planning due to lower ability to process materials.	Climate conditions are an inevitable part of operation that will be mitigated with robust indoor facilities for all AMANDA employees
	Energy Consumption Regulations	Costs will be driven up as a result of regulation	AMANDA will mitigate this risk by having solar panels on top of all facilities and invest in using only renewable energy to power its operations thus decreasing energy costs and compliance costs.
	CSR and ESG	Corporate social responsibility (CSR) and environmental, social, and governance (ESG) emphasis will increase operational cost.	Aligning with these requirements will increase the public perception of the company despite marginally higher costs

By considering these factors, AMANDA can strategically position itself to maximize corporate utility while marginalizing risk, guaranteeing a consulting service that is both cost-effective and future-proof, prepared against all manner of mitigating circumstance in the advanced material industry sector.

## 16 Conclusion

The European Union's circular economy strategy emphasizes increasing collection and recycling rates and improving material recovery. Within these flows it is becoming increasingly common to find advanced (nano) materials such as graphene. However, the fate of these materials when embedded or layered in composites or matrices, remains uncertain during the recycling processes as well as their final disposal whereabouts and accumulation throughout the years.

The study highlights the current and implementable recycling technologies by 2050 on the market in the EU27(+NO+CH+UK), but gaps in knowledge, particularly regarding the behaviour of advanced nano) materials during recycling, persist. The use of methods such as pyrolysis could help close the loop fully in the graphene flows, however not much is known about the reaction when already existing graphene enters, yet. This trend is true for other ADM as well. However, if not closing the loop there is high chance of encapsulation of these materials as fillers for concrete, bituminous materials and epoxy resins. Further, it was observed that recycling systems have a lot of auxiliary processes and generated wastes, such as the light-shredded fraction, which could largely change the flow of an ANM even without instigating chemical changes to the system.

On a larger scale it was shown that improper disposal and export of waste, influenced by economic and regulatory factors, contribute to inefficiencies in material recovery. Additionally, discrepancies in recycling terminology and standards across EU member states complicate the assessment of recycling efficacy. The study underscores the need for more uniform definitions,

improved recycling technologies, and comprehensive economic and environmental analyses (LCA and energy flows) to improve future decision making for the circularity of materials in the EU's waste management systems.

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