Material and Energy Valorisation of Waste in a Circular Economy

IEA Bioenergy: Task 36

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Preface

This is the final report for the triennium workplan for IEA Bioenergy Task 36 *Material and Energy Valorisation of Waste in a Circular Economy*.

IEA Bioenergy Task 36 seeks to raise public awareness of sustainable energy generation and material recovery from waste streams, as well as supporting technical information dissemination. This report summarises some of the key activities undertaken by the task over the 2019–2021 triennium, which focused on understanding what role energy from waste has in a circular economy where materials recovery and recycling are becoming increasingly-important drivers. While much of the work program considered current and emerging technologies in this context, there was also some consideration given to the non-technical aspects of a transition to a circular economy, highlighting the importance of policy settings, the regulatory environment, and community acceptance.

Much of this report summarises the work published in more detail over the course of the triennium. These reports, case studies, and workshop reports are listed in the Bibliography, and are accessible on the IEA Bioenergy Task 36 website: https://task36.ieabioenergy.com

Executive Summary

Waste-to-energy, commonly via a combustion-based process, is an effective component of a modern waste management strategy, whereby landfill-bound waste streams are converted to heat and power. The technologies supporting these pathways are mature and well-developed and have for many years contributed positively to sustainable waste management processes. In more recent times there has been the emergence of principles associated with the 'circular economy', an economy-wide concept moving from a make-use-dispose model to one where reuse, remaking, and recycling underpin a move away from reliance on resource extraction. Circular economy principles are embedded in business models, in consumer behaviours, and government policy, and have implications for the waste management sector.

These circular economy principles demand more from inherently linear combustion-based waste to energy processes. In response to this, there has been technology development and deployment that supports additional resource recovery: recovery of nutrients from composting, digestion, and combustion process; extraction of useful metals and salts from combustion residues; and the beneficial re-use of ash from incineration plants to further reduce the volume of material sent to landfill.

Increasingly-stringent regulations, however, are driving the need for new technology pathways to be deployed—ones that support the use of waste as a feedstock for new recycling pathways, new manufacturing processes, and a more diverse suite of energy products. These pathways are not based on established combustion processes, but on ones that produce useful intermediates (e.g. gasification for syngas production) that can in turn be used as industrial feedstocks for a range of applications. As well as an energy-recovery pathway, this supports the notion of 'keeping molecules in use for longer' and allows the waste management sector to play an important role in a broader transition towards a circular economy.

Transitioning to new technologies, however, is not without challenges. Any adoption of new technology comes at a cost, and we have seen that play out in some early demonstrations of some of these at scale. This highlights the role of supportive policies and regulations that incentivize and encourage pathways that are more sustainable over the long term, which support ongoing deployment which, in turn, drives down costs.

The challenges are not all technical, however. Community acceptance is an ongoing challenge for almost any waste-to-energy project, and this process can be further complicated if the technology suite in question is less mature or the public have less experience with their operation. Information is important, but by no means the most important factor at play here—with significant effort needed for communication, engagement, and an appreciation of the different factors that are important for developed vs the less-developed countries.

The planned work of the task for the next triennium will seek to understand these emerging pathways in more detail, with a focus on sustainability, and the role of advanced sorting technologies and the emergence of new waste streams and product opportunities (such as clean hydrogen)—all with the goal of supporting the transition of the waste sector towards more circular principles.

Introduction

WASTE MANAGEMENT AND ENERGY RECOVERY

Brief history

Managing waste has always been a challenge, one which increased in importance as population densities increased and health impacts of poor waste management systems became significant. Combustion of waste as a management strategy is centuries old, with large grate systems appearing in Europe in the 19th century – motivated by health concerns rather than issues related to environmental performance or sustainability. Driven by developments in the coal sector, the moving grate technology and advances in combustion engineering supported further deployment. These systems were entirely focused on waste destruction, and energy recovery from such systems was not a motivation.

It was not until the 1960s and 70s that air quality issues began to be considered in detail, and management strategies developed for combustion-based waste management plants. An industrial accident in Italy in 1976 raised awareness of the potential impacts of dioxins, and subsequent work in the Netherlands linked waste incineration to dioxin formation, leading to the strong association of incineration plants with poor environmental outcomes. This drove legislative change in Europe and North America, while the large number of small plants in Japan continued to create problems due to dioxin and other pollutant emissions – right up until the late 1990s where Japanese policy finally reflected the known links between waste incineration and dioxin formation, and how plant scale and flue gas scrubbing can have significant benefits.

State of the Art

While these poor environmental outcomes of the mid-to-late 20th century still drive a lot of the debate regarding the safety and effectiveness of combustion-based waste-to-energy systems, advances in flue gas cleaning, combustion engineering, and boiler design mean that modern plants are safe and effective and play an important role in providing renewable heat and power while actively managing waste.

Contemporary systems for waste management integrate heat recovery and power generation and are largely based on a modern version of the moving grate incinerator. They are able to handle large volumes of mixed waste and produce a flue gas that are able to exceed stringent requirements for emissions of a range of potential pollutants. Modern facilities are often integrated with pre-treatment processes, ensuring the removal of recyclable and re-usable material.

Regardless of the known performance of these systems from an environmental perspective, there remains some opposition to their use in waste management. This opposition is sometimes grounded in the belief that the technologies are environmentally damaging, and sometimes in the belief that their use 'cannibalizes' recyclable material and effectively decreases the impact of recycling strategies. While there are very few data in support of these positions, and considerable evidence that well-designed WtE installations now support an increase in the rate of recycling (see Figure 1) they remain a contentious part of the public discussion regarding the role of energy recovery in waste management, in particular in jurisdictions where there is little or no experience.

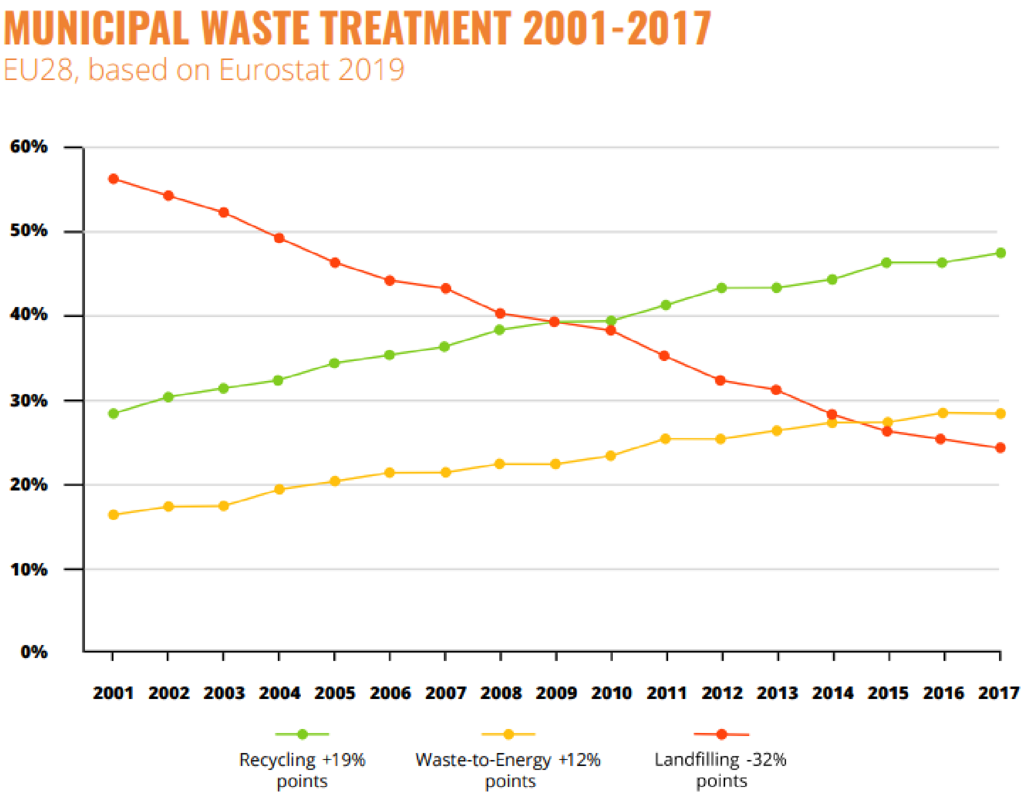

Figure 1: MSW treatment strategies over time in Europe. Graph by CEWEP, Source: Eurostat 2019.

Expectations of waste management systems, however, are changing. Single-use products are being phased out or banned altogether, and many countries now legislate minimum thresholds for the use of recyclable material in manufacturing processes. Greater emphasis is being placed on avoiding carbon emissions from power generation and industrial processes, and a range of energy and non-energy products are becoming technically and economically viable from waste treatment processes – the traditional combustion-based systems were not designed to meet these expectations.

Emerging and alternative technologies

These shifts in expectations of advanced waste management systems, combined with the continued lack of public support for combustion-based waste to energy in some countries, has seen new technologies emerge. Some of these are designed to integrate with combustion-based systems to improve nutrient or other resource recovery; others are new processes with built-in ability to keep molecules in use for longer while generating power and heat for local use.

Establishing a better understanding of the roles of these emerging and advanced technologies in the context of an evolving set of requirements for waste management is a high-level objective of the Task's work for this triennium. Of the drivers discussed, however, the emergence of 'Circular Economy' principles is by far the most significant and is likely to require fundamental shifts in how waste management and energy recovery are integrated. The next section discusses these principles and outlines the work of the Task in this context.

EMERGENCE OF CIRCULAR ECONOMY PRINCIPLES

Circular Economy Principles

The mainstream model of consumption and use is often referred to as a ‘linear model’: goods are purchased, used, and at the end of their useful life (or often before that) they are disposed of. Global recycling rates are low, which means that most of the energy and materials embodied in these goods are sent to landfill. Replenishing this model requires resource extraction and energy generation, much of which is considered finite in supply, and often non-renewable.

A Circular Economy is, fundamentally, an economic principle, but one which integrates aspects of resource management, manufacturing, energy, supply chain security, environmental management, behavioural science, policy development, and more. It relies on a philosophical shift from this make-use-dispose model to one where reuse, remaking, and recycling underpin a move away from reliance on resource extraction. The principles of a Circular Economy are embedded in business models, in consumer behaviours, and government policy – but in order to achieve the goals at an industrial scale, new technologies and pathways are needed.

Implications for Energy Recovery from Waste

The waste management sector is critical to the success of the Circular Economy movement. While the manufacturing sector clearly plays an important role from the perspective of 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 CE principles, yet despite the push for increasing the proportion of recycled materials used in manufacturing and construction [1], global recycling rates are generally low, with a significant proportion of waste being sent to landfills of varying quality (Figure 2 and Figure 3).

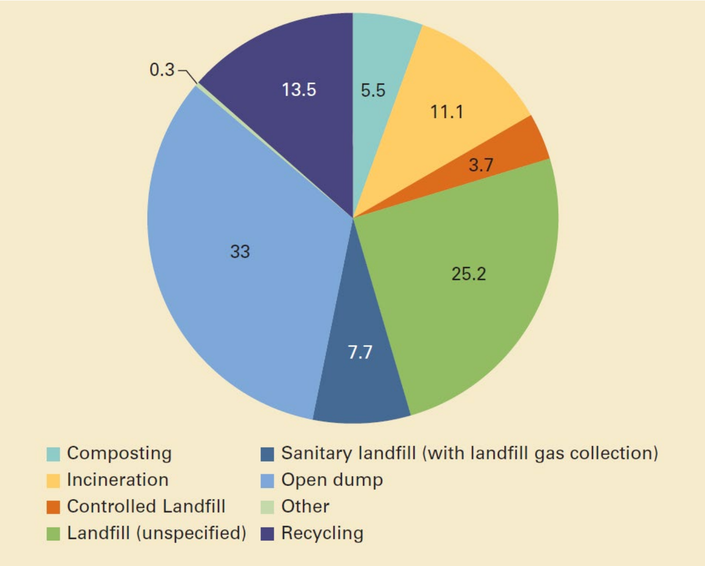

Figure 2: Global treatment and disposal of waste, % [2].

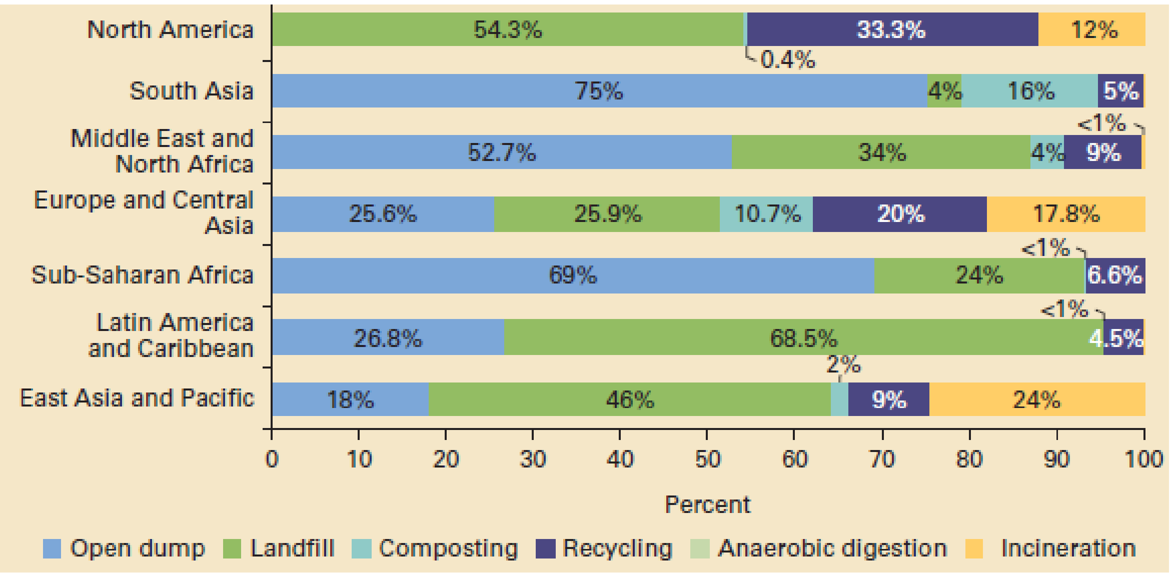

Figure 3: Waste disposal methods broken down by region [2].

Energy recovery, typically via combustion, is more common in some EU, 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 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, meaning they also contribute to increased rates of recycling. It remains, however, a fundamentally linear process, providing little additional scope for the reuse, remaking, or recycling of the waste streams generated encouraged by the objectives of a circular economy.

As we touched on in the introduction, 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. 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 a transition. Task 36 over the 2019-2021 triennium has been considering these aspects.

TASK SUMMARY AND WORKPLAN

Overview and Summary

During 2019-2021, Task 36 *Material and Energy Valorisation of Waste in a Circular Economy* has considered environmental and economic aspects as well as resource efficiency of waste management in the context of a circular economy. An important part of the work has been dedicated to energy products from waste and, especially, valorisation of the biomass/biogenic component of the waste.

The core of the Task's work is the role of waste in a circular economy that is further broken down into 6 different areas (Figure 4) covering policy aspects, adaptation, and role of EfW and recycling technologies to a circular model. Other relevant topics of interests for the Task have been the flexibility of EfW technologies (e.g. carbon capture and storage technology - CCS) and waste streams to adapt to the circular model, and the assessment of non-economic aspects related to waste management (e.g. social aspects).

The work carried out by the task on the subjects mentioned above is gathered in a collection of publications (see publications list in Section 0) in the form of topic reports, case studies and workshop reports that are published with open access. In addition, these topics have been discussed in internal and external workshops/seminars and conferences.

Figure 4: Summary of Task 36 work program

This Report

This is the final report of the Task's work for the triennium. It aims to provide a summary of the key outcomes from the Task's workshops, and to summarise the learnings from the Task's case studies highlighting aspects of emerging technologies, issues related to acceptance and sustainability. This report will bring these results together and discuss the important role of energy recovery and waste management in the emerging Circular Economy.

Waste Management in a Circular Economy: Emerging Themes

An important part of the work program for the Task was regular workshops to explore in more detail emerging aspects of energy from waste in the context of emerging circular economy principles. Each of these workshops has a report detailing the activities, presentations, and discussions; this section takes the learnings from those reports and considers them in the context of the theme of this final report: what roles can energy-from-waste play in support of a circular economy?

NUTRIENT RECOVERY FROM WASTE [3]

Nutrient Recovery in Waste-to-Energy

Combustion-based energy-from-waste is traditionally a linear process, and as circular economy principles emerge more attention is being given to how existing processes can contribute more in terms of nutrient recovery – or, perhaps, be competitive with processes based on biological systems, where nutrients can be more bio-available. Phosphorous, for example, is of particular interest – the diversity of global supply chains is limited, and for example in the US, the domestic reserve of phosphorous may not last more than 40 years. Phosphorous resources are unevenly distributed globally, with up to 70% of the global reserves located in Morocco. There is, therefore, an emerging global drive to extract phosphorous from waste management processes, and wastewater treatment is at the top of that list.

There are a few drivers for nutrient recovery from waste management processes, and these reflect the variability in the maturity of waste management systems around the world and the extent to which they are being adopted as CE principles emerge. One driver is to support the technical operation of the waste management facilities (especially wastewater treatment plants), and the other is to actively seek to extract nutrients, such as phosphorous, for economic or legislative reasons.

Phosphorous from Wastewater Treatment

Primary wastewater treatment plants often have operational challenges with struvite, a mineral precipitating from a mixture of magnesium, phosphorous, and ammonia. This is a common pathway for extracting phosphorous, albeit not primarily for nutrient recovery.

The solid by-product of wastewater treatment, biosolids, remain a good source of phosphorous, amongst other nutrients including nitrogen. Direct land application is commonplace in many countries, and phosphorous and other nutrients are generally available to the soil. There are emerging concerns, however, regarding health issues associated with the use of these materials, and the extent to which land application will be permitted as a long-term strategy is uncertain. Some countries have banned the approach (such as Switzerland) and there are targets in place for other countries to reduce the reliance on this approach and increase the extent to which phosphorous is recovered.

Incineration of biosolids and sewage sludge is common as a disposal strategy where land application is not possible. The high moisture content of these materials generally precludes these processes from recovering energy; however, the phosphorous-rich nature of the residue has seen the emergence of a range of technologies designed to extract the phosphorous from the ash. Most of these add to the already-high relative cost of biosolids management, however, and there remains the opportunity to better integrate waste management with nutrient recovery in the context of a circular economy.

Barriers, Opportunities, and the Circular Economy

These drivers towards circularity: movement away from land applications, increased demand on non-linear incineration pathways, and a growing requirement for phosphorous and other nutrient recovery, are seeing new approaches developed which are at various stages of maturity. Cost-effective solutions here are in high demand: there is even some stockpiling of biosolids incineration ash in Denmark temporarily in anticipation of economically viable phosphorous-extracting technologies.

This is seeing some approaches that have been ‘emerging’ for some time reach demonstration scales. Thermal treatment of biosolids to produce biochar is gaining increasing interest, as the biochar material can act as a soil ameliorant and phosphorous recovery can occur in parallel. In the USA there are processes being scaled up that extract nitrogen and phosphorous from algal biofuels production processes.

In subsequent workshop summaries we will see how advanced technologies can offer the potential for integrating waste management, energy recovery, and alternative products (including nutrient recovery) via new pathways and processes.

FLY ASH VALORISATION [4]

The drive to recover nutrients such as phosphorous from combustion residues represents a wider challenge for integrating circular economy principles with linear waste management technologies. As we have seen in the previous section, key amongst those is the combustion residues (bottom ash, fly ash, and APC residues[1]) and the role they can play in a circular economy. For power generation based on coal, ash utilisation has long been an important part of managing the waste streams from the processes, and there exist some established pathways for construction and road building, amongst other things, but a globally inconsistent approach to regulation that supports the update of these pathways.

Fly Ash from Waste Combustion

There is a specific challenge with ash from municipal solid waste combustion. Due to the nature of MSW and the fact that this leads to ash with varying content of leachable metals, MSWI fly ash is usually considered as hazardous waste, which dictates a specific set of requirements regarding its handling, use, and disposal.

This means that most MSWI fly ashes are landfilled in dedicated storage sites, some of these accepting wastes from other jurisdictions. The shifts we have been exploring so far in this report regarding moving towards circular economy principles are driving change in the way fly ash is managed. As with nutrients such as phosphorous in sewage sludge, fly ash contains a range of strategically relevant metals and minerals (as well as salts); there is an increasing expectation that these be ‘valorised’ to support material recycling and reuse.

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[1] APC residues are ‘air pollution control’ system residues.

Fly Ash Valorisation: the State of the Art

Japan's approach to managing fly ash from waste combustion is focused on stabilisation of the ash components to support subsequent reuse or disposal, with the majority still disposed of. Much of this is achieved via thermal stabilisation (melting to form stable glass-like materials). While bottom ashes can be stabilised to be used for road base, cement, or as a construction material, there is still considerable amounts of combustion residues disposed of in landfill. There are some advanced thermal processes emerging, such as the Swedish ARCFUME process which uses plasma to melt the ash materials supporting recovery of metals and ultimate use as a construction material.

Non-thermal (chemical) stabilisation pathways also exist, such as the commercially deployed OCO technology in the UK, where it is used to handle ash residues from three UK EfW facilities with more planned deployments underway.

There exist several technology approaches that treat fly ashes using various combinations of washing, acid treatment, and salts and metals recovery. Some of these are constructing their first full-scale plants, such as the ASH2SALT and HALOSEP technologies in Sweden, and others are commercial with many deployments, such as the AIK Technik AG technology in Switzerland. There exist others at various stages of development – noting the regulatory drivers for the development and deployment of such systems (e.g. the requirement by Swiss law to extract zinc).

Table 1 lists the technologies discussed at the webinar, and its footnote provides a link to the presentations and a recording of the event.

Offering	**Organization**
Ash2Salt®	Ragn-Sells
Fluwa/Flurec®	AIK Technik
Halosep®	Stena Recycling
Arcfume®	ScanArc
Fly ash washing and salts recovery	NOAH
Stabilisation and aggregate from fly ash	O.C.O Technology
Zn recovery	Renova and Chalmers University

Table 1: Technologies discussed at the 'Fly Ash Valorisation' webinar[2].

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[2] https://task36.ieabioenergy.com/publications/webinar-valorisation-of-fly-ash-from-waste-to-energy/

Fly ash in a Circular Economy: Challenges and Barriers

There is a difference between stabilising ash to render it ‘non-hazardous’ in order to simplify its disposal in landfill and processing ash to support the extraction of salts, minerals, metals, and other useful species. The latter is more consistent with circular economy drivers, and we are now seeing a range of technological options emerging to support this. There remain challenges, however, with the effectiveness and economics of these approaches, and these can be further complicated by scale, variability in ash compositions due to feedstock and process variations, and the slow emergence of a premium market for green or recycled raw materials.

The Task’s webinar exploring this aspect of waste management clearly showed that fly ash valorisation is a hot topic, especially as Circular Economy principles are slowly but surely unfolding into all aspects of society. Several technologies are (or will be) good candidates to contribute to more valorisation and/or re-use of WtE fly ash and possibly less hazardous waste landfilling. However, there is still a large acceptance in the public and the authorities for landfilling in many countries, especially if local opposition to waste processing plants continues to increase in importance. This acceptance is reflected in the relatively affordable costs of landfilling in many regions.

There is a clear desire, however, to bring new technologies to the combustion-based energy-from-waste sector, however, to allow it to contribute and succeed as circular economy principles become legislated. The existence of several fly ash valorisation technologies on the market in the coming years is positive, both for WtE plants operators/owners and society at large. Competition as well as complementarity between the various solutions will ensure that the WtE sector can contribute to a more sustainable Circular Economy as best as possible.

EFFICIENCY GAINS VIA PROCESS HEAT [5]

When discussing traditional incineration based WtE, a lot of the focus is put on the power supplied by that route. However, waste is not the optimal fuel for pure power production. The chemical composition of the waste makes it challenging to push the electrical efficiency while maintaining a high availability of the plant. There is a large, and in many cases untapped, potential in supplying heat from WtE. In a case study within an intertask project about industrial process heat [5], the Åmotfors plant was showcased. The WtE plant supplies a paper mill with both electricity and process steam. In order to supply the steam at 6 bar and 180°C, the original pressure is reduced in a back-pressure turbine, generating electricity.

Considering the numbers of different industries around the world that needs process heat at low or medium temperature range, there could be a far more efficient recovery of the energy from waste into those applications.

ALTERNATIVE TECHNOLOGY PATHWAYS

The previous sections have discussed how adapting linear processes to circular economy applications via new and additional technologies is needed, and how there are emerging pathways to support that. For wholesale change and significant impact, however, new models are needed that do not seek to adapt linear pathways to better suit circular principles, but which fundamentally are more aligned with the notion of ‘keeping molecules in use for longer’.

Emerging Pathways

Energy and materials recovery in the context of a circular economy, as we have seen, will need more than add-ons to existing combustion-based plant. This is clear in the portfolio of projects and technologies emerging from the US DoE bioenergy program that focus on biogas upgrading, CO_2 capture and conversion, and novel hydrothermal liquefaction approaches. These emerging pathways represent technologies that can produce fuels, products, and chemicals from waste and could be employed as the existing fleet of anaerobic digesters, incinerators and other waste to energy plants retire or as additional capacity is required.

As was discussed in Section 0, alternatives to land application or combustion are becoming more important for biosolids management, and the driver for this extends beyond solely nutrient recovery. This is particularly the case in countries like Australia, where incineration is not a strategy that is used for biosolids disposal, and almost all biosolids are disposed of in various land applications, or simply stockpiled.

For example, a biochar pyrolysis/gasification technology is being demonstrated at a wastewater treatment plant in Queensland, Australia[3]. This particular technology was originally designed for biochar production from biomass, but which is now being used in an Australian-first demonstration for converting biosolids to a char with integrated drying. While the project does not incorporate any specific pathways for additional nutrient recovery, the process does remove hazardous and pathogenic compounds from the biosolids as well as microplastics, which leaves the biochar product suitable for use as a soil ameliorant, amongst other things. Success in this project should raise the profile of non-combustion technologies for waste management and highlight their role in nutrient and energy recovery from waste.

Bioenergy with Carbon Capture and Storage (BECCS)

Despite growing global ambitions towards increased material recycling, combustion-based waste-to-energy will likely continue to play an important role in coming decades as a means of managing waste streams that for one reason or another may be difficult to treat otherwise.

Typically, 40–60% of municipal solid waste used as fuel in WtE facilities are of biogenic origin in developed countries, meaning that implementation of carbon capture and storage (CCS) to WtE partially can be classified as bio-CCS and lead to net negative CO_2 emissions.

There are currently several ongoing projects exploring CCS in WtE settings, and this case study presents what is arguably the project that has come the farthest: the FOV (Fortum Oslo Varme) WtE plant in Oslo, Norway. There is currently plenty of CCS activities in Norway, both in the form of the development of a transport and offshore storage infrastructure project called Northern Lights, and in the form of point source capture projects.

The FOV project is being developed as part of a broader ambition of the city of Oslo to reduce its GHG emissions by 95% in the period 2009–2030. With the FOV plant being the city’s largest single emission source, it is imperative to address its CO_2 emissions.

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[3] https://arena.gov.au/projects/logan-city-biosolids-gasification-project/

A first pilot phase of the Fortum project started in 2015 and since then, a series of pilot campaigns and feasibility studies have been conducted on an amine-based CO2 capture system. In parallel, the Norwegian government has investigated and evaluated different options for facilities deemed suitable to be included in the demonstration of a full-scale CCS supply chain. In Autumn 2020, it was announced (under the name Longship) that the FOV project would be one of two facilities that would get governmental funding (the other one being the Heidelberg Norcem cement plant) together with Northern Lights for permanent storage. However, while the Norcem plant (and Northern Lights) would be (presumably 80-90%) funded by the government, funding for the FOV WtE plant has been conditioned on it being able to provide 50% co-funding (~300 million €) from own funding and other sources, the EU Innovation Fund offering the best opportunity.

At the time of writing (October 2021), it is uncertain if this additional funding will be secured. This is now the key factor determining the time plan for full-scale deployment of the CCS project at Fortum, which according to the original schedule is due to come online in 2024. The EU Innovation Fund will decide if FOV receives support. With a positive decision, the CCS plant could be operational by 2026-2027. Despite these remaining uncertainties pertaining to funding, the recent years have seen several other actors in Norway initiating WtE CCS projects.

Broader Considerations

Consideration of these emerging pathways and their potential for producing products other than power and heat demonstrated the importance of naming conventions, technology classifications, and the potential policy impacts of the blurring of lines between energy from waste and materials recovery. It is possible, for example, that EfW doesn't count as recycling, but can count as resource recovery, which has some interesting implications for how multi-product technologies such as hydrothermal liquefaction are classified: HTL counts as EfW if it's making an energy fuel but as materials recovery if the same product is used differently.

The borderline and flexibility in the use of some products from EfW also puts a challenge into the policy framework. In many countries the production of renewable energy is incentivised and encouraged, while the use of the same EfW product for further refinement into new products most often are not. This might cause sub-optimized systems where the largest environmental gain might not be encouraged.

Definitions, regulations, and policies can have an impact on technological choices, preferences, and policy settings that extend beyond their performance. For example, the EU (Ref. Brussels, 3.12.2008 COM(2008) 811 final GREEN PAPER *On the management of bio-waste in the European Union*) defines AD biogas production for energy purposes as energy recovery. AD may be classified as recycling (material recovery) when the digestate is used on land (biofertilizer). Furthermore, the fact that liquid biofuels are considered as energy recovery may (at least partially) explain why technology developers working on chemical recycling (mainly for plastic waste) tune their process towards the production of chemicals, i.e. material recovery (rather than biofuels) as this will make their technology very attractive as a potential contributor in achieving the EU material recycling targets.

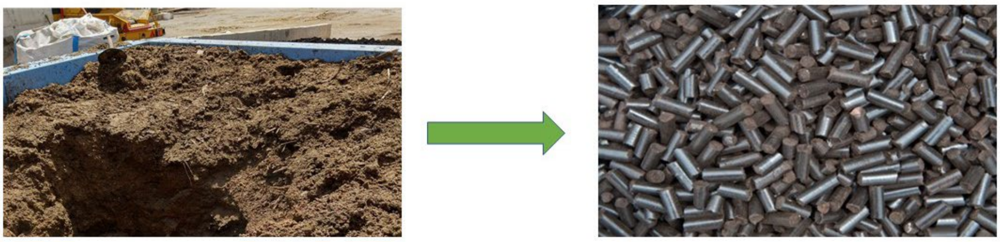
Another key consideration is the relative value that a community or government places on landfill diversion. Certain technologies are interesting to communities because they can result in significant increases in waste reduction compared to the business-as-usual practices (e.g. anaerobic digestion). An example being explored in several countries is the use of HTL which can convert >90% of municipal sludge and greatly reduce disposal liabilities to the entities responsible for managing it.

These kinds of considerations are also relevant when considering the public acceptance of waste-to-energy technologies, and the importance of terms such as ‘incineration’ to the social licence to operate. While this is particularly stark in countries such as Australia, where the general public’s familiarity with the technology concepts is low, it is also a challenge in EU and North America and can form another driver for ‘advanced’ technologies such as those under discussion so far. We will consider this in some more detail in subsequent sections.

Examples

Hydrothermal Carbonization [6]

Torrefaction is often considered as a pathway for increasing the energy density of woody biomass materials. Hydrothermal carbonization is a related but different process, often used to covert organic waste streams and sludges into stable, storable fuels that can be used as feedstocks to a range of processes. Operating at lower temperatures (~210°C for the Ingelia[4] process) but higher pressures (20 bar) than typical torrefaction processes, HTC allows materials with high moisture contents to be converted into coal-like pellets (Figure 5).



	Hunidity (%)	Volatiles (%)	Ashes (%)	Fixed coal (%)
Paper sludge	68,8	64,9	23,1	12
Ingelia Char	7,5	66,5	16,4	17,1

	C (% DAF)	S (% DAF)
Paper sludge	55,3	0,22
Ingelia Char	64,4	0,29

Figure 5: An example of paper sludge conversion to ‘hydrochar’ using Ingelia’s technology [6].

As well as the production of a stable, carbon-rich feedstock, the HTC process by-products can have beneficial re-use pathways. Water is produced, and depending on the technology configuration, can be the basis of production of a liquid fertilizer. The agricultural applications of the HTC process by-products have the potential to offset carbon-intensive fertiliser production and use, although as with all such potential pathways, associated

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[4] https://ingelia.com

environmental impacts (such as eutrophication) must be considered. From a greenhouse gas perspective, the HTC process (Figure 6) has a considerable energy demand, due to the thermal demand of the system and its pressurised operation – there is, therefore, the potential to add to the avoided emissions (if the pellets are used to replace coal, for example) by integrating an HTC system with low-carbon sources of heat (e.g. solar thermal) or power.

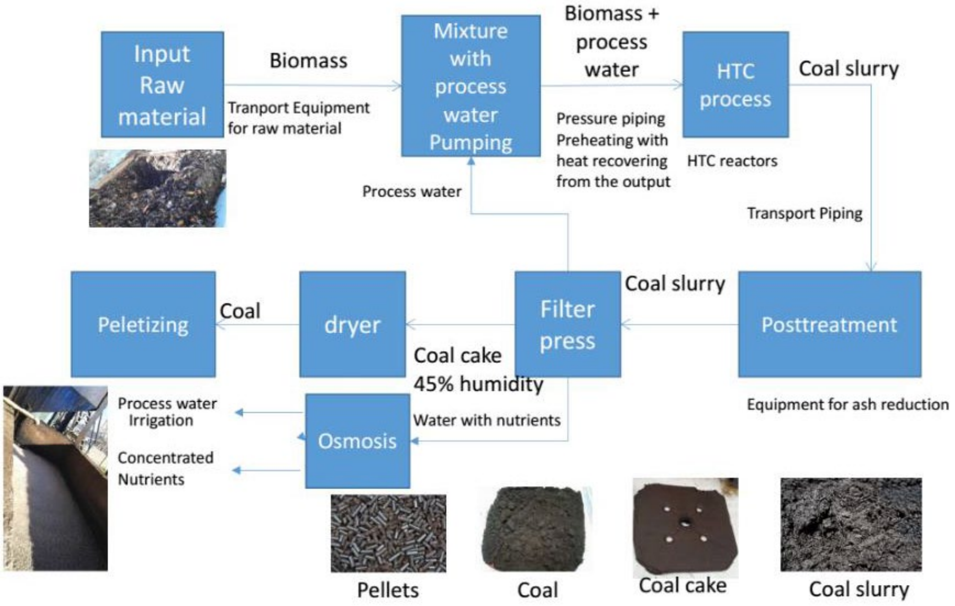

Figure 6: Ingelia HTC Technology flow diagram [6].

Waste to Products: Enerkem

Enerkem's Edmonton plant is a high-profile commercial facility which uses gasification and syngas processing technologies to convert non-compostable and non-recyclable household waste—processed into a refuse derived fuel (RDF)—into products such as methanol and ethanol [7]. This facility demonstrates that chemical recycling of carbon containing wastes can be done as a sustainable alternative to conventional waste management practices. This approach is potentially very attractive in the context of a circular economy. However, there are very limited data available for both technical and cost associated with operating of Enerkem facilities – and as one of the first of its kind, it has had some challenges.

Enerkem uses a proprietary bubbling fluidized bed (BFB) gasification technology to produce syngas which contains mainly carbon monoxide and hydrogen—key building block molecules used in many modern chemical processes [8]. In order to avoid N_2 dilution of this syngas, steam and oxygen are used as the gasification agents. The Enerkem gasifier operates at 1-5 bar and the gasification temperature is reportedly about 750°C [9].

This relatively low temperature operation reduces energy losses but does create a syngas that contains significant quantities of tars as significant cracking of tar requires higher temperatures (>>1000°C). Tar and other impurity removals could be a critical process in

Enerkem technology because these impurities could create safety issues and could impact on the downstream catalytic process as well as the overall system efficiency. The conventional catalysts for methanol synthesis from syngas are very sensitive to deactivation by even traces of the pollutants, which may be present in the syngas derived from feedstock like MSW [10]. Therefore, it is an absolute necessity to remove all impurity from syngas, before sending the gas to methanol synthesis process (Figure 7).

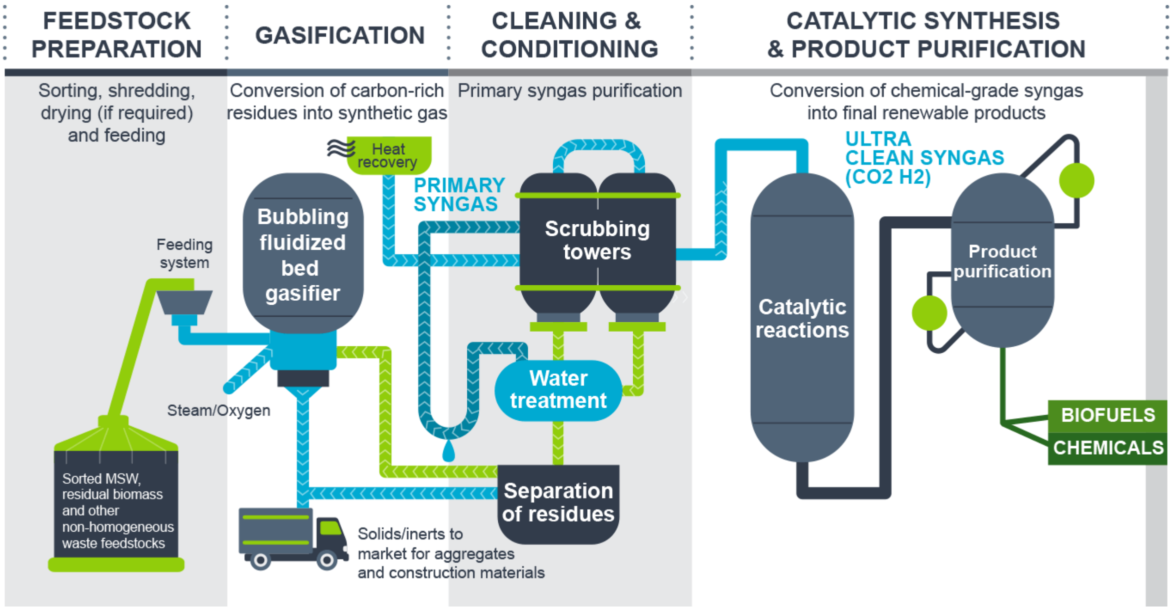

Figure 7: Process flow diagram of Enerkem waste to biofuel system [8]

The residue from the Enerkem process is approximately 15% [11]. Enerkem's plant has designed for 90–92% carbon conversion in the gasifier with the remaining 8% of carbon reporting to the char [12]. The Enerkem process produces small quantities of inert materials (residues). There is possibility to convert those inert into an aggregate to use in construction.

While the project did experience some significant delays and cost impacts during the early stages, this perhaps expected given the fact that it is one of the firsts-of-a-kind in this area. There have also been some legal and project management challenges, which do not reflect on the potential for technology such as this.

After successful operation of Edmonton's plant, Enerkem plan to expend their facilities to build a plant in Rotterdam, the Netherlands with its partners (AkzoNobel, Van Gansewinkel, Air Liquide, AVR) for converting 350,000 tonnes of waste annually into 270 million liters of methanol [13, 14]. Additionally, by collaborating with a waste management specialist Suez, Enerkem plans to construct a household waste-to-methanol facility near Tarragona, Spain. The plant, to be launched in 2022, will transform 400,000 tonnes/y of waste plastic, textiles and paper into 220,000 tonnes of methanol. It will use same Enerkem technology that produces synthesis gas before transforming it to methanol with the aid of catalyst [15, 16].

In December 2020, Enerkem announced the development of a C$875 million biofuels plant in Varennes, Québec, collaborating with a group of energy producing companies including Shell, as lead investor, as well as Suncor and Proman, and Hydro-Québec, which will supply renewable hydrogen and oxygen, and with the support of the governments of Quebec and Canada [17]. While this facility is planned to produce biofuels and renewable chemicals made from non-recyclable residual materials as well as wood waste, it will leverage green hydrogen and oxygen produced through electrolysis, transforming Quebec's excess hydroelectricity capacity into value-added biofuels and renewable chemicals. Commissioning of the first phase of this plan is scheduled for 2023 [16].

Biomethanation

As opposed to traditional biogas upgrading technologies such as the use of amine scrubbing or membranes, biomethanation converts the carbon dioxide in biogas to additional methane. By converting the carbon dioxide found in biogas, the overall yield of biomethane is increased by 60–70% compared to upgrading technologies that separate carbon dioxide. This is accomplished through the use of a non-GMO microorganism that converts this carbon dioxide and hydrogen to methane. The hydrogen is supplied to the system by a polymer electrolyte membrane electrolyzer.

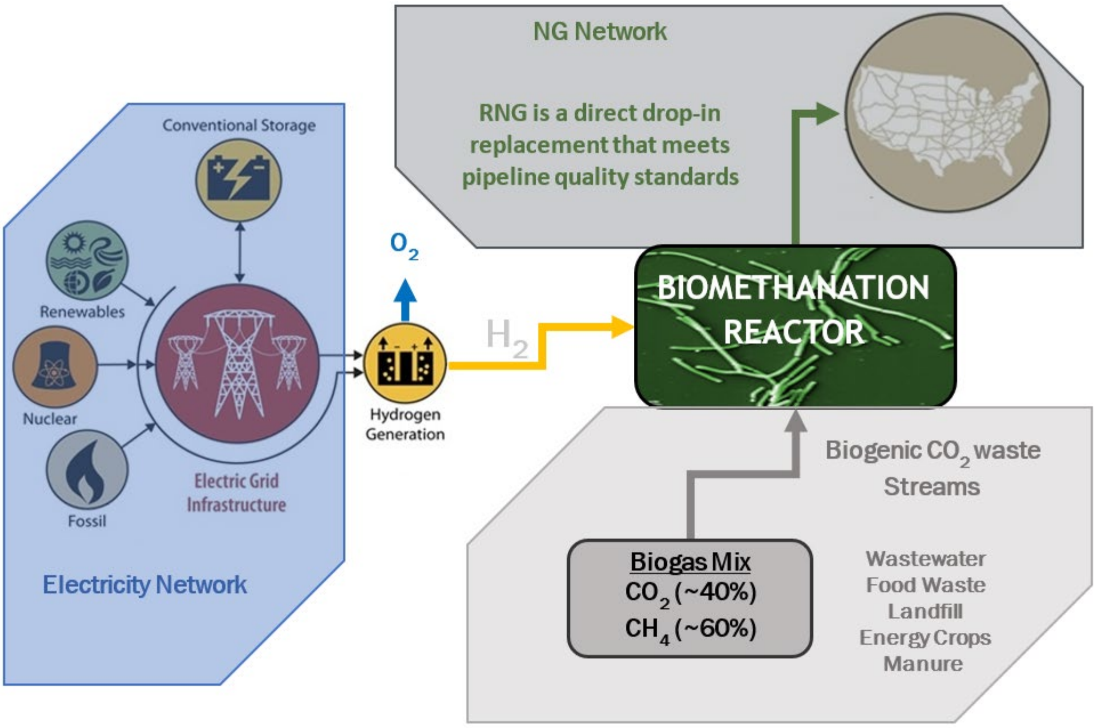

Figure 8: Biomethanation pathways.

The biological organism utilized, a methanogen, is quite robust and demonstrates quick responsiveness to start/stop cycles and tolerance to other impurities found in biogas including hydrogen sulfide. This represents an additional advantage over catalytic methanation processes which often operate at high temperature and sometimes requires conditioning of these species to avoid catalyst deactivation/poisoning. The electrolyzer and organism can both ramp very quickly which offers opportunities for grid-scale energy storage solutions.

With increasing deployment of solar and wind power generation in the United States, there has also been a rise in wind and solar energy curtailments. Without grid-scale storage solutions, this will ultimately prevent deeper renewables penetration. Biomethanation effectively can serve as a load peaking service to store excess electricity in the form of methane.

Depending on the source, the carbon intensity of renewable natural gas can be very low and often is negative. This negative carbon intensity score is due to the fact that the 'business-as-usual' practices can result in fugitive methane emissions. Since methane is more than 25 times more potent in terms of global warming potential, use of the methane in stationary or transportation applications is far preferable to venting or flaring.

There are several policies that have supported the development of this technology in the United States. Landfill organics bans are causing municipalities to explore new solutions to managing food waste, municipal sludge, and other waste streams. Simultaneously, incentive policies such as the Renewable Fuels Standard and Low-Carbon Fuels Standard are offering credits for renewable natural gas. The Low-Carbon Fuel Standard in particular offers lucrative incentives based on the carbon intensity reduction achieved and is driving significant growth in biogas to renewable natural gas projects.

Cambi: Thermal Hydrolysis at DC Water

The District of Columbia Water Treatment Facility (DC Water) is one of the largest in the United States in terms of influent water treated and thus quantity of residual solids managed. In 2015, DC Water began operation of its thermal hydrolysis unit as a way of further reducing wastewater residuals and increasing the amount of energy recovered from this stream. The $470 million project represented the first Cambi® installation in North America and remains the largest thermal hydrolysis unit in the world.

The first Cambi® installation was built and operated in Norway in 1995, and there are at least 20 industrially operating installations of this process worldwide[5]. Cambi is one of a number of thermal hydrolysis processes that all operate on the principle of using heat and pressure to 'pretreat' the residual solids from wastewater treatment. In the DC Water plant, this reduces the recalcitrance of the residual biomass and makes it more convertible during the anaerobic digestion process: increasing total biogas production and reducing the amount of total system solids that require disposal by approximately 40%[6]. To-date this has resulted in a cost-savings of more than $200M USD through reducing in anaerobic digester volume, reduced disposal volumes, and increased biogas yield that offsets the need for additional utilities.

In addition to the operational and capital savings mentioned above, by utilizing a thermal hydrolysis step, the resulting solids are classified as "Class A Exceptional Quality." Thermal treatment that kills pathogens is required for the biosolids to be designated as Class A. These biosolids are sold in bulk under the product name "Bloom" ® in the DC Metropolitan area. Cambi has signed a second contract with another wastewater treatment plant in the region

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[5] Cano et al 2015. (2015) Energy Feasibility Study of Sludge Preatreatments: A Review. Applied Energy. 149 p 176-185.

[6] Cambi Blue Plains Fact Sheet

(the Washington Suburban Sanitation Commission). It is estimated that this project will save more than $3M USD in annual operating costs and reduce greenhouse gas emissions by 15%.[7]

WASTE FOR FEEDSTOCK RECYCLING

Taking the evolution of waste management to the next level is to broaden the notion of energy recovery and diversify both feedstocks and products to truly align waste management with the principles of a circular economy. Conversion of waste to higher value biochemicals and other bioproducts, including energy products such as fuels, is relevant to the Task themes of waste management, energy recovery, and a circular economy as it supports increased materials recycling and will often incorporate aspects of energy recovery.

Drivers for New Waste-to-Product Opportunities

Global recycling rates are low, typically under 40%. There are initiatives in place in Europe and elsewhere to increase recycling rates – these range from aggressive recycling targets to additional taxes on the use of virgin plastics. We are already seeing some impacts of these in Germany, for example, where the availability of recycled material to use as a manufacturing feedstock is a limiting factor [1] and new pathways for recycling ‘non-recyclable’ materials are under development.

Economics are a major driver for waste-to-product approaches. These new pathways confer more risk as there have been limited demonstration plants to convince investors that they are a sound investment. Thus, products with higher market values can attract investor interest to finance these processes and plants. As an example, Enerkem recently announced a facility in Rotterdam, NL that will produce more than 200,000 tons/year of methanol.

There is also the wider issue of global carbon emissions, and an emerging role for waste management in keeping carbon in the loop for longer (and not emitting it as a greenhouse gas). Decreasing the reliance on crude oil to produce plastics and other materials and integrating waste management with manufacturing pathways is important here, as is the more traditional aspect of energy and materials recovery from waste-to-energy processes.

Broadening the notion of waste management to not only include energy recovery but also include their use as feedstocks for biochemicals and other bioproducts will be an important aspect of waste management supporting the circular economy. There are some emerging technologies supporting some new pathways in this regard, and these have the potential to be commercially viable in a meaningful timeframe. This workshop explored some aspects of these technologies from the perspective of priority feedstocks and ‘platform molecules’ that could act as an intermediate for a range of bio-manufacturing processes.

Opportunities

Exploring some of the emerging applications in this space revealed some insights into the feedstocks and product pathways which provide the potential for some prospective new approaches. Figure 9 and Figure 10 summarise the workshop’s perspectives on priority waste streams and intermediates.

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[7] http://biomassmagazine.com/articles/17320/cambi-will-deliver-a-second-project-in-the-washington-dc-area

The organic fraction of MSW (OFMSW) was deemed a priority due mainly to the volumes that require management and the existence of established technology pathways via digestion and biogas production. Similarly, biosolids are a significant challenge in terms of management in the context of a circular economy. This report has already considered biosolids in the context of nutrient recovery and as a feedstock for demonstration of pyrolysis/gasification projects. While these present potentially effective pathways for utilisation of biosolids as part of waste management (as distinct from a simple disposal strategy) there remains a clear need for technologies to support a role in a truly circular economy.

Emerging pathways in this regard involve modifications to the microorganisms in anaerobic digestors, such that methanogenesis is arrested leading to the formation of volatile fatty acids and potentially lactic acid. Such pathways are the subject of considerable R&D and are attractive as they build on existing approaches and link some of the most challenging feedstocks with the most prospective chemical intermediates. The ability for these pathways to be integrated with existing digestion installations offers the additional potential for production of biogas and high value chemical intermediates leading to significant diversification of product streams.

Mixed plastics are emerging as a global challenge, in particular due to the recyclability of different plastics using current mechanical approaches. Their inclusion here comes from the size and impact of the opportunity – the emergence of thermochemical pathways for ‘chemical recycling’ may address some of the challenges of both unrecyclable plastics as well as the need for more recycled inputs into manufacturing processes.

While thermochemical pathways for gasification or pyrolysis of non-recyclable plastics or other carbonaceous waste streams supports the ‘syngas’ pathway identified in the ‘intermediates’ poll (see Figure 10) the ability for traditional syngas processing and utilisation technologies to scale effectively to match many waste conversion processes has been a challenge. There are fermentative pathways using syngas as a feedstock, however, which have been successfully deployed in industrial applications (e.g. Lanzatech). These use microorganisms which can use syngas as its sole energy and carbon source – producing alcohols and biopolymers that form the basis of a range of fuels and biomaterials. These kinds of approaches have the potential to significantly shift project economics and support a range of new pathways that being waste management and circular economy together.

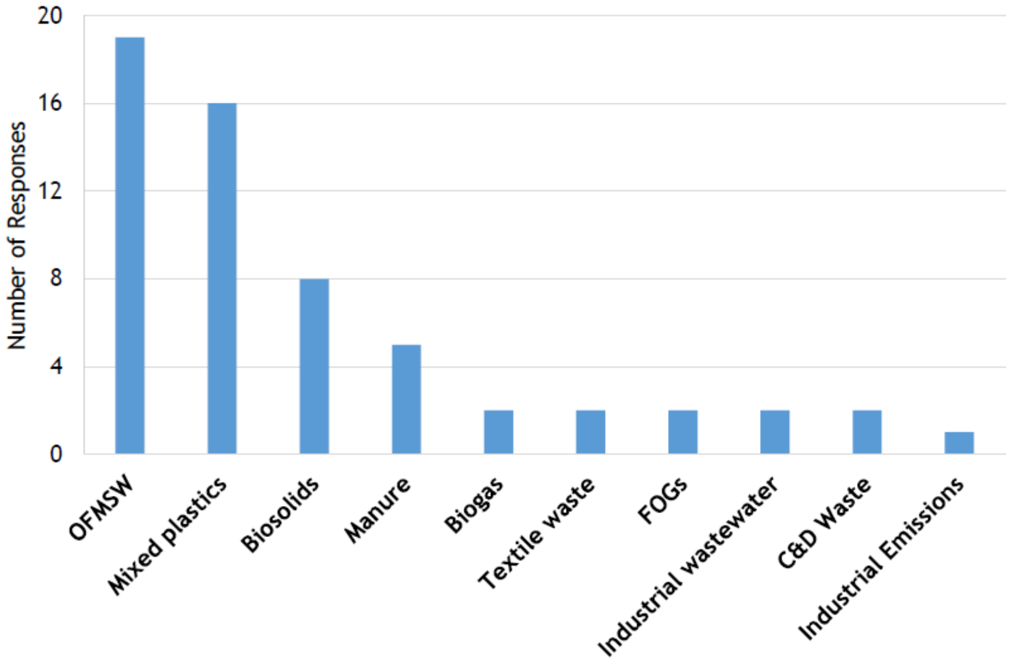

Figure 9: Poll results from workshop on highest profile waste streams (ref Workshop Report 3 in the Bibliography).

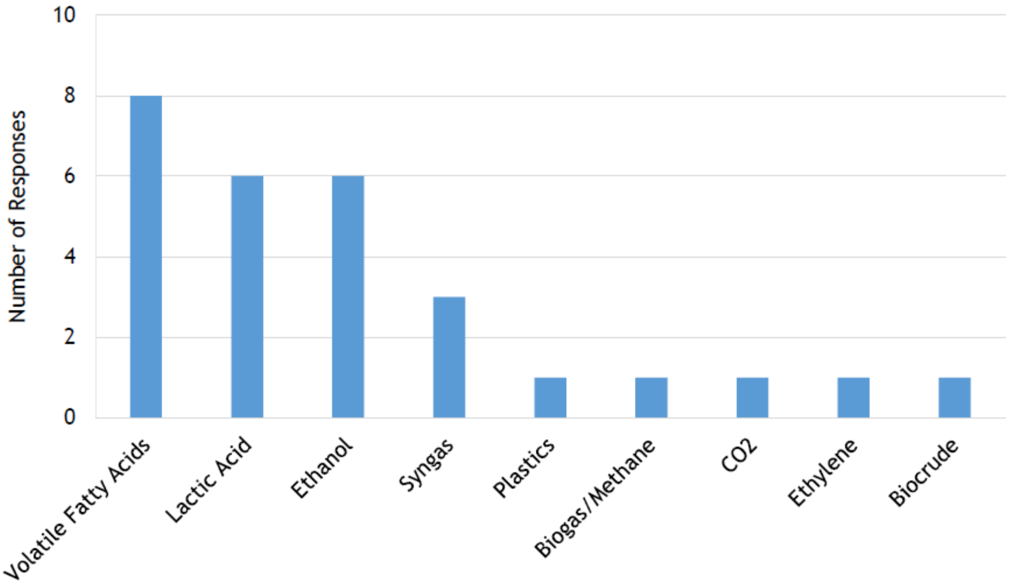

Figure 10: Poll results from workshop on highest potential intermediates (ref Workshop Report 3 in the Bibliography).

Barriers

While the emerging technologies offer some significant opportunities for waste streams to become manufacturing feedstocks rather than solely sources of recovered energy, such pathways are not without their challenges. The concept of ‘upcycling’, and the costs that are inevitably associated with them, places an interesting perspective on the manufacturing of the end products more broadly—one which is driven by the question “why didn’t we just make this in the first place?”. There are clear advantages from emissions, energy, and CE perspectives if a production process based on waste replaces one based on primary resources – this is another driver for the approach to focus on production of generic intermediate (VFAs, lactic acid, syngas, etc) and let the market decide.

The notion of producing intermediates also addresses a potential challenge around market size, market development, and proximity to these markets. For some low-volume, high-value specialty chemicals, saturation if a specific, high-value product is targeted and production scaled to match the volumes of waste that might be available. There are also challenges relating to the variability in waste sorting schemes (even sometimes within states or regions) which impact on technology choice and operability. This is sometimes compounded by the presence of hazardous or pathogenic materials, and complicated by aspects of community acceptance.

Enabling a Waste Management Transition: More than Technologies

Much of the discussion so far has focused on the role of technology in enabling waste management and energy recovery processes to become more consistent with the goals and principles of a circular economy. There is no doubt technology is going to play a critical part in the transition from linear to circular; however, the availability of technological solutions will not be enough. There needs to be policy frameworks in place that support change and address the potential issue of increasing costs associated with new options. There also needs to be a desire for change, and an acceptance of both the new technologies we have been discussing, but also an acceptance of the role of human behavior in a successful transition to a circular economy.

POLICY SETTINGS

We have already discussed how policy shifts in some European countries, for example, are driving change, in particular regarding the use of recycled materials as manufacturing feedstocks, and the secondary effect that has of driving some technological change to make enough recycled inputs available. This highlights clearly the impact that strong policy settings can have and reinforces the fact that while so much of the CE is about processes and pathways, it remains at a high level an economy-wide shift in the way things are done.

The importance of policy is also highlighted by an ongoing theme as we talk about new and emerging technologies: they almost inevitably come at a cost. Policies and incentives are key to driving the uptake of these technologies, which as well as achieving positive outcomes, will lead to reductions in the costs of these approaches as deployment increases and technologies mature.

In general, policies that incentivize greater decarbonization and recycling rates appear to be effective in driving project development as well as technological innovation. One example in the European Union and South Africa (and that has been very recently adopted in portions of the United States) is the Extended Producer's Responsibility which encourages packaging manufacturers to develop materials that are more readily recyclable. Another example is the California Low-Carbon Fuel Standard which gives increased credits depending on the degree of decarbonization. An example from South Africa is the Carbon Tax Act 15 of 2019 which imposes a tax on the carbon dioxide (CO2) equivalent of greenhouse gas and strict reporting and in 2019 the new total ban on disposing of liquid waste to landfill which emphasizes the focus of looking at the various waste streams and moving higher on the waste hierarchy for recycling and re-use as the premium solution. There are examples where existing biofuels producers are modifying their existing plants or supply chains to source more renewable feedstocks and chemicals in order to lower their carbon intensity scores and thereby receive a larger credit.

SOCIAL ACCEPTANCE

Even in jurisdictions where combustion-based EfW is established and has been for some time, public acceptance is a critical component of new project development—and in countries where EfW concepts are not yet established, a lack of public acceptance is regularly cited as one of the reasons for project failure.

There are many factors at play when communities oppose waste-to-energy projects (see Figure 11 for some aspects from a study focussing on combustion-based EfW in Australia where the technology is not common). In general, people will support the avoidance of waste to landfill, and are often opposed to landfilling as part of a sustainable waste management strategy—and yet opposition to new build WtE is almost inevitable. In countries where WtE is emerging, there is often a lack of knowledge about the process, how it works, emissions and other environmental impacts, as well as the extent to which the technology has been effectively deployed around the world. Recent research [18] has shown that this is often coupled strongly with perspectives of ‘distributed fairness’—linked to benefits, trust, and outcomes. It was also clear that the single greatest predictor of community acceptance was people who had lived within 2 km of a facility, suggestion that actual experience was far more important than other educational materials. These are important component of establishing community acceptance, showing that education and awareness campaigns are not sufficient to earn the social license to operate that comes from sufficient community acceptance.

For countries more experienced with WtE, the opposition is often linked to perceptions of scale, and the impact this would have on the need to import waste or take recyclable material away from recycling processes. Again, information and awareness campaigns are important here, but without a strong level of trust and views of positive and fair outcomes, acceptance is unlikely to be strong.

This link between information and engagement to build trust was demonstrated most recently in the Danish Copenhill plant [19]. When the idea of building a WtE plant in an urban area in Copenhagen came out, some expressed their concern at its scale and that the environmental and economic consequences could be the opposite to the expected ones (i.e. hamper recycling). The plants owner developed then a communication strategy with the residents, business owners and representatives from several organizations in the area in which transparency during the whole process and continues exchange of information and open discussion from the very early stage of the process were crucial to ensure social acceptance. Other factors that had a positive impact when gaining social acceptance in this project was: (1) the fact that the WtE plant and recreational area (located on the facility rooftop) share location integrating waste management and social activities in one; (2) the during the construction, the site was used as a place to train new apprentices for future labour market giving back something to the society. In this case, the extra attention given to design and architecture making it a feature of the city (and the highlighting of its proximity to royal residences) also played an important role in its wider acceptance.

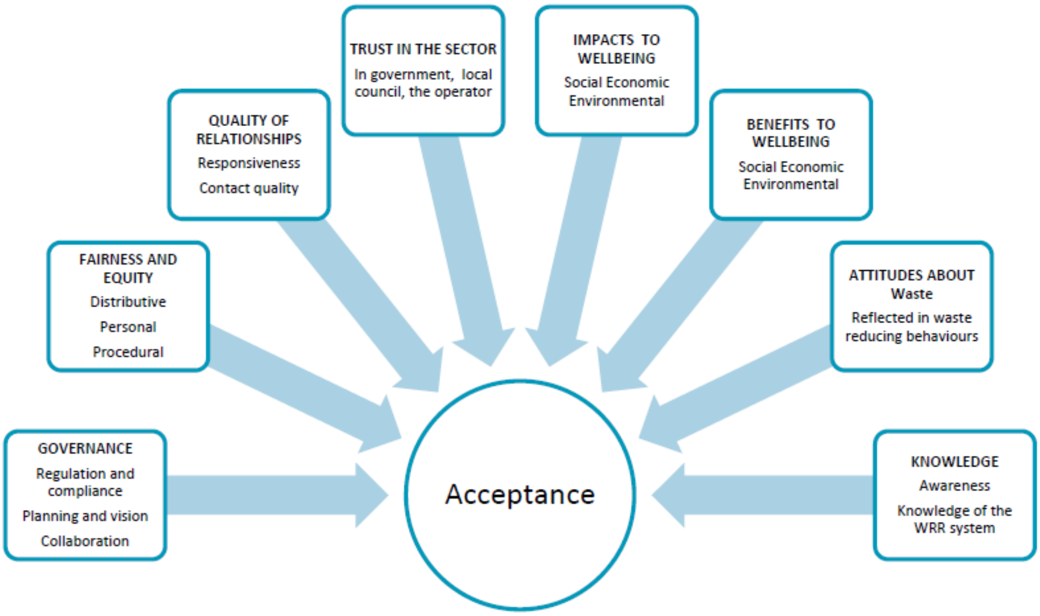

Figure 11: Drivers of social acceptance in the waste domain, based on Australian research in 2016 and 2019 [18].

ENVIRONMENTAL OUTCOMES

A modern waste management strategy comprises of a multitude of traditional, emerging, and advanced technologies, each with different associated environmental impacts. With an increasing emphasis on development of sustainable solutions for waste management, it is important to evaluate the environmental impacts of the different available waste management pathways. Life cycle assessment (LCA) is an internationally accepted tool for assessing the environmental impacts of a product, process or service and is the most comprehensive method currently available for assessment of waste management systems [20]. LCA was carried out on a waste-to-energy system in Ireland, and a large-scale hydrothermal conversion (HTC) plant for conversion of biowaste and sludge (green waste, food waste, organic fraction of municipal solid waste (MSW), and digestate) to high quality hydrochar in Italy, to determine their environmental impacts (global warming, freshwater eutrophication, and terrestrial acidification potentials).

For the waste-to-energy system, the incineration process (resulting in emissions of CO_2, CO, SO_2 and NOx etc.) and provision of electricity to the incinerator are responsible for most of the impacts across the 3 impact categories considered. The study found that the use and avoidance of electricity production by the average national grid mix in Ireland significantly affects the environmental impacts of the incineration process. The environmental impacts and benefits may therefore vary depending on the emissions intensity of the national gird mix of the country which the incinerator is operating.

The hydrochar plant environmental impacts mainly resulted from electricity and thermal energy used in the process, CO_2 produced in the process, and the organic content in the waste streams impacting the environment when applied to land. The application of nutritionally rich (NPK contents) process water stream in place of conventional fertilisers on agricultural land gives and environmental benefit to the system. Again, energy use in the system (particularly electricity) contributes significantly to the overall environmental impacts, such impacts would differ if the HTC process was operating in different parts of the world. Assessment of the differing impacts facilitates the stakeholders to strategically plan the establishment of HTC plants in future in a particular location or country by keeping environmental sustainability in mind.

Summary: the Role of Waste and Bioenergy in a Circular Economy

NEW PRINCIPLES

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'. For the established combustion-based systems, which are inherently linear, 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.

These 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.

From	To
Waste management	Materials recycling and resource handling
Energy recovery	Molecules in use for longer
Heat and power	Energy, chemicals, and manufacturing feedstocks

Table 2: The shift in focus for waste management and energy recovery driven by the emergence of circular economy principles.

NEW TECHNOLOGY PATHWAYS

Combustion-based waste to energy systems are well-established, and at their current state of development are able to generate heat and power from landfill-bound waste while meeting stringent emissions and other environmental requirements. They are by far the most common pathway for large-scale WtE. As circular economy principles emerge the expectations of these technologies is changing. In this report we have explored some of these expectations and considered how they are driving innovation and technology development: recovering nutrients and other valuable materials from combustion (or digestion) residues, increasing the efficiency and quality of heat produced, and considering the integration of carbon capture and storage with a waste combustion facility to provide CO_2 abatement as well as heat and power.

A fundamental challenge with these approaches, however, is the inherent inflexibility in a combustion-based process in the context of products. This report has explored some of the technology options that have emerged in the waste management space that support a greater degree of product flexibility in the context of waste management and energy recovery.

Hydrothermal carbonization and pyrolysis pathways offer the ability to densify and stabilize waste streams, supporting waste use as a fuel in a rage of technologies traditionally used with feedstocks such as coal. By adjusting the pyrolysis process a biochar can be produced, which is being demonstrated using troublesome waste streams (such as biosolids) to both manage their disposal, but also generate heat and inputs into agricultural and soil management processes.

Pathways that produce industrial intermediates, however, are perhaps most aligned with the principles of a circular economy. Biogas methanation is receiving considerable attention globally, due partially to the increasing role of anaerobic digestion in waste-to-energy but mainly due to its potential to produce renewable natural gas without significant emissions of CO_2.

Despite some recent challenges with scaling up, we are seeing waste gasification demonstration projects show the technical viability of these options and take the important first step towards lowering their costs. Syngas is a widely used feedstock in manufacturing and energy applications, and so these pathways offer the potential to contribute to the recycling of non-recyclable materials and the integration of these with a range of manufacturing processes.

We have also seen the emergence of a range of next-generation pathways, some based on syngas, that rely on biological or novel thermochemical pathways that support the production of products that are niche, and high value. These kinds of approaches, which are not typical for the waste management sector, bring with them some new challenges – many of which are not technical, and relate to aspects of market size and saturation, nature and quality of feedstocks and supply, and more fundamental questions about perspectives of manufacturing supply chains and the efficiencies associated with multiple process stages, and the risk of unintended environmental and economic consequences.

POLICIES AND A SOCIAL LICENCE 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.

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.

WHERE TO FROM HERE?

The work undertaken by the Task over the triennium was the beginning of a refocusing of the Task's priority areas away solely from combustion-based waste-to-energy to consider broader aspects in the context of the emerging Circular Economy. We have seen how there are some established and emerging pathways for nutrient and material recovery associated with current technology pathways, and there is a relatively high degree of understanding of the role of these in a broader waste management system.

We have also considered a wide range of emerging and advanced technologies that diversify the feedstocks and products that are relevant when considering waste management, energy recovery, and the Circular Economy. What remains is some uncertainly related to the wide range of TRLs, cost models, and value propositions that exist in this space, the context within which they are feasible, and of course their relative merits from an environmental and economic perspective.

The next triennium will continue this work, seeking to better understand the new technology pathways that have been identified and further evaluate them from a technology readiness, sustainability, and CE perspective (see Figure 12). This will provide some important perspective as waste management authorities and governments continue to seek technological solutions to increasingly complex waste-related problems.

As resource and energy recovery from waste becomes more sophisticated, this will require more advanced solutions and schemes for addressing difficult streams. These could include new processes to sort waste streams through the use of robotics, AI/ML, or other technologies. Aggressive recycling goals will also require the development of more readily recyclable materials and/or development of chemical recycling strategies that can manage plastic streams that cannot currently be recycled through traditional mechanical recycling processes.

Hydrogen is emerging as an important aspect of the decarbonization of a range of sectors including transport, electricity, heavy industry, and manufacturing. Although considered only briefly in the work undertaken this triennium, the projected scale of global demand for renewable and low-carbon hydrogen demand will mean that a range of production pathways are likely to be needed. Hydrogen as a product from waste management is technically-feasible but largely unproven at scale—ongoing work in this Task will consider how waste can be one solution to renewable and low-carbon hydrogen production (via our own activities as well as proposed inter-task activities).

This planned program of work reflects the challenges faced by the waste management sector as the environment within which it operates changes. These include choosing the adoption of new technologies vs the potential to retrofit existing processes; the likelihood (and impact of) changes in policy and legislation; and how to effectively navigate the increasingly-complex number of options with regards to feedstocks, technologies, and products—all while bringing the community along on the transition journey.

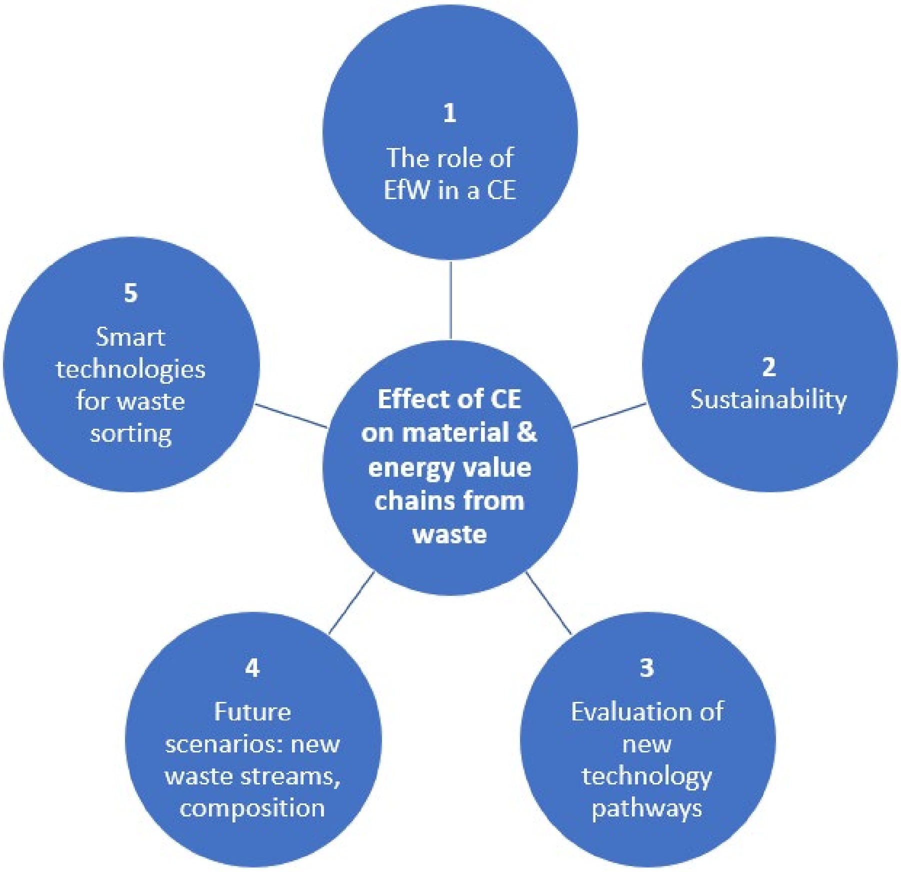

Figure 12: Proposed topics of interest for the next triennium of Task 36 – Material and Energy Valorisation of Waste in a Circular Economy.

Another aspect that emerged from some of the work undertaken in the Task is the different set of drivers in developed vs developing countries, or even countries with little experience in energy recovery from waste vs those with established industrial sectors. The basic needs here are significantly different, and these differences drive decision-making and technology adoption. For example, in countries such as South Africa, there is a push for low-capital-cost biogas pathways that address immediate needs of the management of food and animal wastes in rural villages. In Australia, where large-scale thermal waste-to-energy is yet to be established, the focus is on increasing public acceptance to support project development and doing so using well-established combustion pathways. While any move to increase the recovery of energy and resources from waste streams is likely to be positive, there is a risk that the drivers we are seeing in Europe—which are suggesting that combustion-based EfW is not as circular as new approaches—will be repeated.

More broadly, though, the Circular Economy is about more than energy and materials recovery from waste. It is about behavioural change at all stages of the manufacturing and production supply chains; the tehcnologies that are chosen to manage the residues from these supply chains need to be able to evolve and adapt as the requirements placed on them evolve over time.

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