IEA Bioenergy
Technology Collaboration Programme

Material and Energy Valorization of Waste as Part of a Circular Model

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Material and energy valorization of waste as part of a circular model

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1. Background

According to the last Circularity Gap Report[1], the world is only 8.6% circular. In other words, over 90% of what we use and extract still does not enter a cycle where can be used more than once and thus turns into waste, leaving a significant circularity gap. Consumers, businesses, cities, and governmental bodies need to make an effort to facilitate and increase circularity by (1) reducing virgin material extraction; (2) promoting recovery, reuse and recycling of those materials that already entered the system, and (3) generating energy in a clean and efficient way. Material recovery from waste streams has become an important driver in this transition.

In addition, today's global energy crises resulting from several factors such the pandemic and Russia's invasion of Ukraine[2] is accelerating initiatives to develop new and support the already existing energy efficient solutions. Incineration (waste combustion with energy recovery also referred to as Waste-to-Energy, WtE) technologies at industrial scale has been used as a way of handling waste for few decades and it is well stablished specially in some countries in Europe and Japan. For many years, its reputation was linked to poor environmental output, although changes in legislation and technology improvement (i.e., in flue gas cleaning) has made it possible to provide energy in an efficient and clean way. However, with the emergence of implementing circular models in our societies, and the lack of public support for combustion-based WtE in some countries, new technologies also come into play and could provide energy and material recovery solutions closer to the principles associated with circular economy[3].

Some of these solutions are designed to be integrated with combustion-based systems to improve resource material recovery; others are new processes with built-in ability to keep molecules in use for longer while generating power and heat for local use. Feedstock recycling, wastewater nutrients recovery, carbon capture storage/utilization (CCS/CCU), hydrogen production or hydrothermal carbonization of waste are among those solutions.

[1] The Circularity Gap Report 2022, Circularity Gap Report Initiative. CGR 2022 (circularity-gap.world)

[2] Global Energy Crisis. IEA Bioenergy, 2022 – Link: Global Energy Crisis – Topics - IEA, website visited 13th December 2022.

[3] Material and Energy Valorisation of Waste in a Circular Economy – Roberts D., Edo M., Johansson I., Hoffman B., Becidan M., Ciceri G., Murphy F., Trois C., Curran T. Link: IEA Bioenergy Task 36 report, website visited 13th of December 2022.

2. Today's waste situation

Although there might be differences in the views of what is to be considered waste, there is a lot of it. The World Bank[4] has estimated that there were around 2 billion tonnes of waste generated in 2016 and that it will increase by almost 30% until 2030 and by close to 70% by 2050 (see Figure 1). As expected, the waste generation is not evenly distributed around the world, but rather 34% of the waste is generated by the high-income countries despite only having 16% of the world population.

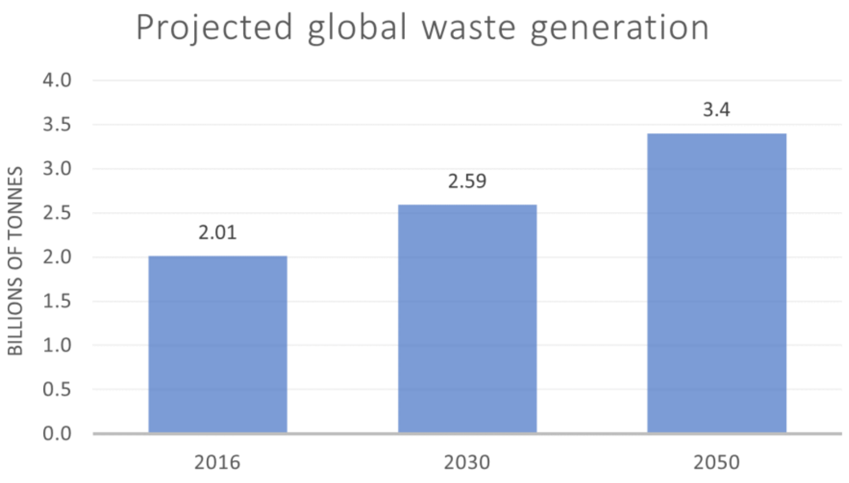

Figure 1. Framework for the EU Biomethane Action Plan

The average global waste composition (Figure 2) indicates that 63% of the waste is organic and corresponds to 1.3 billion tonnes a year globally. The food and green waste is the largest fraction no matter the income, but in high income countries there is a lot more of other materials (metals, glass, paper and plastics) as well.

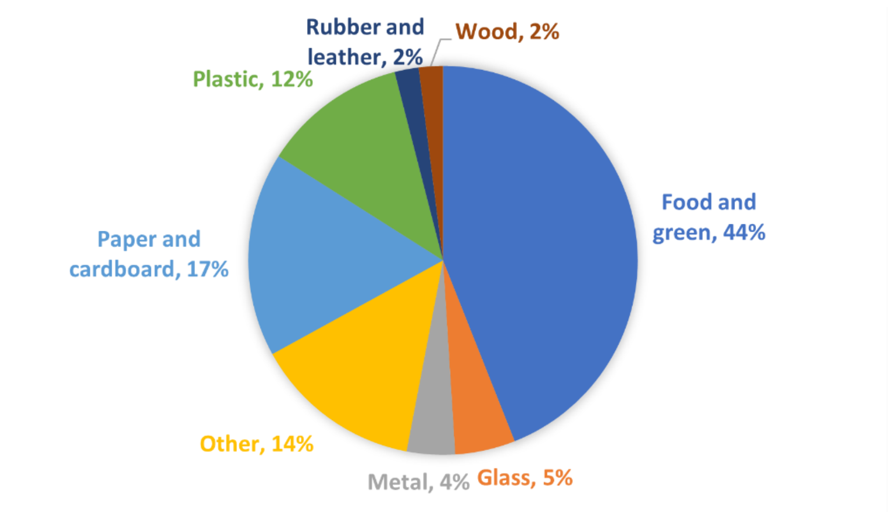

Figure 2. The global waste composition in %[4].

[4] What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Kaza, Silpa; Yao, Lisa C.; Bhada-Tata, Perinaz; Van Woerden, Frank. 2018. Urban Development; Washington DC: World Bank. Link

The waste management sector is critical to the success of the Circular Economy movement[5]. While the manufacturing sector clearly plays an important role from the perspective of material and products design and process, changes to more circular manufacturing practices will have little impact if the waste management sector does not also evolve. Recycling is considered consistent with Circular Economy principles, yet despite the push for increasing the proportion of recycled materials used in manufacturing and construction[6], global recycling rates are generally low, with a significant proportion of waste being sent to landfills of varying quality (Figure 3 and Figure 4) resulting in loss of resources.

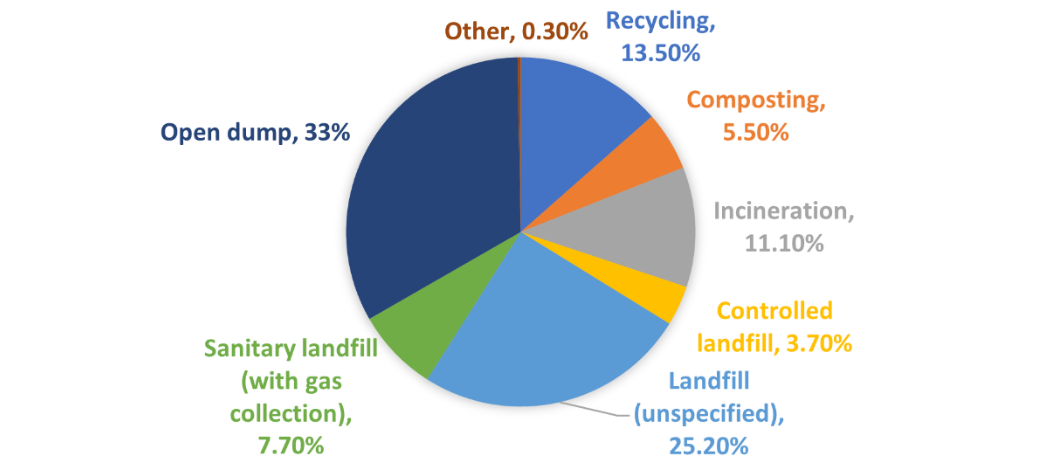

Figure 3. Global treatment and disposal of waste in %[4].

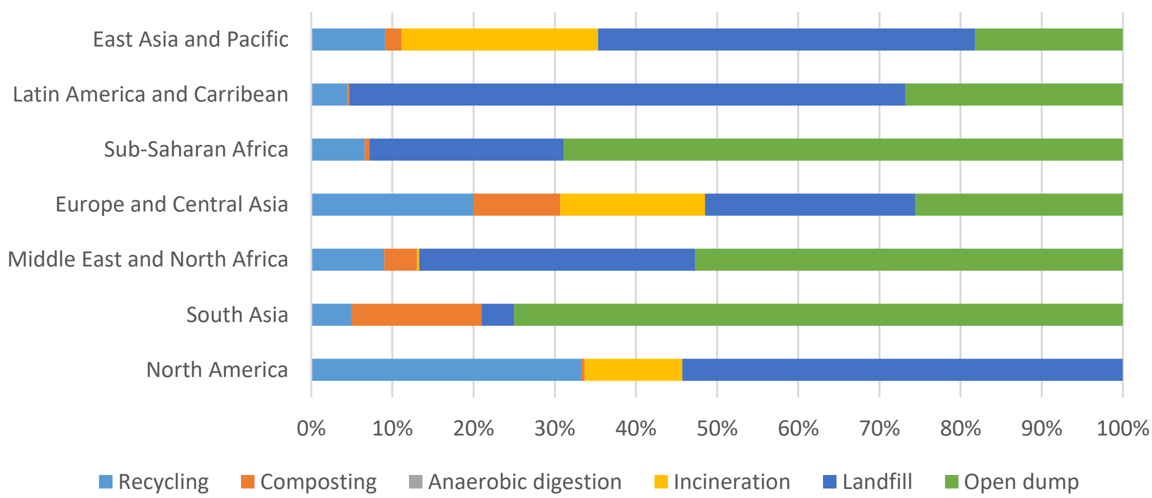

Figure 4. Waste treatment/disposal methods broken down by region[4].

[5] Material and Energy Valorisation of Waste in a Circular Economy – Roberts D., Edo M., Johansson I., Hoffman B., Becidan M., Ciceri G., Murphy F., Trois C., Curran T. Link: IEA Bioenergy Task 36 report, website visited 13th of December 2022.

[6] *Trends and drivers in alternative thermal conversion of waste*. Stapf D., Ciceri G., and Johansson I., IEA Bioenergy Task 36, 2020.

3. Emergence of Circular Economy principles

Circular Economy Principles

A Linear Economy follows a "take-make-dispose" model where virgin materials are extracted; goods are produced and at the end of their useful life, or often before that, they are disposed of (Figure 5). In this economic model, the value is created through producing and selling items and the reuse and recycling rates are usually low, which means that most of the energy and materials embodied in these goods are lost. Replenishing this model requires resource extraction and energy generation, much of which is considered finite in supply, and often non-renewable.

Figure 5. Linear Economy versus Circular Economy[7].

By contrast, a Circular Economy avoids waste generation by "*decoupling economic activity from the consumption of finite resources*"[8] (Figure 6). It integrates aspects of resource management, material development, manufacturing, energy, supply chain security, environmental management, behavioural science, policy development, and more. It relies on a philosophical shift from the linear model to one where reuse, remaking, and recycling underpin a move away from reliance on resource extraction (Figure 5). The principles of a Circular Economy are (1) eliminate waste and pollution; (2) circulate products and materials, and (3) regenerate nature[8,9].

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[7] The Maker Movement and the Disruption of the Producer-Consumer Relation. Unterfrauner, Elisabeth & Voigt, Christian & Schrammel, Maria & Menichinelli, Massimo. (2017). 10.1007/978-3-319-77547-0_9.

[8] *What is a circular economy?*, Ellen MacArthur Foundation. Link to the website visited on the 24th of November 2022.

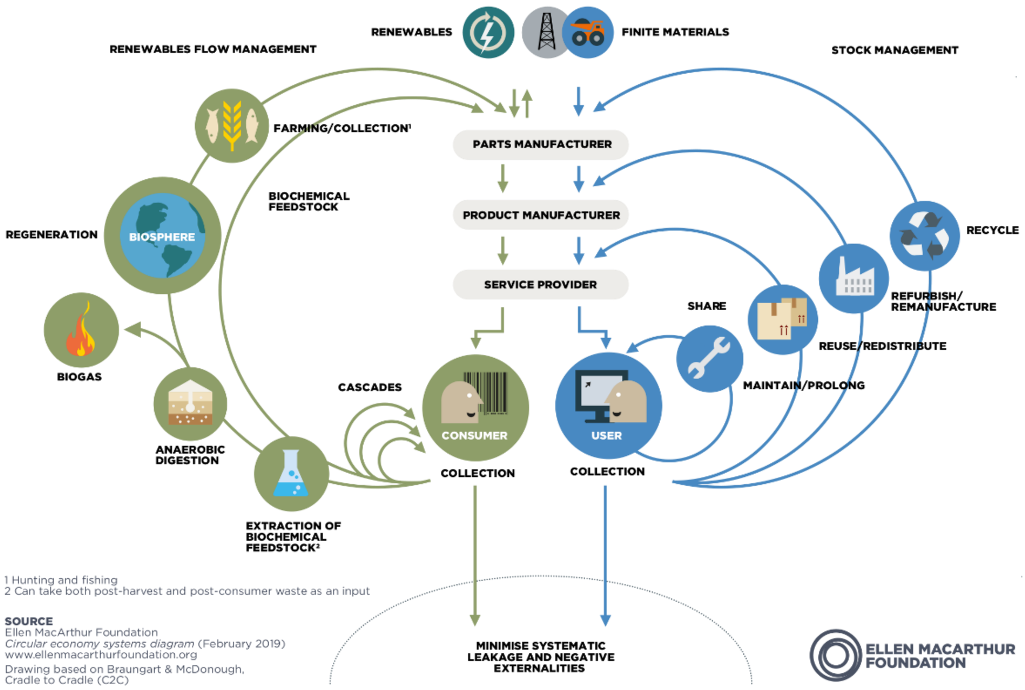

Figure 6. Circular Economy visualization diagram by Ellen MacArthur Foundation[9].

As Circular Economy principles become embedded in the policies of governments and the strategies of organisations around the world, there are greater expectations on waste management systems to contribute to 'keeping molecules in use for longer' (Table 1). For the established combustion-based systems, there is now an expectation that additional recovery of nutrients occurs, and that ash residues are utilised effectively instead of being sent to landfill. Retrofitting and modifying these processes to make them more circular is not without cost and complexity—in some countries this is now shifting the value proposition for new technology pathways to play a greater role.

FROM	*TO*
Waste Management	Material Recycling and resource handling
Energy Recovery	Molecules in use for longer
Heat and Power	Energy, chemicals, and manufacturing feedstocks.

Table 1. The shift in focus for waste management and energy recovery driven by the emergence of circular economy principles[10].

The circular economy principles, and the emerging technology pathways, will see waste management and resource recovery transcend the traditional areas of waste, heat, and power, and intersect more with the manufacturing, construction, and transport sectors. Energy recovery is still important, especially when the waste streams have a significant component that is considered renewable, and the energy can be used to abate greenhouse gas emissions as well as keep molecules in use for longer. The concept of energy can also be broadened, as we see waste conversion pathways emerge that can produce energy carriers such as hydrogen.

[9] Ellen MacArthur Foundation. Link to the Circular Economy visualization diagram.

[10] Material and Energy Valorisation of Waste in a Circular Economy – Roberts D., Edo M., Johansson I., Hoffman B., Becidan M., Ciceri G., Murphy F., Trois C., Curran T. Link: IEA Bioenergy Task 36 report, website visited 13th of December 2022.

Implications for Energy Recovery from Waste

Energy recovery, typically via combustion, is more common in some European, Asian, and North American countries, and is emerging as a new strategy for waste management in Australia. Usually referred to as Waste-to-Energy (or Energy from Waste), this approach is considered by most to be superior to landfilling as it sanitizes and reduces the volumes of material requiring landfilling and the associated greenhouse gas emissions, can produce renewable heat and power (often offsetting the use of fossil fuels), and gives another 'use' to the waste streams generated. Modern waste-to-energy plants usually include advanced separation and resource recovery stages[11], meaning they also contribute to increased recycling rates. Combustion-based waste-to-energy systems were not designed with circular economy principles in mind: waste management in jurisdictions with limited opportunity for landfilling, and the provision of heat and power were traditionally the primary drivers. However, energy recovery from waste plays an important role in the circular economy. From the waste perspective, it ensures a safe treatment of non- recyclable materials[12]; while from the resource perspective, it provides a good use for these materials and reduces CO_2 emissions by replacing fossil fuels.

As Circular Economy principles become more widespread and are emerging as features of government policies and corporate strategies around the world, there is increasing focus on how we can consider these processes as part of a circular economy, and what new technology pathways might be needed to support such a transition.

[11] Example of this kind of facilities: Sorting Technologies: Case study about a MSW sorting facility in Norway-IVAR. Edo M., Meisser R., Nilsson J. Link: IEA Bioenergy Task 36 report, website visited 7th of January, 2023.

[12] CEWEP. The Confederation of European Waste-to-Energy Plants. Link to the website visited on the 25th of November 2022.

4. Recycling and energy recovery

Biogas and Biomethane

Biogas plants play an important role on the development of a circular handling of resources. In a report[13] about the role of biogas and anaerobic digestion in a circular economy, IEA Bioenergy Task 37 defined the future of the biogas plants as "*factories where value is created from previously wasted materials; this ensures sustainability of the environment and potential for financial gain for the local community.*" The fact that a large variety of feedstock can be fed into anaerobic digestors system, leading to a range of products, ensures the crucial role of this technology in a circular and bio-based economy. A clear example of the connection between biogas production, circular and bio-based economy is shown in Figure 7. Waste is upcycled to biogas, a renewable energy, at the same time as sanitized bio-fertilizers are produced. Linked to this latter view is the concept of anaerobic digester based biorefineries[13].

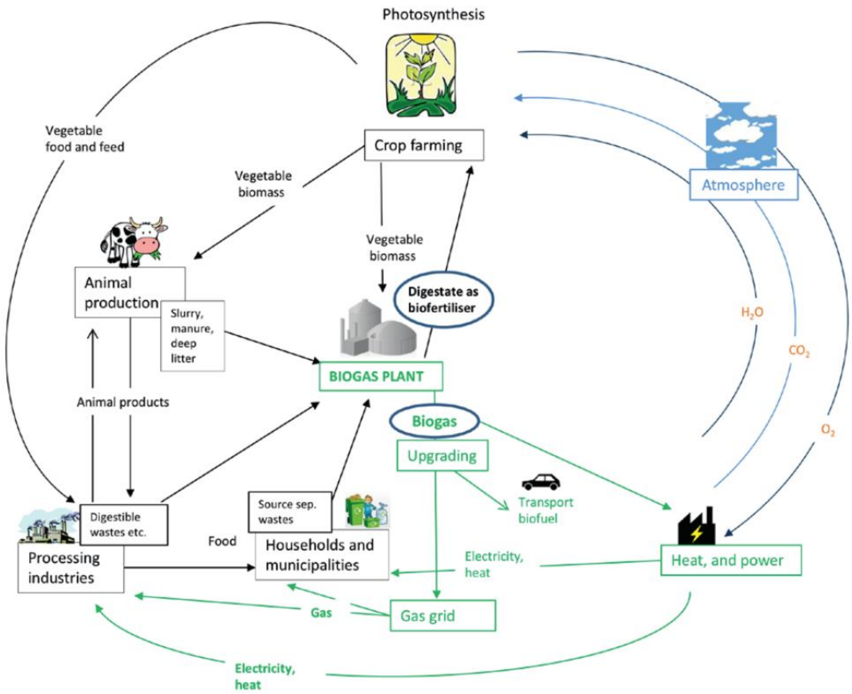

Figure 7. Example of a close loop and main streams of the concept of centralised manure co-digestion in Denmark[14]

Renewable natural gas, also referred as to biomethane, is the product of biogas upgrading where carbon dioxide (CO_2) and other impurities (hydrogen sulphide, water, siloxanes, etc.) are removed rendering it energetically equivalent to fossil-derived natural gas and compatible with existing natural gas engines and infrastructure.

Biogas upgrading technologies are commercially available, with the most common solutions being membrane separations, pressure swing adsorption and other configurations of amine adsorption. In particular, the carbon dioxide separation technologies are operationally intensive as they require significant inputs of energy to regenerate the adsorbent material.

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[13] The role of Anaerobic Digestion and Biogas in the Circular Economy. IEA Bioenergy Task 37, Fagerström A., Al Seadi T., Rasi S., Briseid T, (2018).

[14] Governance of environmental sustainability of manure-based centralised biogas production in Denmark. IEA Bioenergy Task 37 Al Seadi T., Stupak I., Smith,C. T. (2018). Link to the report.

Thus, renewable natural gas is often a considerable price premium relative to fossil natural gas sources[15]. However, there are alternative methods being developed that either might be less expensive or generate other benefits such as an increased yield of biomethane. Biomethanation is one of these pathways that shows promise. Instead of separating the carbon dioxide, it is converted to methane through the addition of hydrogen, thus increasing the yield of the renewable natural gas. There are examples where this is increased by as much as 60-70% compared to traditional upgrading technologies[16].

Nutrients recovery

The previous section highlighted the potential of biogas and the production of a sanitized bio-fertilizers. One large waste stream that still can be used to produce biomethane, but where the utilisation of the fertilizer part is more put in question, is biosolids/sewage sludge. The risk of lingering residues of pharmaceuticals is one of the arguments raised against the use of biosolids on farmland. Some countries, like Germany and Austria, have introduced legislation limiting the possibilities for direct use on farmlands while still demanding that the phosphorus in the biosolids should be recovered.
Although the status in the handling of biosolids differs a lot between different countries[16], the legislation in some countries is now forcing the development of new technologies for the recovery of nutrients. Some of these are combustion oriented, where phosphorus is chemically recovered from the ash, while others rely on pyrolysis or hydrothermal carbonization (HTC). The latter has shown promise in producing a combination of hydrochar (that can both be used for soil amendment as well as energy purposes) and a liquid biofertilizer[17].

Landfilling

Although landfilling is the least desirable option in a circular economy, there will still be wastes that might be best suited for landfilling to phase them out of the Technosphere. Also, the fact is that today, close to 70%[4] of the waste are either ending up in a landfill (with varying quality) or a dumpsite. These are having a severe impact on the greenhouse gas emissions globally, and calculations estimate that 5% of the global greenhouse gas emissions comes from waste treatment and disposal, and a majority of that is from the open dumpsites and landfills without gas collection[18]. In the United States, approximately 15% of the human-related methane emissions are from landfilling, making it the third largest emitting sector of methane[19].
There is a large potential to both decrease the greenhouse gas emissions and contribute to energy production, through collection of gas at the sites that do not do so today, as well as using engineered landfills as a first step away from the open dumps. The World Bank has explored a scenario in Indonesia, where the introduction of controlled landfills together with

[15] Valorisation of biowaste in the United States: Distributed biogas upgrading to Renewable Natural Gas (RNG) using biomethanation. IEA Bioenergy Task 36. Hoffman B. (2022). Link to the report.
[16] Nutrient recovery from waste, Johansson I., Edo M., IEA Bioenergy Task 36 workshop report (Task 36 05:2019). Link to the report.
[17] Case study: HTC Valorisation of organic waste and sewage sludges for hydrochar production and biofertilizers, Ciceri G. , Hernandes Latorre M., Mediboyina M., Murphy F. IEA Bioenergy Task 36 report, October 2021. Link to report
[18] What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Kaza, S., Yao L. C., Bhada-Tata P., Van Woerden F. 2018. Urban Development;. Washington, DC: World Bank. Link to the report.
[19] Basic information about landfill gas, United States Environmental protection agency. Basic Information about Landfill Gas | US EPA, Last accessed 2023-01-08

increasing waste collection rates from 65% to 85% would reduce the greenhouse gas emissions with 21%[20].
In addition, landfill mining has been a subject for research and pilots tests several years. The commercial application of it has been limited but when more environmentally friendly solutions is being sought after and the need for land increases, there might also come an increased demand of remedying the old landfills/dumpsites.

Plastic recycling

Plastics is one of the material streams that are widely debated today. It has gotten a lot of attention in media due to marine debris and the detection of micro-plastics in some of the most isolated places on earth. OECD have estimated that in 2019 around 22 million tonnes of plastic waste leaked to the environment around the world[21], and with business as usual it is foreseen to triple by 2060. The global plastic production in 2021 is estimated to 391 million tonnes of which 1.5% was biobased and 8.3% was recycled material[22].
Efficient recycling of plastic waste is a challenge and there are different reasons for it. One of them is that there is a large number of different plastics, many of them consisting of a combination of different polymers as well as a combination of functional additives.
Today the main pathway for recycling of plastics is mechanical recycling. The principle of the mechanical recycling is that the collected plastic waste goes through a sorting plant where metals, organics and inert materials are sorted out. The plastics is sorted into different polymers as well as (in some cases) different colours. The plastics then are washed and regranulated into a secondary raw material. Since the demand and value of the granulate depends highly on the purity and colour of the granulate, this imposes natural limitations on the mechanical recycling.
Considering the current status where Germany, that has a well-developed waste management and recycling industry, only sent for recycling 42% of their post-consumer plastic wastes (in 2020)[23], it seems evident that to move towards a more circular approach there is a need for recycling of plastics that the mechanical pathway cannot handle.
Chemical recycling encompasses several different technologies like solvolysis, pyrolysis and gasification. The main principle is to break down the plastic waste into a feedstock that can be reprocessed into new materials that can have the same quality as virgin materials. This way you can get rid of unwanted impurities and contaminations. Today, the commercial experience of the chemical recycling is limited but the interest is increasing and there are a few new and upcoming plants in different stages of development[24], and Plastic Europe has stated that their members have plans to invest 7.2 billion Euros until 2030 to get a capacity of recycle 3.4 million tonnes 2030 (which can be compared with the 4.6 million tonnes of post-consumer plastics actually being recycled in EU in 2020[23]).
In a recent publication different potential recycling routes of light weight plastic packaging were compared[25] (see Figure 8
Figure 8). In the performed techno-economic analysis there was a clear outcome that to reach high recycling rates of the carbon, a combination of methods is needed (mechanical and chemical).

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[20] Improvement of Solid Waste Management to Support Regional and Metropolitan Cities. Project Appraisal Document. World Bank, Washington, DC. https://operationsportalws.worldbank.org / Pages / WorkingDocuments.aspx?projectid=P157245

[21] Global Plastics Outlook: Policy Scenarios to 2060, OECD, 2019, Link to the report

[22] Plastics – The facts 2022, Plastics Europe, Oct 2022, Link to the report

[23] The circular economy for plastics – a European overview, Plastics Europe, 2022 Link to the report

[24] Chemical recycling of plastic waste through pyrolysis, Staph D. IEA Bioenergy Task 36 workshop, Durban, South Africa, Nov 30 2022.

[25] Techno-economic Assessment and Comparison of Different Plastic Recycling Pathways -a German Case Study, Volk, R., et al.: Journal of Industrial Ecology, 2021, 1-20; https://doi.org/10.1111/jiec.13145

Table 2 shows that reaching a recycling rate of 74% is economically viable. The combination also generates energy considerable energy savings compared to primary production which is important of times of energy scarcity.
The benefits from recycling of plastics are plenty, from less plastic pollution of our planet to the energy and CO_2 savings that could be accomplished. The fossil based direct emissions from waste incineration would decrease significantly if a larger portion of plastics were recycled. Some of the new processes will also benefit from the possibility to recover excess heat and thus give another perspective to waste-to-Energy. EU has indicated that if all the plastic waste could be recycled that energy savings corresponding to 3.5 billion barrels of oil a year.

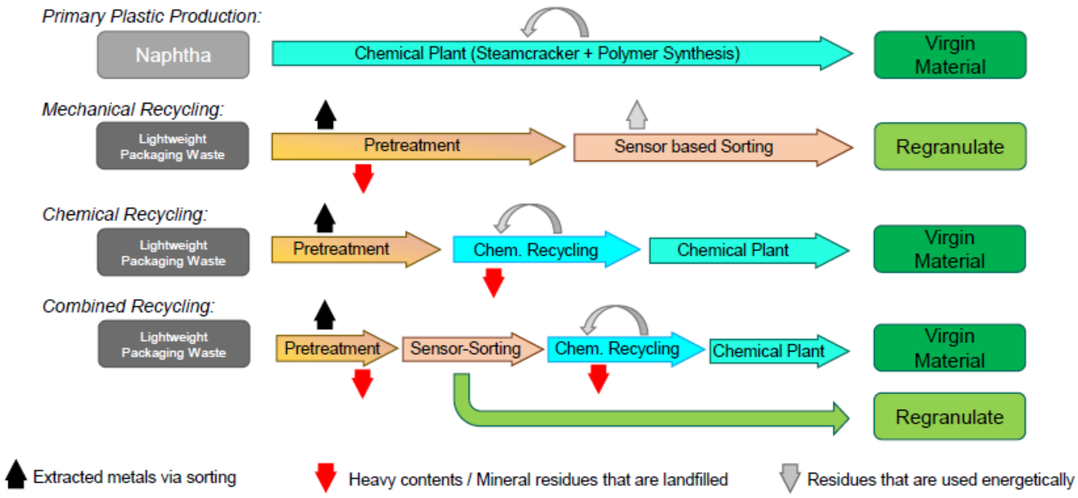

Figure 8. Illustration of potential recycling routes of light weight packaging waste[26].

Recycling scenario	Cost [€/kg_{input}]	Calculated Energy Demand [MJ/kg_{input}]	Global warming potential [$kgCO2_e/kg_{input}$]	Overall carbon recycled
Mechanical, 42% yield	-0.16	-18.1	0.2	42%
Chemical recycling	-0.24	-15.9	0.3	59%
Combined mech. and chem. recycling	-0.29	-30.1	-0.2	74%

Table 2. Evaluation of different recycling routes of LWP compared to primary plastic production of high density polyethene.

Other energy carriers

Some of the technologies (mainly pyrolysis and gasification) used for chemical recycling of plastics can also be used to transform a more mixed stream of waste into other energy carriers like hydrogen or jet fuel. Fulcrum Bioenergy announced in December 2022 that they had successfully produced a synthetic crude oil from waste that would otherwise go to landfill[27].
This segment is not a very mature area, but it shows that there is an interest of converting what we consider as waste into something else with the potential of replacing fossil resources.

[26] Chemical recycling of plastic waste through pyrolysis, Staph D. IEA Bioenergy Task 36 workshop, Durban, South Africa, Nov 30 2022.
[27] Press release, Fulcrum Bioenergy, Fulcrum BioEnergy Successfully Produces First Ever Low-Carbon Fuel from Landfill Waste at its Sierra BioFuels Plant (prnewswire.com)

5. Beyond technologies

Policies and social licenses to operate

For the waste management and energy recovery sector to transition towards a more circular approach, technologies, options, and pathways are not likely to be enough. Policy settings that encourage the deployment and uptake of (often more expensive) new technologies, and regulations that specify the extent to which waste can be landfilled or recyclable material used as manufacturing feedstock, for example, are known to drive change. This is also starting to happen around the world. EU adopted their circular economy action plan in 2020 which put forward initiatives through the life cycle- and not just aimed at the end of pipe solutions (waste management)[28].

Just as important as policy settings and the tools to respond to them is the public's acceptance of new technologies. Combustion-based WtE, even in countries where it is established and demonstrably effective, often attracts opposition and criticism, and countering these is a complex undertaking. Information, while important, is seldom sufficient; strong community engagement processes, coupled with an understanding of expectations and concerns and insights into local issues are critical. While there is a stigma attached to combustion-based WtE in some countries, the emerging alternative pathways are not guaranteed to have a simpler process towards public and community acceptance – there are different challenges associated with technologies that are less proven or less understood[29].
There are also challenges in transforming the waste management system from an unmanaged/unofficial sector into a more governed sector. In many countries there is a strong informal sector providing their livelihood on waste picking. So, changes to these systems also needs to encompass a larger scope than just the environmental and health aspect of the waste management.

Environmental and resource aspects

Any type of waste generates a negative environmental impact – even if managed well and recycled in an efficient way. As was described earlier, there are significant greenhouse gas emissions from (mostly) the not so well managed waste, in addition to that there are sanitary aspects like the spread of disease through rats, leaching of unwanted substances into the environment, emissions of dioxins when uncontrolled fires are initiated at landfills and the list can be made much longer.

There are also greenhouse gases emitted from technologies like combustion based WtE. While preventing the methane emissions that would have occurred if the waste ended up in a landfill, there will instead be direct emissions of fossil carbon dioxide from the plastics in the waste. An increased plastic recycling would be beneficial in this area and mean that a larger portion of the energy would be truly renewable. There is also an increased interest for carbon capture and storage (CCS/BECCS) to handle these emissions where a negative contribution could be accomplished through the CCS of the biogenic carbon while neutralising the fossil emissions. Its potential and drawbacks as well as policy aspects are being widely discussed. As example, IEA Bioenergy inter-task project *Deployment of BECCS/U value chain* provides insight about benefits and obstacles when moving from pilot to full-scale plants, not only from the technological aspects but also business models and

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[28] Circular economy action plan, EU, Circular economy action plan (europa.eu), Last visited 2023-01-08

[29] Material and Energy Valorisation of Waste in a Circular Economy – Roberts D., Edo M., Johansson I., Hoffman B., Becidan M., Ciceri G., Murphy F., Trois C., Curran T. Link: IEA Bioenergy Task 36 report, website visited 13th of December 2022.

policy[30]. Right now, the Klemetsrud plant in Oslo Norway, has secured the funding and taken the decision to invest in full scale CCS which should be operational 2026. The plant will capture around 400 000 tonnes of carbon dioxide yearly[31].

Within the framework of the European Green Deal[32] strategy to make Europe climate neutral by 2050, the European Commission has recently announced[33] the proposal of the development of "*independent tailored certification methods for carbon removal activities*" resulting in an improved capacity for the EU to quantify, monitor and verify these type of activities. The carbon removal actions need to fulfil what the Commission has named as QU.A.L.ITY criteria and that implies that these activities need to be measurable and deliver benefits to the environment and go beyond existing technologies and law requirements. In addition, certifications will be linked to the duration of the storage with the aim to ensure a permanent one; and last, but not least, must be in line and contribute with environmental goals and circularity strategies already set by the Commission.

The unnecessary generation of waste is also limiting the possibilities of generating food to the world's population. FAO estimates that between 20-50% of different foods like cereals, fruits and vegetables, meat and dairy products and fish is lost/wasted each year[34]. This represents both large economic losses, but also loss in resources that could feed people and the loss of resources (energy, nutrients, and soil quality) used to produce that waste.
Another factor, that most consumers are not aware of either when they decide to throw away something that is still fully functioning, is what resources that has been committed when producing that product. A mobile phone generates around 86 kg of waste during its production (mainly mining waste) while a pair of trousers generates around 25 kg of waste up-stream[35].

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[30] Deployment of bio-CCS: case study on Waste-to-Energy. Fortum Oslo Varme (FOV), Oslo, Norway, IEA Bioenergy Task 36, Becidan M., May 2021. Link to the report.

[31] Karbonfangst (CCS), Hafslund Oslo Ceclsio, Hafslund Oslo Celsio, website visited 2023-01-09

[32] European Green Deal Strategy by the European Commission. Link to the website visited on the 2nd of January 2023.

[33] European Green Deal: Commission proposed certification of carbon removal to help reach net zero emission. Press released 30th November 2022. Link to the website visited on the 2nd of January 2023

[34] Global initiative on food loss and waste reduction, Food and Agriculture organisation of the United Nations (FAO), Global Initiative on Food Loss and Waste Reduction (fao.org)

[35] Produkters totala avfall – en studie om avfallsfotavtryck och klimatkostnad, Laurenti R., Stenmarck Å., IVL rapport, 2015, Avfallets fotavtryck och klimatkostnader för utvalda konsumtionsprodukter (ivl.se)

6. Way forward

The circular evolution has just started. Although it will take time overall, some parts will change rapidly while others will take longer time. Material and energy circularity will grow in the coming years and new business models, products and consumption habits will be implemented. Waste will be turned into high value products; waste management will become resource management; energy will come from more sustainable sources; new technologies, materials and products will arise in the market. The waste management system will have to adapt to and innovate to bring forth new solutions that can fit into the circular system and face a transformation into resource management. New waste-to-energy technology solutions will be created, and the “old ones” will either adjust to the new times or make way to the new ones coming.

Will all of this happen automatically? No, definitely not. The need for the change is large all around the globe, but the resources to make it happen is not evenly distributed and the maturity differs as well. For those that do not have an organised waste management system – that will be a priority to get that started- they cannot recycle anything that is not collected. Do they have to go through all the steps that the more mature waste management systems have gone through? Hopefully not! Learning from other countries developments should be able to cut that evolution time and costs down significantly. But to make it happen there will be a need for economic resources in addition to the legal frameworks.

Changes to the legal and policy framework is also needed in the more mature systems. These changes should promote the transition and remove bottlenecks that old legislation often generates. Policy makers also need to consider how to work with the economic and environmental aspects since these are often not aligned, the solutions that might be best for the environment are often not the least expensive ones (at least not in a short run for the companies). Security of supply is another aspect that might be considered when looking at recycling and recycling capacity. The Covid-pandemic and the war in Ukraine has both highlighted some of the weaknesses of complex global supply chains.

Taking care of the waste in a resource efficient way is an end-pipe solution that only takes us that far. There also need to be considerations to the consumption of the products that generates waste. There need to be considerations on how to prolong the lifetime of products, how they could be repaired and upgraded to decrease the amounts of waste generated as well as in possible design the products so that they can be recycled. This would affect both consumer behaviour and business models for the producers.

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