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Technical Steps Towards

Circularity of Carbon-Containing Wastes

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SUMMARY

The objective of this paper is to present an ambitious but realistic vision how carbon containing waste fractions can be utilised in Finland. A pragmatic view on waste sector streams in Finland and technology development are presented to enable understanding of better utilisation potential of those streams in near future. The intention was also to try to define limits of technology and benchmark that against different waste and side streams and their qualities. The paper discusses current situation and regulation of carbon containing waste streams in Finland and the EU. Next the technologies that are currently used to process these waste streams are described together with the technologies that can be considered as future alternatives for better utilisation of those streams. Finally, conclusions and recommendations towards short- and medium-term future will be given to pave the way for circular, green and digital Europe.

Current waste streams can be utilised almost completely when most challenging fractions are utilised as energy and carbon recycling with CCU (carbon capture and utilisation). Today, fibres, metal and electronic waste streams have relatively high recycling rates in Finland. Overall, the recycling rates will still need to be improved to meet the EU obligation for each member state to recycle at least 60% of municipal waste by 2030, and the EU goal of halving residual municipal waste that is landfilled or incinerated by 2030. The biggest future potential to increase recycling (with existing and new technology) is in higher utilisation of mixed household waste, better utilisation of all components in multi-layer packaging and better utilisation of plastic waste fractions, that also has significant upcycling potential. However, in the current light of technologies it is not possible to recycle all reject streams and all composite materials.

Waste streams differ a lot from each other, and they are subject to significant change over time, due to changing consumer behaviour and recycling patterns. There will not be a single or even only few technical solutions suitable for all waste streams. There will be several technical solutions that will together complement each other in a smart way to thrive for very high value utilisation of entire waste streams. Within the timeframe and beyond there will be challenging fractions that end up in combustion and will only then result as CO2 stream that can be further upcycled with introducing renewable hydrogen into the system. In short, waste hierarchy and CCU are not in contradiction rather than supporting each other in reaching very high recycling targets.

Recycling or even upcycling with as little deconstruction of material as possible is the preferred direction of systemic change. This will not only minimise energy needed for the conversion but enable benefitting from the original properties of the material streams. As a recommendation it would be beneficial to advance all ambitious targets related to recycling in the spirit of waste hierarchy and in addition to utilise CO2 form the waste sector only resulting from fractions not suitable to any other process than combustion. At the same time promotion of full benefits from CCU taking into account opportunities to fully utilise all the side streams of the process; heat, electricity, oxygen, water and ashes is seen as an essential part towards circularity and sustainable growth.

TIIVISTELMÄ

Tämä julkaisu esittää kunnianhimoisen, mutta realistisen vision hiilipitoisten jätejakeiden tehokkaammasta hyötykäytöstä Suomessa. Julkaisu on käytännönläheinen näkemys jätesektorin virroista ja niiden käsittelyteknologioiden kehityksestä, joiden avulla pyritään ymmärtämään kyseisten jätevirtojen hyödyntämispotentiaali Suomessa. Tavoite on myös määritellä eri käsittelyteknologioiden tuomat tekniset rajoitukset ja verrata niitä jätevirtojen ominaisuuksiin. Julkaisussa tarkastellaan nykytilan lisäksi hiilipitoisten jätevirtojen lainsäädäntöä Suomessa ja EU:ssa. Eri teknologiaratkaisujen mahdollisuudet jätevirtojen parempaan hyödyntämiseen käydään läpi lähitulevaisuudessa sovellettavien teknologiaratkaisujen osalta ja hahmotellaan, miten paljon paremmin eri jakeet voidaan näillä ratkaisuilla hyödyntää. Lopuksi annetaan lyhyen ja keskipitkän aikavälin suosituksia siirtymään kohti vihreää ja digitaalista Eurooppaa.

Nykyiset jätejakeet ovat teknisesti hyödynnettävissä lähes kokonaan, jos myös energiahyödyntämisen tuotteena syntyvä hiilidioksidivirta hyödynnetään (CCU). Tällä hetkellä kuidut, metallit ja elektroniikkaromu kiertävät suomessa kohtuullisen hyvin. Kokonaisuutena kierrätysasteissa on kuitenkin vielä parannettavaa, jotta saavutetaan EU:n 60 % tavoite yhdyskuntajätteen kierrätyksessä vuoteen 2030 mennessä sekä tavoite puolittaa polttoon tai kaatopaikalle menevän yhdyskuntajätteen määrä 2030 mennessä. Suurin potentiaali lisätä kierrätystä (nykyisillä ja tulevaisuuden teknologioilla) on kotitalousjätteen, monikerrospakkausten ja muovin parempi hyödyntäminen. Erityisesti muovin kierrätyksessä on merkittävä potentiaali hyödynnettäväksi myös siten, että tuotteiden laatu vastaa neitseellisiä tuotteita. Nyt näköpiirissä olevilla teknologioilla ei kuitenkaan päästä jätevirtojen täydelliseen kierrätykseen.

Jätejakeet eroavat toisistaan huomattavasti niin laadultaan kuin määrältään. Lisäksi nämä virrat muuttuvat ajan sekä kulutustottumusten ja kierrätyskäytäntöjen muuttumisen myötä. Yhdistelemällä erilaisia toisiaan täydentäviä teknologioita pystytään parhaalla tavalla hyödyntämään näistä muuttuvista jätevirroista mahdollisimman suuri osa tulevaisuudessa. Joka tapauksessa sekä nyt, että tulevaisuudessa kaikkein huonolaatuisimmat rejektijakeet joudutaan hyödyntämään polttamalla, ja vain silloin jätekierrossa syntyy hiilidioksidia, joka voidaan kierrättää uusiutuvan vedyn avulla uusiksi neitseellistä vastaaviksi tuotteiksi. Lyhyesti sanottuna jätehierarkia ja hiilidioksidin hyötykäyttö tarvitaan täydentämään toisiaan erittäin korkeiden kierrätysasteiden saavuttamiseksi.

Jätteen kierrätys tai jopa hyödyntäminen korkealaatuisina tuotteina on tehokkainta silloin, kun materiaalivirrat vaativat mahdollisimman vähän rakenteellista molekyylitason muokkausta, mikä on toivottu suunta systeemiselle kehitykselle. Tällöin ei vain minimoida systeemin energiantarvetta, vaan samalla hyödynnetään materiaalien alkuperäisiä rakenneominaisuuksia. Suosituksena olisi hyvä edistää kunnianhimoisia kierrätystavoitteita jätehierarkian hengessä ja samalla hyödyntää vain virtojen käsittelystä muodostuva välttämätön hiilidioksidi. Tämä tarkoittaa polttoprosesseja, joissa käsitellään vain ne jakeet, joita ei teknisesti muuten pystytä hyödyntämään, ottaen huomioon myös syntyvä sähkö, lämpö, sivutuotehappi, vesi ja tuhkat osana kiertotaloutta ja kestävää kasvua.

FOREWORD

This vision paper is produced to present a pragmatic view on carbon containing waste sector streams in Finland and technology development to enable better utilisation of those streams. The intention was also to try to define limits of technology and benchmark that against different waste and side streams and their qualities. This paper is produced as a part of Vantaa Energy carbon negative roadmap. The work was financed by Vantaa Energy but the authors responsible of the contents created the outlook independently and based solely on VTT expertise.

1

INTRODUCTION

THE OBJECTIVE of this paper is to present an ambitious but realistic vision how carbon containing waste fractions can be utilised in Finland. Waste hierarchy (Figure 1) and EU regulation are followed but focus is on technological opportunities for the utilisation of waste fractions in Finland. The focus is on waste i.e., prevention of waste is not considered as such even it is the priority in waste hierarchy.

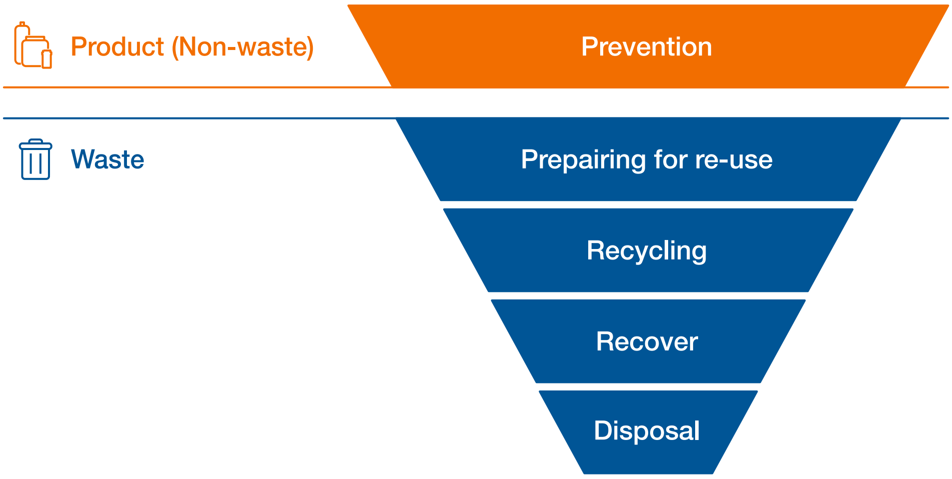


Figure 1. Waste hierarchy. Priority is to prevent waste by several means. When product cannot be used anymore, it is waste and should be utilised in the presented order (European commission 2022).

The carbon containing waste fractions investigated in this paper include both mixed waste and separately collected streams:

- Municipal solid waste (MSW)
- Wood waste
- Textiles
- Paper and carton board
- Plastics from
    - Packaging
    - Construction
    - Electronics and Vehicles
    - Enterprises
- Biowaste

First, the paper discusses current situation and regulation of these waste streams in Finland and in the EU in Section 2. Section 3 describes visions on how technologies can develop and how those developments would enable to increase recycling rates of separate streams. Ingredient recycling and carbon capture and utilisation (CCU) is discussed in Section 4. Finally, conclusions and recommendations towards short and medium term future will be given to pave the way for circular, green and digital Europe.

2

CURRENT SITUATION OF WASTE STREAMS IN FINLAND AND IN THE EU

2.1 MUNICIPAL SOLID WASTE

505 kg of municipal waste per capita were generated in the EU in 2020. 48% of municipal waste in the EU was recycled (material recycling and composting) in 2020. Finns generate slightly more than the average EU citizen; 596 kg/capita versus the European average 505 kg/capita in 2019. Opposite to the average trend in the EU, waste generation has also steadily increased during the last 15 years in Finland. On the other hand, only 1% is currently landfilled, while 62% goes to energy recovery and 37% material recycling (incl. composting). Increase in energy recovery was 4% in 2021 if compared to the previous year. In Europe, 23% is still landfilled and 27% incinerated. Status of municipal waste treatment in Finland is summarised in Figure 2.

MUNICIPAL SOLID WASTE IN FINLAND 2021

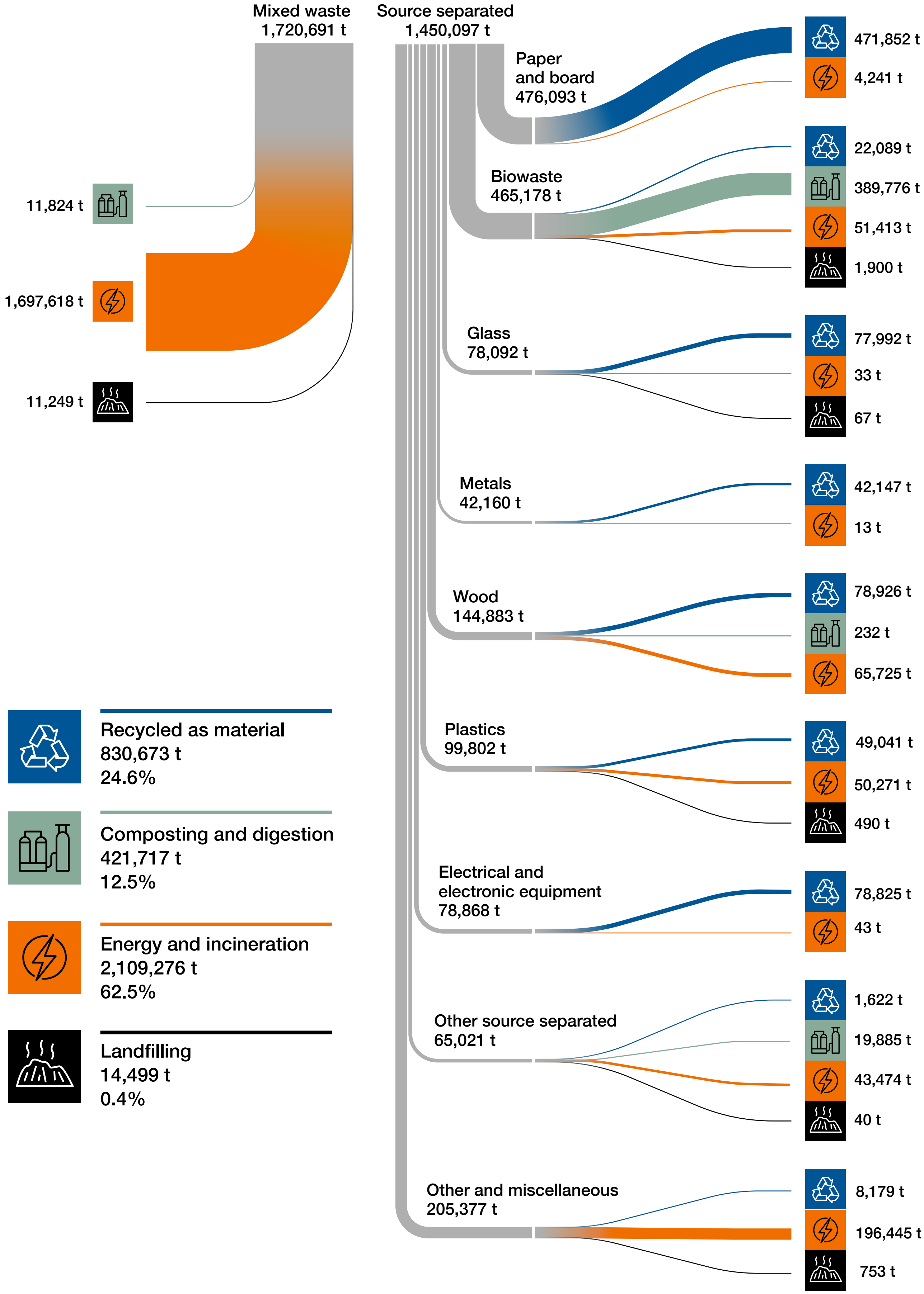


Figure 2. Municipal solid waste treatment in Finland based on waste statistics 2021 (Statistics Finland 2022).

Based on available data on the composition and volumes of collected waste and their current treatment schemes (Statistics Finland, Karppinen et al., 2021), we estimate that circa 78% of the municipal waste are carbon containing fractions (bio-waste, paper, wood etc) and 11% fossil carbon (i.e., plastics). Figure 3 depicts the amount of carbon in collected municipal solid waste and the shares of fossil and non-fossil carbon in relation to how the waste is collected.

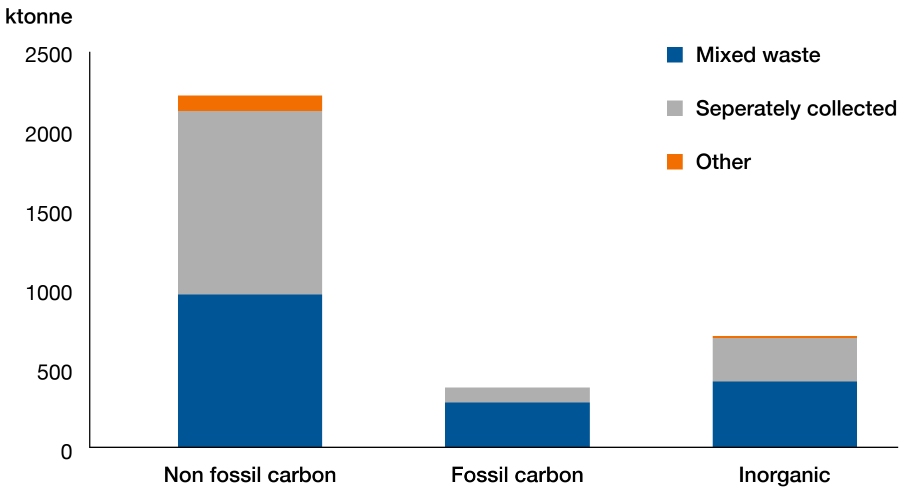


Figure 3. Municipal solid waste in Finland: Carbon content and proportion of fossil carbon calculated from waste data by Statistics Finland 2021 and Karppinen et al. 2021.

By 2025, 55% of municipal waste and 65% of packaging waste are to be recycled (Government Decree on Waste 978/2021 & Packaging and packaging waste 1029/2021). In the case of Finland, the main challenges in the strive for higher recycling rates are to increase the separation of packaging waste from mixed municipal waste and other plastic waste and biowaste. The objectives for municipal waste recycling will tighten further. In 2030, 60% of municipal waste needs to be recycled, and by 2035, 65% (Government Decree on Waste 978/2021).

High proportions of municipal waste are being incinerated

During the last 5-10 years packaging waste has appeared as a priority waste type both in Europe (Europe's Circular Economy strategy) and in other regions around the world. The background is increasing consumerism resulting in significant increase in packaging. In addition to the specific targets mentioned above, the EU waste legislation includes "mandatory essential requirements" for all packaging placed on the market. The Commission's aim is to make all packaging placed on the EU market reusable or recyclable in an economically viable way by 2030.

In this context the Finnish waste management system, with a high proportion of (municipal) waste being incinerated, has been assessed and policy options for increasing economically viable complementary solutions evaluated. Voluntary agreements ("Green deals") are seen as efficient compared to e.g., a waste incineration tax, which would not result in significant recycling or emissions impacts (Bröckl et al. 2021).

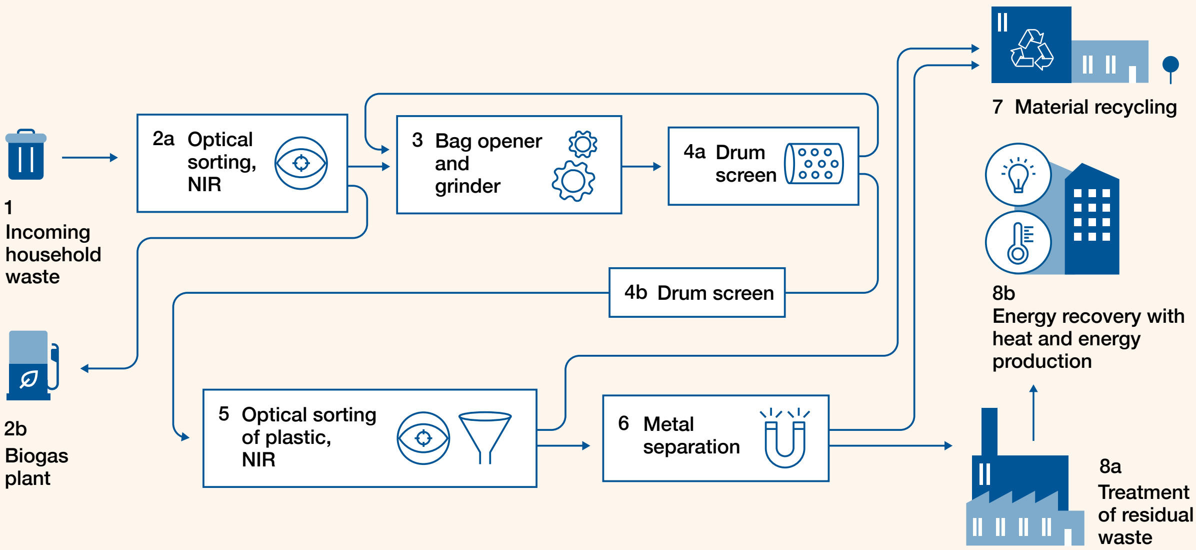
Although considerable development has taken place over the last couple of years, both regarding package eco-design and recycling technology, recycling rates of especially plastic and polymer-coated packaging remain relatively low. In Europe, the reported plastic packaging recycling rate is approximately 40%, compared to approximately 80% for paperboard on both continents. A well-run recycling system depends not only on the local recycling capacity but also on the collection and sorting infrastructure, which is still less than adequate in many countries across the world.

Post-collection separation

Post-collection separation of mixed waste has in many cases been claimed to have its advantage in a higher separation rate and over all lower installation cost for municipalities and householders. A handful of full-scale separation installations are in operation in Europe (e.g., Norway, the Netherlands) with one of the latest in Brista, Sweden, which was inaugurated 2021 as a cooperation between Stockholm Exergi and the recycling company SÖRAB.

It complements households' own sorting and recovery of additional recyclable materials before energy recovery. The plant mechanically sorts food waste, plastic and metals from the mixed waste. Plastic is sorted using IR technology which identifies different types of plastics and metals are sorted using magnet and Eddy current separators (Stockholm Exergi 2022).

The investment, ca 36 M€ has been strongly motivated by its positive climate impact and the ambition of the associated waste incineration plant to lower its carbon footprint (Eriksson 2021).



2.2 BIOWASTE

In 2020 almost 500,000 tonnes of biowaste was separately collected in Finland. 83% (412,000 t) of this was composted or digested, 5.5% material recycled and 10.8% was directed to energy recovery (Statistics Finland 2021).

The mixed waste still contains considerable amounts of biowaste. Based on a number of sorting analyses, the average share of biowaste in residual mixed waste is 32%, the major part (80%) of it being kitchen waste (KIVO 2021). Metropolitan area households show a lower tendency for source separation, there the share of biowaste in mixed waste is almost 40% meaning 51 kg/ inhabitant and year (HSY 2022). Obligation to organise separate collection of biowaste is being extended by new Finnish Decree on Waste (978/2021), which probably decreases the share of biowaste in mixed waste.

2.3 WOOD WASTE

Finland's industry and households generate circa 3.15 Mt wood waste per year (Statistics Finland 2022). The major share is generated in sawmills and the paper industry, where most is classified as a by-product. Here, over 95% is incinerated with energy recovery. Construction and demolition (C&D) again generate circa 12% of total with more variable End-of Life destinations.

Construction and demolition waste is considered one priority waste stream for recycling

As C&D waste is the largest waste stream in the EU representing ca 1/3 of all waste produced, it is considered a priority waste streams with high recycling ambition. EU's target, 70% recycling by 2020, was however not reached. In Finland, less than 30% is material recycled, while in the EU, the average recycling rate for C&D wood waste is 47% (Eurostat 2022).

2.4 TEXTILES

According to official sources, ca 6% of municipal waste is textiles, i.e., 105,842 tonnes is yearly generated (KIVO 2021). Textile waste is also separately collected at civic amenity sites around Finland, but data on these volumes is not available.

EU countries will have to ensure promoting circular textiles, with EU guidance on the separate collection of textile waste to be adopted by 2025. In Finland, regional collection points for textile waste will be organised at the latest in 2023 (Ministry of the Environment, 2021).

2.5 PAPER AND CARDBOARD

Over 500,000 tonnes of paper and cardboard waste is generated in Finland, and a major part of it in households and retail. With a well-established recycling system, Finland material recycles 98% of all collected paper waste. Only 2% is directed to energy recovery. According to Finland's producer organisations, 91% of paper put on the market was recovered and recycled in 2020 (Ministry of the Environment 2022). To note is that this figure represents only the volumes separately collected and counted for (212,000 tonnes in 2020).

The amount of printing paper put on to the market has reduced significantly in the recent years. In 2016 more than 295 kt was put on the market and in 2020 only 170 kt. This has also influence to the share of waste paper in MSW. At the same time, material recycling rate increased from 74 to 91% (ibid).

In 2020, 335,510 tonnes of fibre packages was collected from households and the industry. The major part is corrugated carton board, which accounted for 71% (239 kt) of the material. When Finland's fibre recycling organisation estimates that 266,800 tonnes of fibre packages was put on the market in 2020, the calculated recycling rate was 123% (Kuitukierrätys 2021). The recycling target for fibre packages collected in households is set to 75% in 2025, and in Finland this target is exceeded. The EU regulatory target for fibre packaging will be increased to 85% by 2030.

While the volumes of other packaging material remained on the same level, fibre-based packaging increased 10% compared to the previous year. This is mostly due to increased e-commerce and the popularity of take-away food.

2.6 PLASTICS

The European Union (EU) has defined a strategic approach to plastics as part of its transition to circular economy. Among others, the targets for recycling of plastic packaging waste have been set at 50% by 2025 and 55% by 2030 and bans are put on certain single use plastic products. Stricter regulations and ambitious targets for plastic recycling have driven both technology and market development during recent years. The regulative targets are very challenging to be met using current collection system and recycling technologies. This would potentially mean rethinking of recovery of end-of-life plastic products and adoption of advanced recycling technologies. While there is substantial market pull for sustainable products, the availability of sorted waste plastics is limited and applicable technologies for the processing of various polymer combinations are still developing to meet the needs of both the industry and policy makers.

The regulative targets are very challenging to be met using current collection system and recycling technologies

In Finland, most plastics (40%) are used in packaging. The construction industry uses about 20%, the automotive industry about 10% and the electronics industry about 8%. In total, about 600,000 t/a of plastics are used in the manufacture of products in Finland.

2.6.1 PACKAGING

Exact figures on plastics waste generation are not available, but in 2017, about 130,000 tonnes of plastic packaging ended up on the Finnish market. In addition, various industrial plastics are generated (e.g., plastics industry rejects, building materials). Although separate collection of plastics is now available for households throughout Finland, a large share still ends up in the mixed waste. Latest sorting analyses give that mixed waste contain 10-13% of plastics (Tuominen 2022), which means that 150-210 kt of plastic are currently incinerated (with energy recovery). The volume of separate collection in 2020 was 92,662 t (Statistics Finland 2021). In total, 133,320 t of plastic packaging under producer responsibility was placed on the market in 2019, and less than half of this, 56 kt, was delivered for material recycling (Ministry of the Environment 2020).

According to Finnish Plastics Industry Association, the recycling rate of plastic packaging in Finland is 27%. The figure includes consumer and business packaging as well as pledged packaging. The recycling rate of beverage packaging included in the deposit scheme is over 90%. In all, Finland is, like most other member states, behind the EU target for recycling. The EU stipulates that 50% of plastic packaging should be recycled by 2025. The recent proposal of the European commission for a new Packaging and Packaging Waste Regulation (published Nov. 30, 2022), contains mandatory recycled content targets for plastic packaging. The proposal includes ambitious targets for 2030 and especially for 2040: e.g., a 10% mandatory recycled content for contact sensitive plastic packaging like food wraps (50% as of 2040) and 35% for other plastic packaging (65% as of 2040), excluding bottles. When implemented, it will boost the market for recycled plastics and increase significantly the recycling of plastics and requirements for the quality of recycled plastics.

2.6.2 CONSTRUCTION WASTE PLASTICS

Waste statistics on the construction industry give that the amount of plastic waste can be estimated at <46,000 t/a (as part of the “household and miscellaneous” and “other” fractions). Based on a sorting study by Kinnunen and Kupiainen (2019), most of the separately collected plastic in construction sites is PE-LD film plastic used for protection and packaging.

As such the use of plastic is increasing in buildings and will in the future make a higher proportion of the demolition waste. These plastics are very diverse and frequently contaminated, imbedded in other demolition material and source separation at site is not yet common. However, with Europe’s ambitious strategies to increase recycling of construction and demolition waste, material recycling, enabled by post sorting facilities will become common.

Plastic films recovery was initiated in Finland’s plastic road map as a Green Deal between parties in the whole value chain. With the aim to achieve a 40%

recycled content target, this initiative has effectively increased both separate collection at construction sites and uptake of recyclates in plastic film manufacturing (Kärhä 2022).

2.6.3 PLASTICS IN WASTE ELECTRONICS (WEEE) AND END OF LIFE VEHICLES (ELV)

The share of Waste Electronic and Electrical Equipment (WEEE) in total municipal solid waste is circa 2%, but it is the fastest growing waste fraction globally. In 2019, approximately 12 Mt of e-waste was generated in Europe and 5.1 Mt of it was documented to be collected and properly recycled.

On average 20–30% of WEEE is plastics and the share is foreseen to rise (Maisel et al. 2020). The EU WEEE directive stipulates a minimum collection rate of 65% of the average weight of EEE placed on the market or 85% of e-waste generated. Strict mass-based recycling quotas cannot be achieved with metal or glass recycling alone. In addition, due to the increasing share of plastic in EEE, rising collection targets and to achieve higher quality of the recycled plastics, an efficient plastics recycling is necessary. There are basically three options for the recycling of plastics, which differ in terms of the applied process technology, the type and quality of the recovered secondary materials as well as the degree of utilisation: material recycling, feedstock or chemical recycling and thermal recycling (Maisel et al. 2020).

In 2019, the e-waste collection rate in Finland was 59%, giving room for higher improvement (Statistics Finland 2022). Saying that, collection is higher than the European average. The share of properly recycled e-waste of the e-waste stream in Europe is roughly 42.5%. (Forti et al. 2020).

The average ELV (End of Life Vehicles) in Finland contains circa 25% organic material (plastic, textiles etc). Plastics account for 9%, containing a wide variety of different polymers, partly dirty and with halogen containing fire retardants, making recycling difficult.

In Finland, of the 113 kt collected (circa 101,000 vehicles), circa 10% goes for reuse, the rest being recycled/incinerated (Pirkanmaan ELY-keskus 2021). According to Eurostat, 11.5 kt was incinerated with energy recovery in 2019. This share is in accordance with the ELV directive, stipulating indirectly that maximally 10% can go to energy recovery.

2.6.4 PLASTIC WASTE FROM ENTERPRISES

In addition to construction, automotive and electronics industries are the largest users of plastics in Finland, However, there are currently no accurate statistics on the amount of plastic waste generated by industries.

3

TECHNICAL SOLUTIONS TO INCREASE RECYCLING

THIS CHAPTER DESCRIBES technologies that are currently used to process waste streams and technologies that can be considered as future options for better utilisation of these streams. In addition to describing technologies and their outlook briefly, this chapter discusses how efficient these technologies are in converting the streams into electricity, heat, recyclable material and upcyclable material. Waste-based materials to be used as fuels or other means to generate energy, be incinerated, backfilled or landfilled, cannot be counted towards the recycling targets.

3.1 MUNICIPAL SOLID WASTE

Today, energy utilisation is the main process for mixed municipal solid waste. The majority of boilers in use are grate fired boilers with moderate steam parameters and hence moderate electrical efficiency. Today, electrical efficiency is in the range of 30% and in CHP production an overall efficiency (electricity + heat) of 90% can be reached. Heat recovery can be further increased with a flue-gas condenser. Also fluidized bed reactors are possible, but overall efficiencies remain in the same range. Metals in the stream can ultimately be recovered from the residual ashes after incineration.

While the general target is to source separate recyclables from at household levels, the current mixed MSW still contains a large proportion of recyclables (Figure 4). In the future, mechanical separation of MSW is foreseen to be enhanced allowing for better utilisation of different fractions (see page 13). The biogenic fraction of the stream, plastics and ferrous components can be separated. The reject after separating these streams remain only to be utilised in thermal processes, likely combustion, due to its low quality. Combustion is based on grate firing or kiln type of combustor. Because of challenging substances and elements in the feed stream, the potential of electrical efficiencies is lower than with better quality fuels (even lower compared to unseparated MSW). Combustion process still allows for the recovery of metals and minerals in the future, but especially mineral recovery technologies are still in the development phases and yet not commercially available. Utilising CO2 generated in these processes is also technically possible (refining with hydrogen).

Gasification of municipal solid waste is an alternative process for the thermal treatment of solid waste with potential benefits over traditional combustion of MSW. Syngas produced from the gasification of MSW can be utilised as a gas fuel for heat and power production. Also, it can be used as a building block for producing chemicals or other forms of fuel energy.

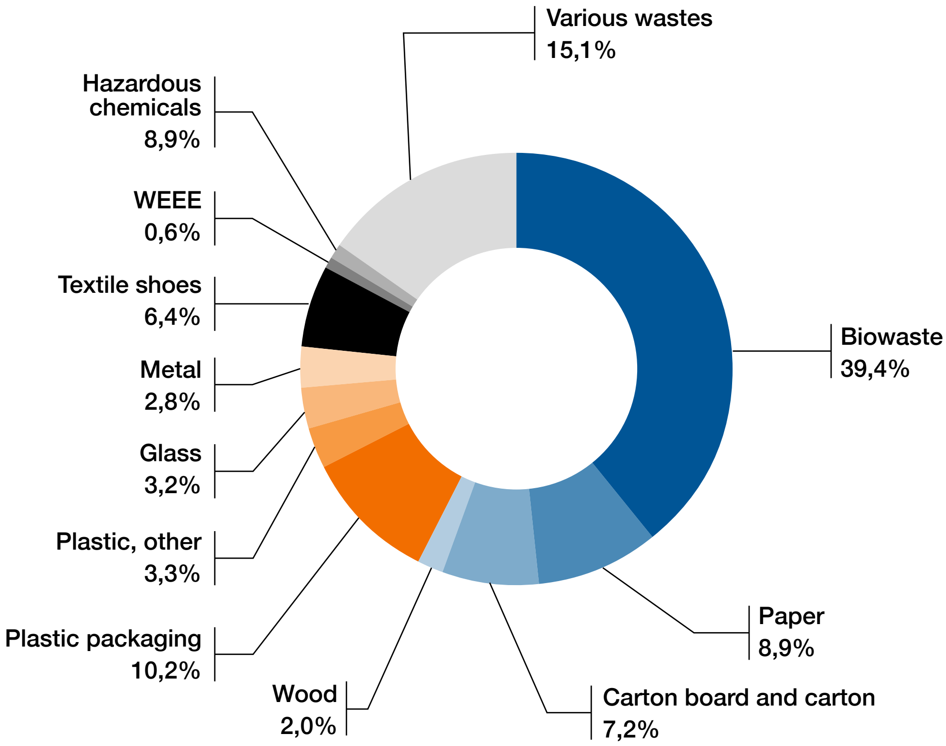


Figure 4. Composition of mixed solid waste (HSY 2022).

3.2 BIO WASTE

Two mainstream treatment methods are available for biowaste: composting and anaerobic digestion (AD).

Composting is the dominant form of recycling of bio-waste in the EU at present. Over 90% of the separately collected food and garden waste is processed into compost. Composting is a rather straightforward process that requires a relatively modest capital investment.

Alternatively, biowaste can undergo an anaerobic digestion process to harvest the renewable biogas and the remaining material after the digester (called digestate) can then be composted. Anaerobic digestion provides the added value of renewable gas generation in addition to the material recovery aspect given with composting.

For biowaste treatment to count towards the recycling targets, it must first be separately collected and then result in material recycling. The amount of municipal biodegradable waste that enters aerobic or anaerobic treatment may be counted as recycled, where that treatment generates compost, digestate, or other output with similar quantity of recycled content in relation to input, which is to be used as a recycled product, material or substance. Where the output is used on land, it may only be considered as recycled if resulting in agriculture or ecological improvement.

Biogas produced in anaerobic digestion contains CO2, which needs to be separated before end-use. Yield of methane can be increased by methanation of CO2 if excess of hydrogen is available. Both in-situ and ex-situ methanation technologies are being developed and not commercially available yet.

New innovative solutions to recycle residues from organic fraction of municipal solid waste treatment are needed to avoid incineration of the material

Recycling of compost, digestate or reject water from AD in agriculture, soil amendment or landscaping is regulated by the fertilizer product legislation. At present source separated biowaste is accepted as raw material for fertilizer products, but biowaste separated from mixed waste is currently excluded from the positive raw material list. There is a concern that the organic fraction (OF) separated from MSW contains heavy metals and other harmful substances that can end up to food chain. New innovative solutions to recycle or upcycle residues from organic fraction of municipal solid waste treatment are needed to avoid incineration of the material. Thermochemical treatments, e.g., pyrolysis, hydrothermal carbonisation (HTC) and gasification have been proposed as possible treatments methods to produce valuable carbon products from the residues. Developed utilisation pathways typically require extensive drying which is important cost factor.

3.3 WOOD WASTE

Energy recovery in heat and power plants is currently the main treatment method for wood waste. Material recycling of crushed waste wood is possible in composite materials, but the volume is minor compared to energy recovery. Large volumes of pure waste wood fractions are formed as by-products in forest industry, whereas construction and demolition wood may contain mechanical or chemical impurities, which makes the recycling more complicated. Mechanical impurities (such as stones, plastic, metals, concrete etc) can typically be removed using normal sorting and separation methods. Chemical impurities (such as coatings, wood preservatives) are almost invariably integral to the wood material, which makes them extremely difficult to separate and remove (Alakangas et al. 2016). Depending on the origin, content of heavy metals and certain other elements, a waste incineration permit may be needed for energy recovery from waste wood.

Waste wood is a possible raw material for production of biochar or activated carbon in the future. Biochar is a very stable, solid form of carbon that can endure in soil for long periods of time and thus is an efficient carbon removal method. Biochar is produced from biomass by slow pyrolysis process in oxygen-free conditions at 350 – 800 °C depending on the targeted products. Yield of biochar is typically 30 – 40w-% and it contains 50 – 60% of the raw material energy content. 25 – 30w-% of liquid and 25 – 35w-% of gaseous by-products are formed also. Dry (moisture ~10%) raw material is needed for pyrolysis, so it is an advantage to use waste wood that typically does not require separate drying process. Numerous end-use options for biochar are presented, but the main use currently is as soil amendment material, which use is covered by fertilizer product regulations. There are restrictions for the raw materials of biochar to be used as or in fertilizer products, which may cause challenges for utilisation of waste wood originated biochar. Biochar can be further refined to activated carbon, which can be used to substitute current commercial products, mainly produced from coal.

Gasification is an option for thermal treatment of organic process streams, that also allows recovery of inorganic fractions of the feed. Product from gasification is syngas, a mixture of hydrogen, carbon monoxide and carbon dioxide (and nitrogen). This gas stream can be very well cleaned and does not contain harmful amounts of contaminants. There are many technologies for gasification, but fluidised bed processes are considered as most potential options for solid heterogenous feed streams. This is a mature technology for relatively good quality waste fractions and can be tailored for specific needs. Syngas can be further utilised as energy (heat and power) or further synthesized into organic products, such as plastics or fuel components. Upcycling efficiency can reach above 50% while still recovering more than 30% of the energy content as heat.

3.4 TEXTILE WASTE

Material recycling of textile waste is in its early phase meaning that organisation of collection systems and development of recycling processes are ongoing. Textiles which cannot be reused as such, can be directed to the industry as raw material (insulation material etc.). However, waste textiles are currently mainly combusted in MSW incinerators and thus only the energy recovered.

The proportion of polyester is 55% of the total production volume of fibres and the rest are covered by cotton, wool, cellulose, polypropene, acryl, and polyamide (Ellen MacArthur Foundation 2017). The recycling of textile waste can be challenging due to contaminations (stains) and harmful chemicals (dyes, flame retardants, water repellents etc). These contaminating substances and harmful chemicals are required to be cleaned, washed, or sorted out before material recycling (Kamppuri et al. 2019).

Recycling of textile fibre have two main options. Mechanical processes are typically dry, accepting a broad spectrum of different types of recycled textile materials. However, problems with colour control and harsh processing conditions lead to 4-10% losses in fibre quality and yield (Auranen 2018). This means the mechanical recycles are used for e.g., insulation materials 45-75% and less in textile yarns. Alternatively, chemical recycling can be applied by means of selective dissolving or more commonly hydrolysing other components. Main challenges are in sorting, chemicals consumption and activation of remaining cotton, but result is typically a fibre which is comparable to virgin fibre (Le 2018). Each kg of mechanically recycled polyester represents a reduction in GHG emissions by more than 70% as compared to virgin polyester (Sustainable Apparel Coalition's Higg Material Sustainability Index – raw materials "Higg MSI").

Cotton hydrolysis to fermentable sugars seems economically not feasible. Alternatively the cotton fraction can be extracted e.g. in alkaline dissolving (ReNewCel) or in cellulose carbamate process (Infinited Fiber Company). The chemical recycling of polyester can be executed by two different routes: by solvolysis or by thermolysis. Solvolysis is a chemical degradation by solvent, which includes methods such as hydrolysis, methanolysis, glycolysis, ammonolysis, and aminolysis. The thermolysis route includes chemical degradation or rupture by the effect of heat. The tertiary recycling processes yield monomers and various other products.

Solvolysis of polyester

In the polyester solvolysis, the functional ester groups of the polyester chains are cleaved by the solvents. The applicable solvents in different methods include water, alcohols, acids, glycols, and amines (Karayannidis & Achilias 2007).

The hydrolysis of the polyester can be executed in different conditions. The possible variations for the hydrolysis are neutral, alkaline, and acidic hydrolysis. The main disadvantages of the hydrolysis methods are the usage of high temperatures, high pressures, time-consumption to complete the depolymerization, and challenges on the product purification (Sinha et al. 2010). The alkaline hydrolysis plant with the annual capacity of 40 kilotonnes of terephthalic acid operated with capacity 85% has capital investment of approximately 70-92 million €, which enables the pay-back time between 3.1 years and up to 4.5 years. The carbon equivalent of the process included the carbon emissions of the process and utilities, which was a total of 0.49 CO2 tonnes per tonne of the product (Harlin 2021).

3.5 PAPER AND CARDBOARD

Currently recycling rates for paper are high. According to the European Paper Recycling Council 71.4% of all paper and board consumed in Europe was recycled in 2021 (Cepi 2022). According to some statistics, paper packaging has already reached an 82% recycling rate (Euractiv 2022). Majority of paper, or fibres in paper are recycled to tissue production. Cardboard (fibres) are mainly recycled back to cardboard production. There are technologies and practices for recycling of fibres from clean fractions of paper and cardboard, whereas e.g., packaging materials containing layers of different materials is more difficult to handle, and thus the recycling rates are not nearly as high as with clean fractions. For example, liquid packaging cardboards often used as an example of a complex material to recycle have several layers including cardboard, aluminium and/or several plastics layers of different types that are difficult to separate. It is therefore challenging to recycle both fibres and plastic fraction as materials simultaneously. There are research efforts to solve challenges of separating these different layers and components in the recycling process. Currently the plastic fraction typically ends up in incineration.

There are both research and several industrial initiatives aiming to enhance collection, sorting and recycling of challenging paper packaging materials containing also non-fibrous layers. These include development towards thinner and fewer plastic layers, alternative coating materials and additives, and technologies for a more efficient separation of individual layers which could then be processed even back into valuable materials. Development of a single recycling technology is not necessary seen as a primary solution to increase recycling as no reliable solutions are seen that could simultaneously recover clean fibre and plastic fractions. Although there are paper mills specialised in processing, for example, liquid packaging cartons and cup stock, emphasis has traditionally been on the fibre fraction (Eunomia & Zero Waste Europe 2020). Economically viable technologies are also needed for further processing of the non-fibrous fractions. New types of, for example, dispersion coated paper and paperboards, that can provide required functionality for specific packaging applications, potentially pose a challenge for recycling of the entire carbon content without thermal treatment and/or CCU. Also, biodegradable materials can be challenging in this respect. However, the current trend is towards fibre-based packaging formats with added functional layers. The role of recycling aspect already in the package design is important and selection of “good enough materials” instead of “the best materials” can provide answers also to recyclability of these streams.

3.6 PLASTICS

In 2021, plastics recyclate production was 8.2 million tonnes, with an annual growth rate of 5.6% predicted up until 2030. Based on an estimated 35.6 million tonnes of commodity plastic entering waste streams in 2021, this figure implies that Europe achieved an overall plastic recycling rate of 23.1% (Packaging Europe 2022). The alternatives ways to recycle plastics are illustrated in Figure 5 below (Broeren et al. 2022).

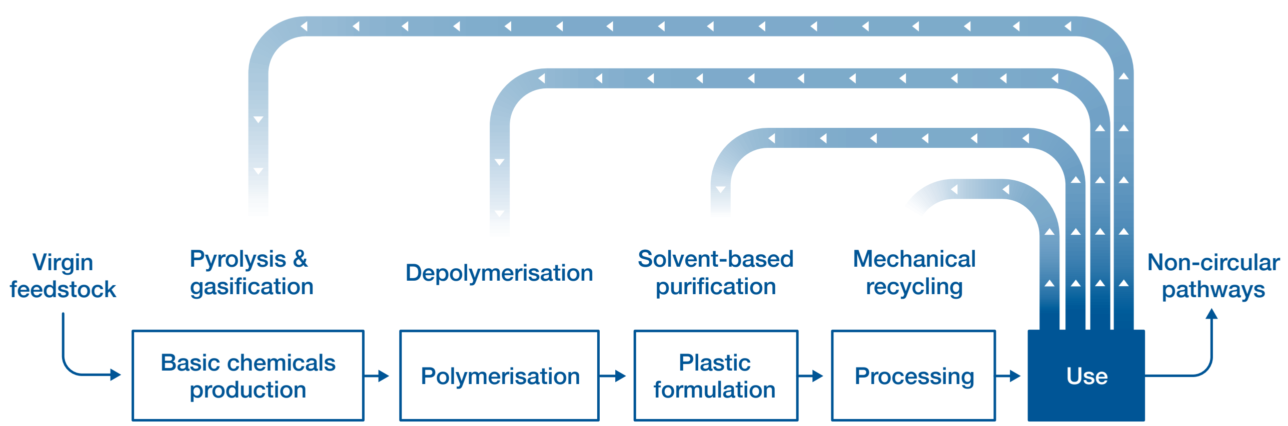


Figure 5. Positioning of different technologies for plastic recycling (Broeren et al. 2022).

Plastics are currently mainly mechanically recycled i.e., source separated plastic waste is sorted, washed, and ground or crushed to a raw material for recycled plastics. Mechanical recycling can be applied only to relatively clean homogenous plastic fractions and e.g., multilayers and composites end up in the reject, which is typically 30-50% of the incoming waste flow, depending on the sorting efficiency and original flow. The reject usually ends up in incineration or is exported. Typically, most of the other plastics than polyolefins (PE, PP) in the mixed plastic waste are currently separated and incinerated.

The key route to increase volumes of mechanical recycling is through increased plastic waste collection. In Finland, as well as in most European countries, plastic waste collection this is done by separate collection organised by producer responsibility organisations. In some European countries, e.g., the Netherlands, Norway and Sweden also separation of plastic waste fraction from MSW is applied. Enhanced industrial sorting and washing to more pure polymer fractions is the main strategy to improve the quality and thus increase use potential of the mechanically recycled plastics. An emerging technology to improve effectiveness of plastic waste sorting is so called digital watermarks (https://www.digitalwatermarks.eu), where an optically readable code for the plastics used is printed on the packaging.

To reach the future target level of plastic recycling and recycled contents, chemical recycling is seen as a needed complement to mechanical recycling (Tenhunen & Böhler (eds.) 2020). The increase in potential that chemical recycling brings come from both high-quality products and applicable feedstock. Chemical recycling produces virgin-quality plastics that can be used in many applications not possible for mechanically recycled, and the feedstock for chemical recycling can be more mixed than for mechanical recycling.

Chemical recycling produces virgin-quality plastics that can be used in many applications not possible for mechanically recycled

Chemical recycling of plastics has many routes. The far largest and rapidly growing is to utilise pyrolysis-based route including liquefaction by pyrolysis, upgrading of the pyrolysis oil, monomer production by steam cracker and further polymerisation to new virgin-quality plastics (Ragaert et al. 2017, Kusenberg et al. 2022, Seitz et al. 2020). The pyrolysis route is predominantly used for recycling of polyolefin rich mixed plastic waste which cannot as such be mechanically recycled. Pyrolysis based route has also been industrially used to recycle polystyrene to polymerizable styrene monomers. Another rapidly developing route is so called chemolysis or depolymerisation of polyester (PET) to monomers which can be repolymerised to PET (chemolysis is also called solvolysis or depolymerisation). Third and highly potential, but not much applied route, is so called synthesis gas route. The mixed plastics or plastic containing MSWs are gasified to synthesis gas, purified, and further converted in multi-step processes to polymerizable monomers. This route has benefit to accept very mixed feedstock, but there are still challenges in technologies and cost of operation and investments (BEIS 2021).

The multi-step recycling routes of chemical recycling technologies can lead to relatively low plastic-to-plastic yields, since most of these steps have less than 100% yield. Plastic-to-plastic yield of 49% is reported when using pyrolysis-based recycling route and 34% for the synthesis gas route (Broeren et al. 2022). The main reasons for relatively low figures are some material losses in the purification steps and that some part of the products is used for the energy needed to depolymerise (or crack) the plastics. For example, in pyrolysis is typically formed 70–80% pyro-oil and 10–15% gas, and rest coke (Qureshi 2019), and a steam cracker usually produces polymerizable olefins about 50% from the naphtha feed. However, the cracker side products such as other chemicals (e.g., aromatics) and fuels have value as well, and part of those components can be recycled back to materials increasing the total recycling yield. Use of catalyst technologies and process electrification can be tools to improve the yields of chemical recycling processes.

Dissolution is a process where a single target polymer present in a mixed plastics waste is selectively dissolved, allowing it to be separated from the waste and recovered in a pure form without changing its chemical nature (Plastics Europe 2022, Schlummer et al. 2020). Dissolution is considered a more environmentally friendly option and it has higher total yield than chemical recycling. It seems to be most easy to apply for recycling of polystyrene. The technology is, however, still evolving and at present few full-scale installations exist globally.

In Europe the current capacity of post-consumer or industrial plastic waste recycling is almost completely for mechanical recycling. It includes both recycling of separately collected non-deposit packaging plastics and PET bottles collected through a deposit system. The European capacity of chemical recycling in 2022 is estimated to be about 115 kt/a, but the growth in the coming years is expected to be rapid. If the announced investments would materialise, the capacity in 2025 would be ten times higher, 1.1 Mt/a (Sewell 2022). The main drives are the large petrochemical companies who have announced notable investment in both the pyrolysis and chemolysis based recycling routes. The recycling capacity in Finland is as well expected to be notably increased in coming 2-3 years through improved collection of plastic waste and new investments to both mechanical and chemical recycling capacities.

There is no yet uniform legal definition of chemical recycling. It may be classified as recycling if the application is new materials, not fuels or other energy use, as defined by the Circular Economy Act, Waste Framework Directive and recently renewed Finnish waste legislation and packaging regulation. The key challenge for chemical recycling is that legally accepted calculation schemes to include chemically recycled plastics in the recycling quota are still largely missing. However, it is expected that EU guidelines for such calculation methods to be defined in 2023, including the exact instructions how utilise certified mass balance accounting for the recycled content of chemically recycled plastics.

4

UNAVOIDABLE CO_2 AND CCU

RE-USE AND RECYCLING are favourable over incineration and recovery of energy, as illustrated in Figure 1. In practice, all fractions of waste streams cannot be re-used or recycled e.g., if fractions contain persistent organic pollutants (POPs) or other harmful substances. Several reject streams are formed in separation and recycling processes, and combustible gases can be formed. Especially composites of several materials may be difficult to recycle. Many rejects and gases can be utilised as energy by combustion, producing heat, steam, and electricity. In cases where combustion is the only realistic option, resulting CO2 is called unavoidable CO2. Unavoidable CO2 can be recycled by capturing CO2 from flue gases.

Unavoidable CO2 can be recycled by capturing CO2 from flue gases

There are several pathways how CO2 can be utilised with very high efficiencies for recycling of carbon from feed material to intermediate hydrocarbon products (in the range of 90%). The most important options for near-term are presented in Figure 6. CO2 is already utilised by many of the presented ways and there is a market for product grade CO2. The average market price for CO2 as a product in Finland has been between 89-97 €/tCO2 during 2015-2020 (Statistics Finland 2022). As most of the product CO2 in Europe has been captured from natural gas reforming processes, price of CO2 has increased significantly during gas crisis in 2022. However, the existing market is limited and scenarios for future volumes of CO2 captured for utilisation clearly exceed the demand. Therefore, new applications for CO2 utilisation are developed and conversions of CO2 with hydrogen to several hydrocarbons offer the largest potential. The key to enable large volume of conversions with hydrogen is low-cost and emission-free hydrogen i.e., a huge increase in the capacity of emission-free electricity production and hydrogen production by electrolysis

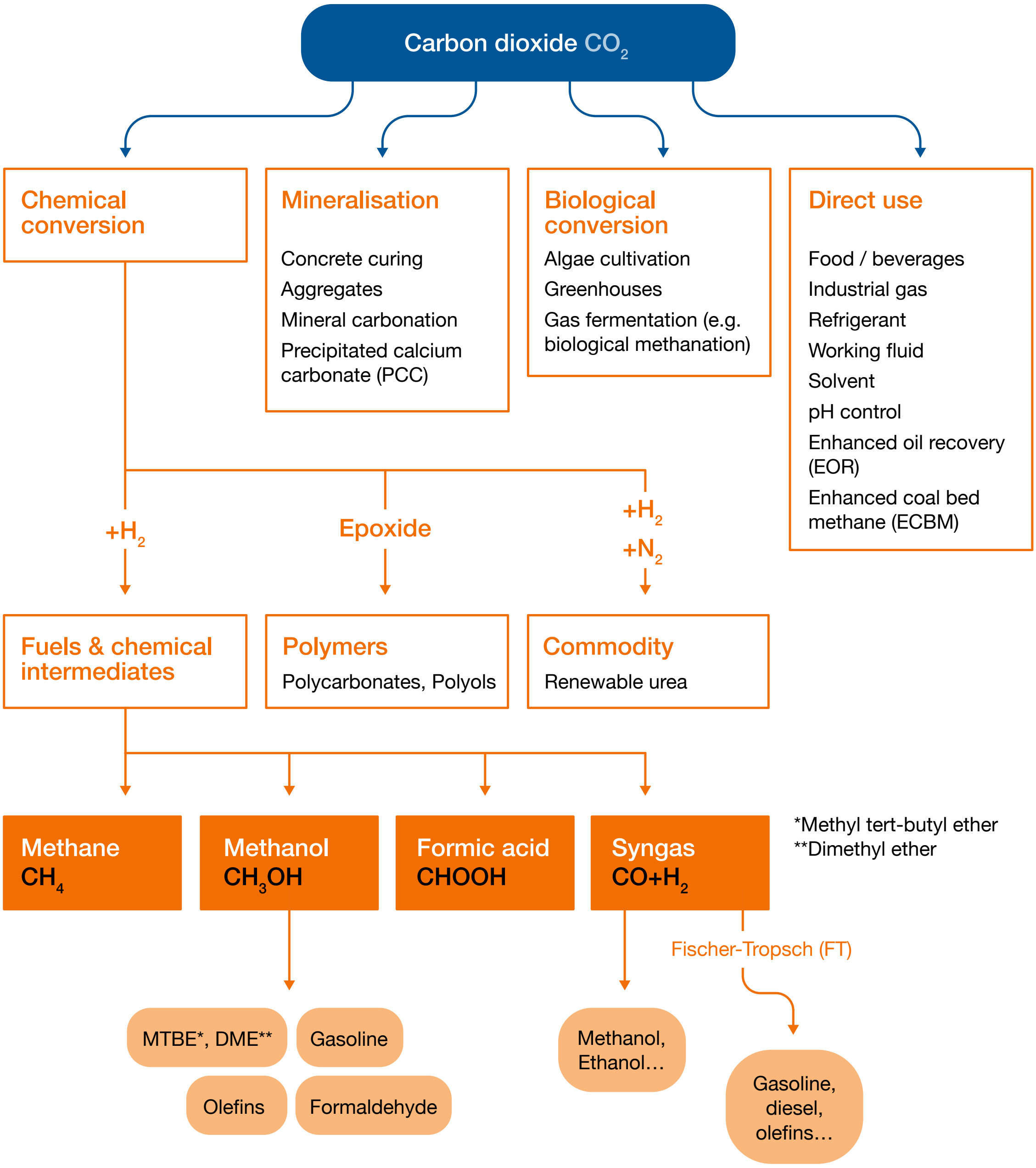


Figure 6. CO_2 utilisation pathways.

NOTE: The diagram presents only the most important options for the near-term. There are other routes such electrochemical and photochemical routes and hundreds of other possible products.

Depending on the requirements of processes utilising CO2, purification steps and compression and/or liquefaction of CO2 are often required. Some processes, e.g., mineralisation options, can use also lower concentration CO2 but transportation of such CO2 may not be feasible and sets the requirements for concentration, purification and compression.

In addition to recycling of resources, utilisation of CO2 is an effective tool for climate change mitigation. The quantitative impact is ambiguous and dependent on several factors, such as reference case and system boundaries (Figure 7). However, from climate change mitigation perspective, there are three important requirements for CCU:

- Utilisation of CO2 cannot legitimate CO2 emissions (CO2 is unavoidable or regulated by other mechanism e.g., EU ETS)
- Increased demand for hydrogen should not increase emissions from electricity production system, including potential impacts on electricity exports and imports (e.g., enable/facilitate increase in solar and wind power)
- Utilisation of CO2 does not increase the consumption of the products made from CO2 (fossil raw materials are replaced).

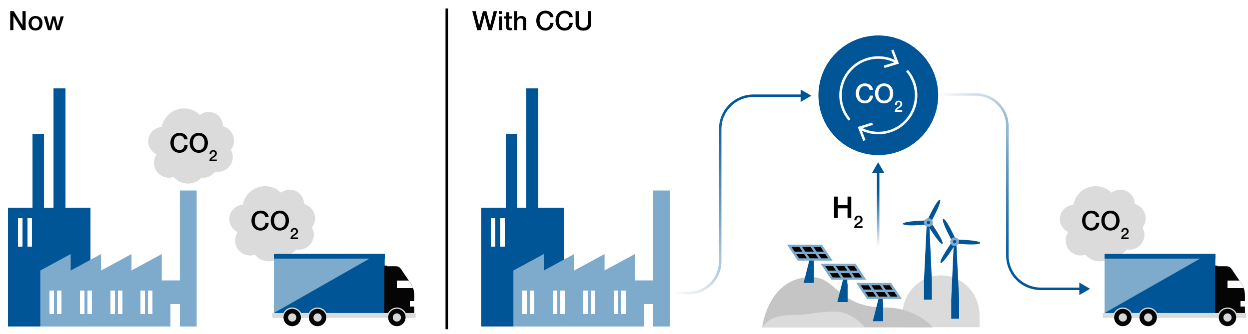


Figure 7. CCU is a powerful tool for climate change mitigation.

As massive amounts of hydrogen are needed for large scale CO2 utilisation, there will be also increase in oxygen production, which is a by-product from electrolysis of water. Oxygen is commonly used gas in industries, but the increase in hydrogen production by electrolysis, and consequent increase in oxygen production, may overcome the existing usage of oxygen in near-term. Imbalance between supply and demand is highlighted locally. If there is no local use of oxygen in industries, large volumes of oxygen can be used for enrichment of combustion air. This may be more feasible than purification, liquefaction and transportation, as these steps are not needed for oxygen enrichment. In the case of waste incineration, oxygen enrichment can compensate the decreased amount and heating value of combusted waste in the case of improved re-use and recycling. There may be other benefits as well from oxygen enrichment, such as emission control, efficiency, demand side response and capacity increase.

5

DEVELOPMENT OF MSW TREATMENT IN FINLAND

BASED ON the national and EU level targets, and presumed technology development, a foreseeable status of municipal solid waste management 2030 in Finland is presented in Figure 8.

The following assumptions were made to create the vision:

- Total amount of municipal solid waste remains almost at the same level as in the beginning of 2020's
- The objective to recycle 60% of municipal solid waste is fulfilled by 2030
- Material recycling from mixed waste is increasing:
    - Mixed waste contains recyclable materials, e.g., 10 – 13% of plastics. Half of the plastics is separated and recycled as material by 2030.
- Increase in separately collected waste fractions
    - The amount of separately collected biowaste increases ca 55% and it is mostly composted or digested.
    - The amount of separately collected board increases remarkably, and the amount of paper decreases, the total volume increases ca 25%.
    - The amount of glass and metal wastes remains at the previous level.
    - Volume and material recycling of waste wood increases.
    - The volume of separately collected plastics increases, and the share of material recycling increases.
    - The volume of WEEE increases.
    - Separate textile waste collection begins, material recycling is the objective. (Included in other source separated in Fig. 8)

The vision has been created based on technical opportunities to meet the ambitious recycling targets. The analysis shows, that significant improvements in waste management system are needed in order to meet the targets. This will not happen without advancing technologies and a comprehensive systemic approach and following strategy to make the most out of synergies of fractions, handling, and combination of different technologies.

One of the crucial questions for future waste management system is how successfully and feasibly can source separation be arranged and where it is feasible (technical, environmental, and economic aspects considered). E.g., in densely populated areas there are potentially higher prospects of larger fractions to be successfully collected with qualities that enable high yields in recycling processes. Another technically developing option is to advance technologies capable of sorting different fractions from mixed waste to be recycled (alternative vision). Technological solutions already exist and are being further developed to enable meeting the required high recycling rates. However, current legislative framework does not support the recycling of MSW fractions.

VISION: MUNICIPAL SOLID WASTE IN FINLAND 2030

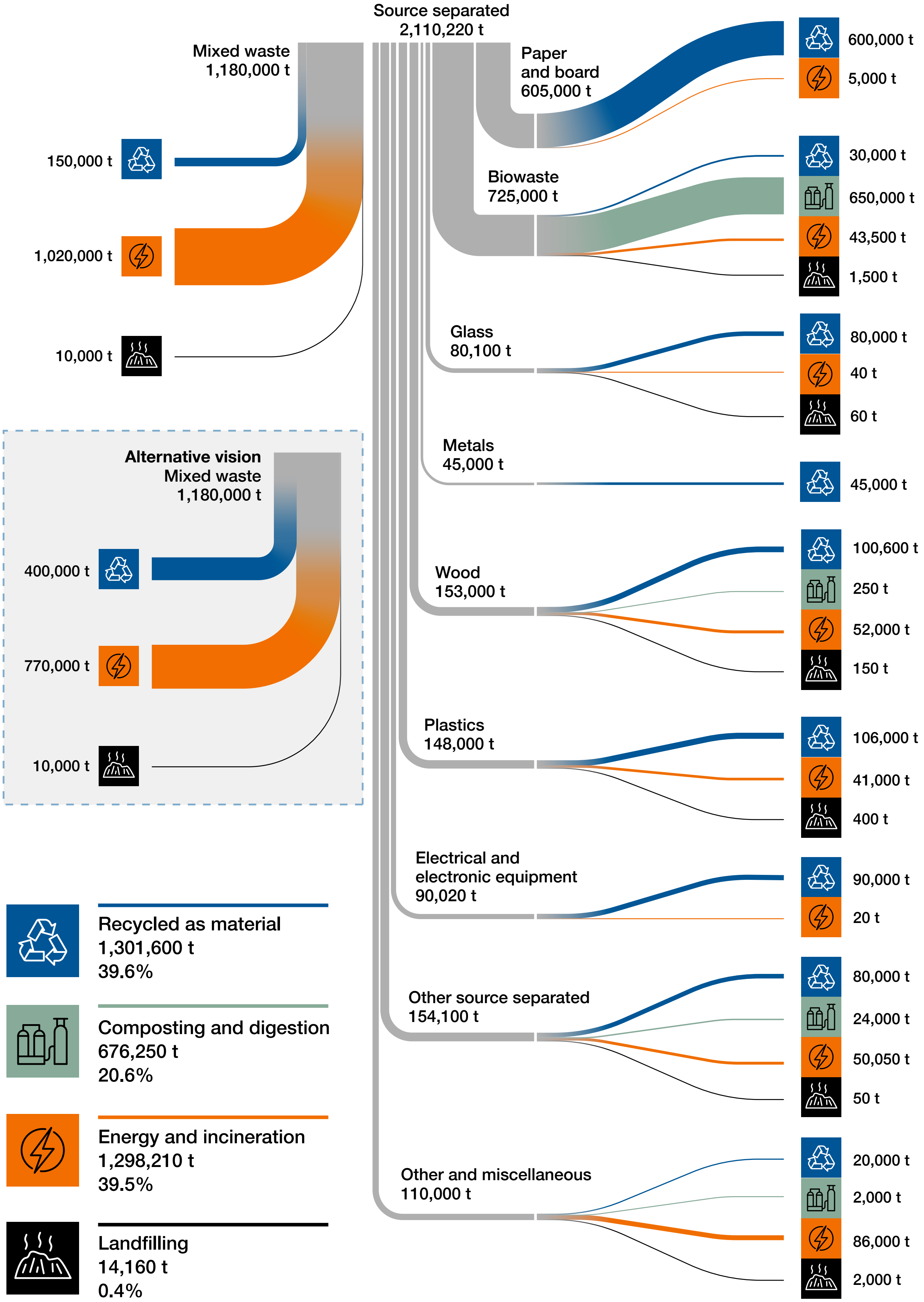


Figure 8. Estimated status of municipal solid waste treatment in Finland 2030.

6

CONCLUSIONS AND RECOMMENDATIONS

CURRENT WASTE STREAMS can be utilised almost completely also considering utilisation as energy coupled with CCU (carbon capture and utilisation). Today, fibres, metal and electronic waste streams have relatively high recycling rates in Finland. The recycling rates will still need to be improved in order to meet the EU obligation for each member state to recycle at least 60% of municipal waste by 2030, and the EU goal of halving residual municipal waste that is landfilled or incinerated by 2030 (EEA 2022). The biggest future potential to increase recycling (with existing and new technology) is in higher utilisation of mixed household waste, upcycling of plastic waste fractions and better utilisation of all components in multi-layer packaging.

However, in the current light of technologies it is not possible to recycle all reject streams and all composite materials. Within the timeframe and beyond there will be fractions that can only be handled by combustion and will then result as CO2 stream. That CO2 stream can be further upcycled by introducing renewable hydrogen into the system. In short, waste hierarchy and CCU are not in contradiction rather than supporting each other in reaching very high recycling targets. However, as CCU is a very energy intensive process, all other prior steps of waste hierarchy are preferred over CCU. On principal level, VTT vision on circular plastics can be expanded on to all carbon containing waste streams presented in Figure 9.

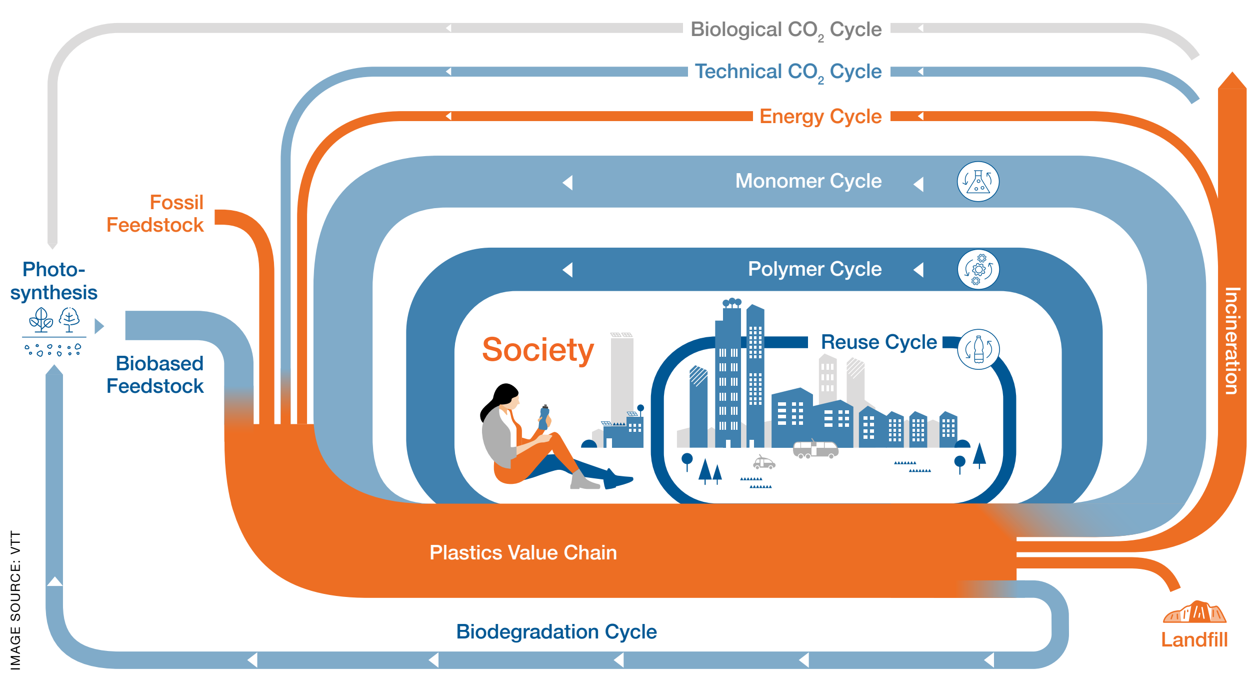


Figure 9. Overview of VTT's vision for circularity of plastics (Tenhunen & Pöhler (eds.) 2020).

Generally,

- Waste streams differ a lot from each other, and they are subject to significant change over time. There will not be a single or even only few technical solutions suitable for all waste streams. There will be several technical solutions that will together complement each other in a smart way to thrive for very high value utilisation of entire waste streams.

- Complete, 100% recycling of all waste streams would require infinite amount of energy and significantly oversized investments if it would even be technically feasible in the first place.

- Recycling technologies develop all the time. It can be seen, that in the future even higher recycling rates can be achieved with technologies under development. However, all these solutions are not commercially available today.

- The larger amount of waste stream is recycled, the worse quality reject stream is left and the more difficult it is to utilise that reject stream. Majority of the potential harmful compounds end up in these streams. Therefore, thermal treatment of some fractions is seen to be needed also in the future. This is needed to minimize the volume of truly harmful streams. The thermal treatment also opens up the possibility to rebuild useful products from molecules (syngas, CO2 and H2) and upcycle these streams.

- In theory, the less treatment or breaking of compounds in a stream is required, the less energy is needed for processing. Therefore, it is seen better, and energy efficient to utilise e.g., fibres as fibres or polymers as polymers without breaking the matter into molecular level if sufficient quality can be achieved. If we need to go through the lowest energy potential, CO2 so to say we will always be wasting energy in conversion process. Hence combustion and CCU should only be considered with waste streams if no alternative recycling technologies or methods are available. Heat recovery potential from these processes is significant and should always be considered when appropriate.

Suggested, multi-technological approach for steps towards circularity of carbon-containing wastes would be an approach with recycling or even upcycling with minimum processing and additional energy input to the system. During the design phase of products, attention should be paid to the composition, structural design, and materials chosen to enable better recyclability. As a recommendation it would be beneficial to advance all ambitious targets related to recycling in the spirit of waste hierarchy, and in addition to utilise CO2 form the waste sector resulting only from fractions not suitable to any other process than combustion, while at the same time promote full benefits from CCU. Also exploiting full benefits of utilising all the side streams of the process; heat, electricity, oxygen, water and ashes from especially thermal treatment processes.

REFERENCES

- Alakangas, E., Hurskainen, M., Laatikainen-Luntama, J., Korhonen, J., 2016. Properties of indigenous fuels in Finland. VTT Technology 272.
- Auranen, A., 2018. Tekstiilijätteestä mekaanisesti kierrätetty kuitu ja sen soveltuvuus eri prosesseihin. Metropolia University of Applied Sciences.
- BEIS, 2021. Advanced Gasification Technologies - Review and Benchmarking, Summary report, Research Paper Number 2021/038 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1022923/agt-benchmarking-summary-report.pdf
- Broeren, Uijttewaal, Bergsma, 2022. Monitoring chemical recycling, How to include chemical recycling in plastic recycling monitoring?, CE Delft, March 2022, Publication code: 22.210126.044
- Bröckl, M., Kiuru, H., Heads, S., Kämäräinen, K., Patronen, J., Luoma-aho, K., Armila, N., Sipilä, E., Semkin, N., 2021. Possibilities to impact CO2 emissions and to promote circular economy by different policy instruments targeting waste incineration (in Finnish), Publications of the Government´s analysis, assessment, and research activities No 2021:8, Prime Minister's Office (urn.fi/URN:ISBN:978-952-383-093-6)
- Cepi, 2022. Key statistics 2021, European Pulp & Paper Industry. https://www.cepi.org/wp-content/uploads/2022/07/Key-Statistics-2021-Final.pdf
- EEA, 2022. Reaching 2030's residual municipal waste target – why recycling is not enough. EEA Briefing 22.4.2022. Available at: https://www.eea.europa.eu/publications/reaching-2030s-residual-municipal-waste/reaching-2030s-residual-municipal-waste
- Ellen MacArthur Foundation, 2017.
- Eriksson, M., 2021. Stockholm exergy. Presentation at CLIC Plast-In seminar 21.9.2021. Helsinki
- Eunomia & Zero Waste Europe, 2020. Recycling of multilayer composite packaging; the beverage carton.
- https://zerowasteeurope.eu/wp-content/uploads/2020/12/zero_waste_europe_report_-beverage-carton_en.pdf
- Euractiv, 2022. News article by Frédéric Simon: Recycling cannot meet 100% of demand for packaging, EU official cautions. https://www.euractiv.com/section/circular-economy/news/recycling-cannot-meet-100-of-demand-for-packaging-eu-official-cautions/ Accessed 5.12.2022
- European commission, 2022. Environment, Green growth, waste prevention and management. https://ec.europa.eu/environment/green-growth/waste-prevention-and-management/index_en.htm
- Eurostat, 2022 Waste data. https://ec.europa.eu/eurostat/web/waste/data/database
- Forti, V., Baldé, C. P., Kuehr, R. & Bel, G., 2020. The Global E-waste Monitor 2020. Quantities, flows, and the circular economy potential.
- https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf. Accessed 8.3.2022
- Government Decree on Waste, 978/2021. Valtioneuvoston asetus jätteistä. In Finnish. https://finlex.fi/fi/laki/alkup/2021/20210978
- Government Decree on Packaging and packaging waste, 1029/2021. Valtioneuvoston asetus pakkauksista ja pakkausjätteistä. In Finnish. https://finlex.fi/fi/laki/alkup/2021/20211029
- Harlin, V., 2021. Tertiary recycling of textile polyester waste – feasibility of the alkaline hydrolysis. Master thesis 2021, Oulun yliopisto.
- HSY, 2022. Pääkaupunkiseudun sekajätteen koostumus vuonna 2021. https://julkaisu.hsy.fi/paakaupunkiseudun-sekajatteen-koostumus-vuonna-2021.html
- Kamppuri, T., Heikkilä, P., Pitkänen, M., Saarimäki, E., Cura, K., Zitting, J., Knuutila, H., & Mäkiö, I., 2019. Tekstiilimateriaalien Soveltuvuus Kierrätykseen.
- Karayannidis, G.P. & Achilias, D.S., 2007. Chemical Recycling of Poly(ethylene terephthalate). Macromolecular Materials and Engineering 292: 128-146
- Karppinen, T., Salmenperä, H., Piippo, S., and Mönkkönen, I., 2021. Yhdyskuntajätteen koostumustiedon laadun parantaminen. Ympäristöministeriön julkaisuja 2021:24, 56 s.

- Kinnunen, R. and Kupiainen, R., 2019. Rakennustyömaan muovijätevirrat ja lajittelun ympäristövaikutukset. https://www.theseus.fi/bitstream/handle/10024/167592/Opinn%c3%a4ytety%c3%b6_KinnunenKupiainen.pdf?sequence=2&isAllowed=y.
- KIVO, 2021. Kotitalousjätteen keskimääräinen valtakunnallinen koostumus. https://kivo.fi/ymmarramme/koostumustietopankki/kotitalousjatteen_koostumus_yhteenveto/ Accessed 2.12.2022.
- Kuitukierrätys 2021. Kuitupakkausten kierrätys vuonna 2020. (Recycling of fibre-based packaging 2020) Press release 18.3.2021. https://www.kuitukierratys.fi. Accessed 8.6.2022
- Kusenberg, M., Eschenbacher, A., Delva, L., Djokic, M. R., Zayoud, A., Ragaert, K., De Meester, S. D. & Van Geem, K. M., 2022. Opportunities and challenges for the application of post-consumer plastic waste pyrolysis oils as steam cracker feedstocks: To decontaminate or not to decontaminate?, Waste Management 138 (2022) 83-115, https://doi.org/10.1016/j.wasman.2021.11.009
- Kärhä, V. 2022. Vesa Kärhä, CEO, Finnish Plastics Industries Federation Personal communication. 3.3.2022.
- Le, K., 2018. Textile Recycling Technologies, Colouring and Finishing Methods. UBC Sustainability Scholars report. https://sustain.ubc.ca/sites/default/files/2018-25%20Textile%20Recycling%20Technologies%2C%20Colouring%20and%20Finishing%20Methods_Le.pdf
- Maisel, F., Chancerel, P., Dimitrova, G., Emmerich, J., Nissen, N., Schneider-Ramelow, M., 2020. Preparing WEEE plastics for recycling – How optimal particle sizes in pre-processing can improve the separation efficiency of high quality plastics. Resources, Conservation and Recycling, Vol.154, 104619
- Ministry of the Environment, 2020. Pakkausjätetilastot 11.12.2020. https://www.ymparisto.fi/fi-FI/Kartat_ja_tilastot/Jatetilastot/Tuottajavastuun_tilastot/Pakkausjatetilastot Accessed 4.3.2022
- Ministry of the Environment, 2021. Uusi jäteasetus velvoittaa nykyistä tehokkaampaan erilliskeräykseen ja kierrätykseen – Communication by the Ministry of Environment 18.11.2021. Available at: https://ym.fi/-/uusi-jateasetus-velvoittaa-nykyista-tehokkaampaan-erilliskeraykseen-ja-kierratykseen
- Ministry of the Environment, 2022. Keräyspaperitilastot 17.6.2021 https://www.ymparisto.fi/fi-FI/Kartat_ja_tilastot/Jatetilastot/Tuottajavastuun_tilastot/Kerayspaperitilastot Accessed 8.3.2022
- Packaging Europe, 2022. European plastic mechanical recycling rate at 23%, says AMI. Packaging Europe e-magazine March 2022. https://packagingeurope.com/news/
- Pirkanmaan Ely-keskus 2021 Romuajoneuvotilastot vuosilta 2005-2019. 24.6.2021. Available at: https://www.ely-keskus.fi/web/tuottajavastuu/kierratystavoitteet-ja-tulokset
- Plastics Europe, 2022. Recycling technologies. https://plasticseurope.org/sustainability/circularity/recycling/recycling-technologies/. Accessed 5.9.2022.
- Qureshi, M., 2019. Role of thermolysis (pyrolysis) of plastics in feedstock recycling. Presentation (5/2019), CircWaste -seminar Kiertotalouden kirittäjät – tuloksia kiertotaloushankkeista Suomessa.
- Ragaert, K., Delva, L., Van Geem, K., 2017. Mechanical and Chemical Recycling of Solid Plastic Waste. Waste Management 69, (2017) 24-58, https://doi.org/10.1016/j.wasman.2017.07.044
- Schlummer, M., Fell, T., Mäurer, A., Altnau, G., 2020. The Role of Chemistry in Plastics Recycling - A Comparison of Physical and Chemical Plastics Recycling. Kunststoffe international 5, 2020, 34-37 https://www.ivv.fraunhofer.de/content/dam/ivv/en/documents/Leistungsangebot/Recycling_Environment/The-Role-of-Chemistry-in-Plastics-Recycling.pdf
- Seitz, Klätte, Pohl, 2020. Evaluierung von thermisch-chemischen Depolymerisationstechnologien zur Verwertung von Kunststoffabfällen in: Thiel, S.; Thomé-Kozmiensky, E.; Quicker, P.; Gosten, A. (Hrsg.), Energie aus Abfall, Band 17, S. 105–114, Thomé-Kozmiensky Verlag GmbH, Neuruppin 2020.
- Sinha, V., Patel, M. R. & Patel, J. V., 2010. Pet Waste Management by Chemical Recycling: A Review. Journal of Polymers and the Environment 18: 8-25.
- Statistics Finland, 2021. Jätetilasto 2020, Yhdyskuntajätteet Tilastokeskus - Tilastot aiheittain – Jätetilasto https://www.stat.fi/til/jate/2020/13/jate_2020_13_2021-12-09_tau_001_fi.html
- Statistics Finland, 2022. Jätetilasto 2021, https://stat.fi/tilasto/jate. Accessed 19.12.2022.
- Statistics Finland, 2022. Database search, https://pxdata.stat.fi/PxWeb/pxweb/fi/StatFin/StatFin__tti/statfin_tti_pxt_11b7.px/
- Stockholm Exergi, 2022. Annual report 2022. https://www.virtualmagnet.eu/pub/123/Stockholm-Exergi-2021-in-brief/#p=1 accessed 10.6.2022.
- Tenhunen, A., & Pöhler, H. (Eds.), 2020. A Circular Economy of Plastics: A vision of redesigning plastics value chains. VTT Technical Research Centre of Finland. VTT Discussion paper https://doi.org/10.32040/2020.978- 951-38-8824-4
- Tuominen L. HSY. Personal communication, e-mail 14.1.2022

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