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Evolution of Mechanical Heat Treatment for resource recovery from Municipal Solid Waste in the UK

Resource Recovery from Waste

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Authors: Anne Velenturf, Eleni Iacovidou, Kok Siew Ng, Joel Millward-Hopkins

Reviewers: Phil Purnell, Juliet Jopson

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1 INTRODUCTION

1.1 BACKGROUND

This report is the outcome of a Resource Recovery from Waste mini-project[1] led by University of Leeds. The project aimed to explore higher value applications of fibre recovered through a steam rotating autoclave, which is a form of a Mechanical Heat Treatment (MHT) process. It processes mixed municipal solid waste or materials with similar characteristics, by converting the biogenic fraction into sanitised fibre and leaving a stream of recyclable materials. Currently the fibres are used in combustion process to generate power, which is considered as a low-value application. It is hence the interest of the present study to explore alternative options in converting fibre into higher value products. One way to achieve such higher value could be through the processing of segregated waste streams and coffee cups are of particular societal interest.

1.2 MECHANICAL HEAT TREATMENT

Mechanical Heat Treatment (MHT) is a process used to separate a mixed waste stream into several component parts, via a range of mechanical and thermal treatment configurations including steam based technologies. Due to the thermal technologies involved, MHT processes can sanitise the waste, and may also reduce its moisture content. Application of MHT for the treatment of municipal solid waste (MSW) is relatively new with the first plants being introduced at around 2003 (discussed in detail in Chapter 5). The most common MHT system that is increasingly being promoted for the treatment of MSW (discussed in Chapter 2) is the autoclaving process. This process is a proven technology as it has been used for many years to sterilise hospital and surgical equipment and some clinical wastes, as well as for rendering processes for animal wastes, prior to their landfilling [1].

Autoclaving uses steam and pressure to break down the organic waste into a fibre fraction that is sanitised, leaving a clean stream of recyclables materials that go through a post-heat mechanical sorting process. Glass bottles and tins are de-labelled during the autoclave process, as the glue disintegrates under the action of the heat, generating a high-quality glass and metal (ferrous and non-ferrous) stream that is cleaned and can be extracted for recycling [1]. Dense plastics are also de-labelled, and while certain types of plastics are only softened and slightly deformed by the heat, others are completely softened forming hard balls that are often rejected to landfill as these may not be favoured by some reprocessors. Small amounts of fibre material may often be trapped within containers destined for recycling, which presents another quality challenge for reprocessors.

[1] https://rrfw.org.uk/projects/mini-projects/formulating-the-environmental-and-social-business-case-for-a-resource-recovery-from-waste-process/

1.3 REPORT OUTLINE

This report analyses the co-evolution of MSW composition and volume in the UK (Chapter 2), the waste infrastructure required for their management (Chapter 3) and trends that are driving changes in MSW composition and treatment infrastructure (Chapter 4). Within this context, the report analyses the emergence of MHT technologies in the UK (Chapter 5). Analyses of economic scenarios identifies potential pathways to increase the viability of the business case for resource recovery using this emerging technology (Chapter 6). The report concludes with an outlook for further research to investigate whether the separate treatment of waste streams such as coffee cups waste would significantly increase the quality of recovered resources and enable higher value applications (Chapter 7).

2 CHANGING COMPOSITION OF MUNICIPAL SOLID WASTE

Municipal solid waste (MSW) became an issue due to increasing urbanisation and consumption of a greater diversity of products since the 1930s [2, 3]. The changes in our production system and lifestyles altered the volume and composition of wastes over time (Figure 1). In the UK, MSW consisted for more than 50% of dust and cinder in the 1930s. The Clean Air Act in 1956 that prohibited dark smoke emissions from chimneys brought the first significant change in the composition of MSW [3]. In the mid-1960s plastics were introduced to the market and became an increasing part of the waste stream. In the year 2000 MSW consisted of a variety of materials such as plastics, metals, paper, glass, and organics [2].

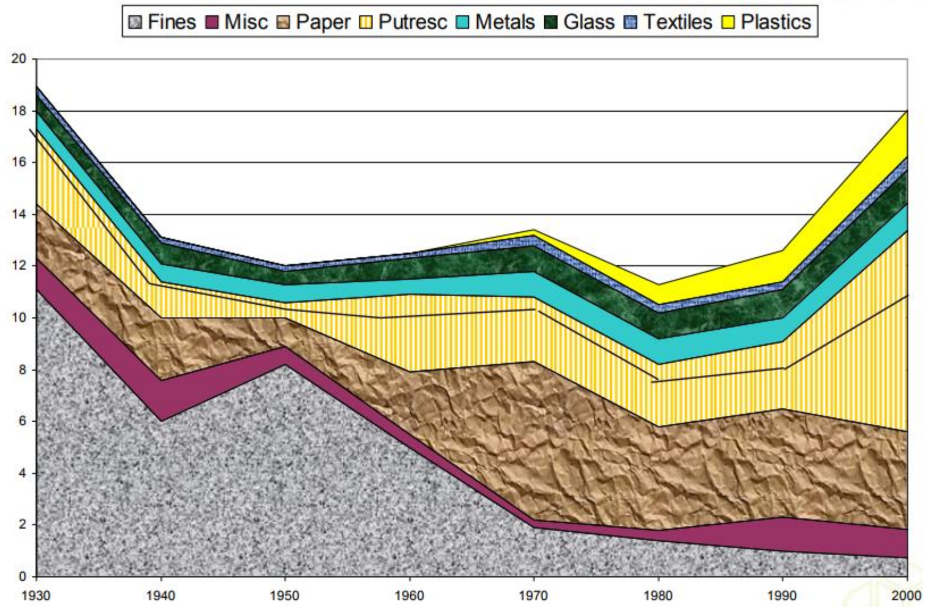

Figure 1: Composition of UK MSW from 1930 – 2000 (adapted from Parfitt 2009)

From a regulatory perspective, MSW is understood as wastes collected by local authorities from households and it can be mixed with some commercial and industrial wastes (e.g. from offices, schools, shops etc.) that is of similar nature to household waste; this is called local authority collected municipal waste (LACMW). The black bin waste fraction of LACMW is called residual municipal solid waste (rMSW). rMSW is collected by local authorities or a commercial company contracted to provide collection services on their behalf [4]. Generally this waste is considered to be unsuitable for reuse, recycling or composting. Some wastes that are initially disposed of via the recycling bins, may also be added to the rMSW after the sorting and recycling process due to their unsuitablility for material recovery or the lack of demand for secondary resources.

A study conducted in 2011 on the composition of MSW in England, revealed that MSW mostly consists of food and garden wastes, followed by paper, glass and plastics (Figure 2) [5]. Garden- and food wastes are increasingly treated and kept out of the landfill; there has been a 71% reduction in biodegradable municipal waste disposed of to landfill between 1995 and 2015. Over the same period, recycling has increased from nil to 45% [6]. There is still a considerably high fraction of rMSW generated in England, which in 2006/07 was estimated at 20.21Mt [7].

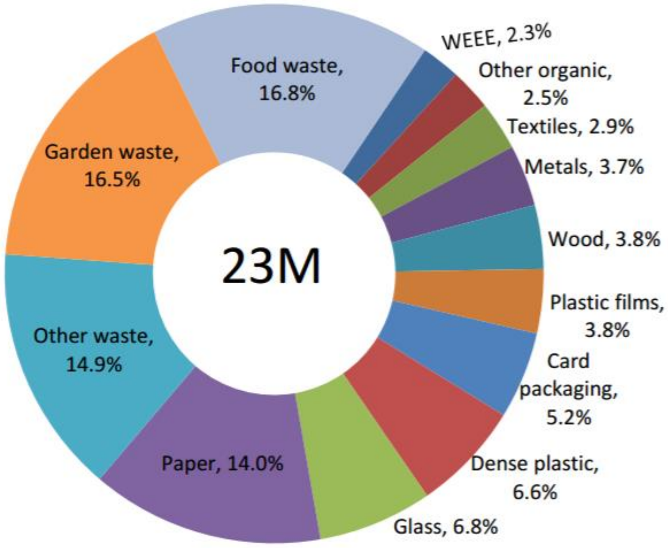

Figure 2: Local authority collected waste composition in 2011 [5]

Recent changes in waste management include a growing problem of "on-the-go" wastes, and this has led to government questions into disposable packaging such as plastic bottles and coffee cups[2]. About 2.5Bn i.e. 30kt of coffee cups are disposed of annually in the UK. While this is only 0.1% of total waste in the UK, it is perceived as particularly challenging because only 1 in 400 coffee cups are currently recycled. The problem is thought to grow, with the number of coffee cups growing from 5,000 in the year 2000 up to ca 20,000 in 2017. MHT is an interesting technology in this respect, because it can separate the paper- and polymer fractions in coffee cups. In theory, this could enable closed loop recycling of the paper fraction of the coffee cups.

[2] https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/657/657.pdf

3 EVOLVING WASTE INFRASTRUCTURE

Due to the changes in the volume and composition of MSW as well as a number of other factors, waste infrastructure emerged and continued to evolve in the UK.

Since the end of the 19th century, waste management has been a highly political issue due to its direct impact on public health and the environment in the UK. This led to the introduction of waste furnaces known as “destructors” to effectively remove the nuisance and health threats posed by the waste accumulation in dumpsites [2], with around 200-250 incinerators being built in the UK up until the beginning of first world war [3]. In the late 1960s/early 1970s there was a decline in the use of incinerators because landfill was introduced as a much cheaper alternative; becoming the dominant MSW management option in the UK [3, 8].

In the 1970s, incinerators with energy recovery potential, now widely known as energy from waste (EfW) plants, were introduced in the UK for the treatment of MSW as a response to the energy crisis. However, their economic disadvantage compared to landfill [3], coupled with increased environmental awareness and public health concerns over the nitrous oxides, sulphur oxides, dioxins and furans emissions that contributed significantly to environmental problems such as acidification, human toxicity, eco-toxicity, eutrophication, and summer- and winter smog [2, 9], led to their closure in the 1990s [8]. This was also a result of the EU directives on controlling the incineration of waste, and introducing pollution control measures to mitigate air pollution and dioxin emissions. Retrofitting existing incineration facilities with gas cleaning equipment was very costly for local authorities[3] and landfill was once again on the forefront as an economically attractive alternative.

The privatisation of local government’s waste collection and disposal services, and the introduction of compulsory competitive tendering, stimulated a significant restructuring and consolidation of the waste management industry in the 1990s [3, 8]. Technological sophistication brought in by large firms that could benefit from the economies of scale, had influenced the waste management landscape, and market forces were gaining an important role in the spatial distribution of waste-management facilities, including incineration.

Large firms played an important role in supporting the development of integrated waste management systems. They focused on the provision of a combination of different waste treatment technologies, achieving the best outcome in line with the continuously evolving EU regulations and standards and the changing MSW composition. Recovering a diversity of different materials was technically feasible, and in the mid-1990s recycling was back on the UK waste management agenda. However, the lack of a coherent governance structure and policy on waste management at a national and regional level, combined with organisational and marketability constraints surrounding recycling, investment in recycling infrastructure was reduced [10-12]. Driven by the pressures of the EU Landfill Directive (99/31/EC) that focused on the diversion of MSW from landfill, investment in EfW plants was gaining

[3] Originally local authorities (LAs) in the UK were responsible for the collection and disposal of waste as mandated by the 1936 Public Health Act

traction instead, disguised as an efficient, less polluting and economic way of recovering energy and complementing recycling as part of an integrated waste strategy.

This was also a side effect of the first waste hierarchy that placed EfW incineration at the same level as recycling and composting, and of the introduction of the Landfill Tax by the UK government which made landfill more expensive, providing an impetus for incineration [8]. Environmental- and public pressure groups argued that incineration was pulling down recycling and waste minimisation initiatives and warned of a wasted opportunity to reverse the UK's poor track record in waste practices [8]. However, these voices were marginalised, and investment in EfW plants continued to be considered an attractive waste management practice.

The end of 1990s, following the development of Agenda 21 objectives for waste management [13], has spawned a new generation of waste management strategies in the UK. These strategies emphasised waste minimisation, reuse and recycling [12]. A transition from simply combustion to mixed strategies combining EfW, recycling and composting could be observed to increasingly promote the recovery of materials, nutrients and calorific content. First attempts to promote these practices were constrained by inadequate financial and resource mechanisms [12]; a problem reinforced by the lack of knowledge on the growth and composition of MSW waste streams and the traditional split between collection and disposal/management systems [8].

Local authority Private Finance Initiative (PFI) schemes were introduced in 2006 as a mechanism to support large waste infrastructure projects underpinned by long-term contracts (typically 25-30 years) as part of the Waste Infrastructure Delivery Programme [8]. These schemes stimulated the development of a number of large-scale recycling facilities. They have also brought change in waste management practices, focusing more on the recovery of recyclable materials from MSW and the treatment of the residual fraction in specialised facilities.

A number of infrastructure projects for the treatment of rMSW were financed by the PFI schemes in order to enable the UK to meet the landfill diversion targets. Amongst these projects, EfW facilities continued to be funded and a number of new alternative technologies such as mechanical and biological treatment (MBT) and MHT technologies started to make their entrance into the waste management landscape. The impetus to using MBT and MHT process for the treatment of rMSW was not only to avoid landfill disposal charges and taxes, but also to meet the recycling targets required by the Waste Framework Directive (WFD) through the recovery of dry recyclables [14].

MBT originated in Germany in 1999, where it was introduced as an alternative MSW process as a response to regulatory restrictions on the disposal of biodegradable municipal waste to landfill (EU Landfill Directive [1999/31/EC]), the rising costs of waste disposal to landfill and the increasing demand for alternative fuels [15, 16]. Shortly after, the EU Landfill Directive drove the introduction of MBT plants in the UK. MBT plants stabilise organic matter present in rMSW and lead to the recovery and recycling of other materials such as ferrous and non-ferrous metals, plastics, glass and paper [17]. Depending on the exact configuration of the

MBT plant, Solid Recovered Fuel (SRF) can be produced as an alternative fuel to substitute coal in cement kilns as well as in other industrial processes [18]. The focus of MBT technology has over the years been placed on fuel production (biogas and SRF) and landfill diversion, making the recovery of dry recyclable materials, such as metals, plastics and glass, a lower priority for operators [19]. This was largely driven by the low proportion of recyclables in the overall output and their heavily contaminated nature, which in turn meant that they were of lower quality than those derived from a separate household recycling collection system. As a result these secondary materials would have a lower potential of being redistributed in high value markets [16, 20].

The benefit of MHT, converse to MBT configurations focused on fuel production, is that it produces a cleaner fraction of secondary recyclables. As introduced in Chapter 1, MHT are increasingly considered as part of an integrated waste management system, suitable in maximising the recovery of rMSW value and avoiding its disposal to landfill. The use of thermal autoclave for the treatment of MSW is relatively new, and its commercialisation is presently gaining pace in the UK [1].

Whilst most incineration, MBT and MHT projects funded through PFI have been successful, delays and challenges primarily driven by socio-technical aspects still impede their development and use. Public opposition to incineration facilities has led to substantial delays and often rejection of the planning permit applications for new incineration developments. Fibre output from MHT is subject to regulatory uncertainty due to a lack of protocol for an end-of-waste accreditation and eligibility for renewable energy subsidies. Moreover, volatility in policy and regulation and the absence of a clear long-term vision are also known to constrain investment.

Despite PFI contracts bringing up major changes in the waste management landscape, they were considered to be inappropriate. The amount of waste produced in the future, and its composition, can be difficult to predict. PFIs were considered to bring long-term stability in waste management rather than maintaining flexibility in the deploying of continuously evolving technologies. Concerns were that this would lock-in waste streams into long-term contracts that did not optimise material recovery.

However, with a growing interest in resource efficiency and a transition towards a growing low-carbon economy, local government and waste management providers are striving to create partnerships that can help them accelerate innovation and progress towards sustainable and circular waste management. Putting in place the right infrastructure is important, yet the different tiers of government and stakeholders responsible for the management, operational and planning functions of waste management, and of rMSW specifically, make it difficult to achieve. As long as national strategy and practice are isolated from one another, the transition to a circular, low-carbon economy will remain a challenging task. There are, however, a number of trends that increasingly necessitate waste minimisation and material recovery.

4 TRENDS DRIVING CHANGES IN WASTE COMPOSITION AND INFRASTRUCTURE

The changes in waste composition and volume are directed by life style changes and living standards, urbanisation, attitudes to waste disposal and recycling, waste management costs and benefits, environmental impacts, legislation, population size, and pre-treatment and recycling activities and available technological solutions [21, 22]. Other factors impacting on changing waste composition include focus on waste prevention and product design for durability and recycling, the volatility in policy and regulation and the absence of a clear long-term vision on product consumption, disposal and management [6].

Looking into global megatrends influencing resource use and consumption patterns, the following predictions for waste composition and treatment could be derived[4]:

1. **More waste due to a growing, aging population:** Population is expected to grow globally and in the UK growth is expected from 66M in 2016 to 70M in 2026[5]. Composition of the British population is expected to shift towards a relatively high proportion of people aged over 60 and 75, while average household size is expected to decrease. These demographics are likely to affect waste arisings, as retired people produce more waste per person on average[6].
2. **More WEEE:** Globally and in the UK people are increasingly moving into urbanised areas. In the UK, urbanisation occurs mostly around the edges of cities and there is also a reverse trend of with some people moving into rural areas. Urbanisation has been associated with changing consumption patterns, including consumption of more food (especially meat and dairy products), energy, and durable goods such as electrical items. This may mean a greater proportion of the future waste stream constitutes WEEE, posing particular challenges considering the next megatrend.
3. **New and flexible waste management solutions for small components:** Accelerating technological change, especially in the areas of information, communication, and nano- and biotechnology. The latter are expected to be present in all aspects of life by 2040-2050, which will increase demand for waste management technologies that can recover such small and bioengineered materials. Moreover, high innovation rates in products reaching consumers, and consequently resource recovery at a later stage, will require greater flexibility of the waste management sector to change to this continuously changing waste offering.
4. **New recovery solutions for low-carbon technology:** Further technological changes are strived for in the UK, as part of continued economic growth into clean and low-

[4] EEA (2015) European environment — state and outlook 2015: Assessment of global megatrends. European Environment Agency, Copenhagen. https://www.eea.europa.eu/soer-2015/global/action-download-pdf
[5] ONS https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/datasets/tablea11principalprojectionuksummary
[6] Burnley et al 2007 https://www.sciencedirect.com/science/article/pii/S0921344906000620

carbon activities[7]. Such technologies require new resource recovery technologies, not least to secure critical materials to ensure low-carbon technologies can be maintained in the UK in the future [6].

5. **More automated solutions:** The increasingly multipolar world, with the economies growing in developing countries and the already industrialised economies putting pressure on wages, especially in developed countries. This may result in less dependence on labour and instead adopt more robotics to keep resource recovery globally competitive, whilst also enabling recovery of materials from increasingly complex products with small (nano) components.
6. **Shift to solutions higher up the waste hierarchy:** Growing global competition for resources may have a dual effect on waste management. First it promotes investment in renewable and circular technologies. Second, reduced consumption of materials is increasingly necessary, including more innovation, efficiency and reducing waste i.e. overall waste arisings may decrease while demand for reuse, repair, recycling etc is likely to grow.
7. **Organic waste processing reduces and concentrates on energy recovery:** Pressure on ecosystems is growing and this may have various impacts in the UK and waste management. With less space to grow primary biomass, such as food, animal feed and energy feedstock, consumption of meat may need to decrease while food waste in general needs to be reduced. Moreover, using primary biomass for power, fuel and heat will be increasingly contentious, which in turn may push demand for energy from secondary biomass. Overall, there may be less demand for infrastructure handling biological wastes while the remaining infrastructure focuses more on energy recovery.
8. **Coastal landfills need to be cleared up:** Climate change and rising sea levels will also exacerbate coastal erosion. The UK has hundreds of old MSW landfills on the coast, affected by erosion with wastes likely to wash into the marine environment. These sites need urgent attention and clearing up to prevent pollution.
9. **Stricter environmental regulation:** Globally more environmental pollution is anticipated, which may result in stronger international agreements and stricter regulations in the UK.
10. **More global governance and local industry impact:** Diversifying approaches to governance, with more influence from international agreements such as the Climate Change Agreement and the UN Sustainable Development Goals. Additionally, non-state actors are gaining in influence, giving industry actors more power to impose their interests.

[7] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf and https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf

In sum, waste management in the UK needs to adapt to handle continuously changing wastes (particularly electrical items), use robotics to recover resources (especially small/ nanocomponents) in a globally competitive manner, recover critical materials upon which the low-carbon economy depends, overall reduce capacity for biowaste treatment while growing energy demand and pressure on land availability pushes for more bioenergy from waste, initiate landfill mining in coastal areas, and capitalise on opportunities promoting circular practices higher up the waste hierarchy such as prevention, reuse and remanufacturing.

Investment patterns into waste-, or rather circular economy, infrastructure need to respond to these changes in waste composition and processing requirements. Radical changes to align waste management infrastructure with circular economy aspirations will require a very different pattern of investment and incentives [6]. However, the current pattern of investment into EfW, doubling capacity from 5 to 12 Mtpa by 2020, will mean that a considerable proportion of MSW is likely to be "treated" by combustion with energy recovery until 2040-2045.

In addition to EfW, there is now an abundance of waste treatment options that may be used as part of a waste management strategy. These include advanced thermal treatment (ATT) processes (i.e. gasification and pyrolysis), advanced biological treatment (ABT) (i.e. anaerobic digestion) processes, mechanical biological treatment (MBT) and MHT. Other technologies that are close to market include flexible, reconfigurable multi-material recycling facilities that sort residual waste using size and density, optical or infra-red material sensing technology and air separation to recover plastics, paper, cardboard, glass and metals, and this responds to an extent to the trend regarding demand for increasingly flexible waste management solutions that is outlined above[8].

However, overall the currently available technologies and establishing technologies appear to be ill-equipped for the forthcoming changes. Investment still focuses on energy recovery, while the urgent need for a push higher up the waste hierarchy is evident. Effective and efficient solutions for the recycling of WEEE, nano- and bioengineered components and low-carbon technologies are generally in embryonic stages of development. Automated solutions are upcoming. Only for organic waste are technologies reasonably future proof.

MHT can play a valuable role in the increased recovery of secondary recyclables for reprocessing, extracting biogenic contents for energy applications and generating syngas alongside the recovery process. The analyses of megatrends above suggests that MHT operators should perhaps not seek application of biogenic contents for material recovery, and instead remain focused on energy recovery. This may seem counterintuitive since energy recovery destructs technical value of materials, however, it may be the best recovery pathway. Further analyses of the technical, environmental, social and economic values that are created and destructed in energy- and material recovery scenarios is required to inform decision-making.

[8] https://www.birminghambeheard.org.uk/place/from-waste-to-resource/supporting_documents/ED61680%20BCC%20Technology%20Foresighting%20FINAL1.pdf

5 EVOLUTION OF MHT TECHNOLOGY IN THE UK

The application of MHTs with autoclaves to treat MSW is an emerging technology and relatively few full-scale operational plants exist in the UK. The evolution of the sector – and the political, economic, social and environmental challenges it faces – can be grasped by considering the fates of major MHT plants planned for the UK over the past 15-20 years. In the DEFRA (2007, 2013) reports on MHT plants, ten such plants are included. Appendix A shows an overview of the evolution of those MHT plants and we discuss them here.

The earliest MHT plant was planned for Hereford and Worcester councils by *Estech Europe*[9]. Plans were submitted around 2003, and permission was granted in 2005, for a plant capable of processing 100,000 tpa of MSW. The recovered organic resources (i.e. fibres) were planned to be recycled into the construction industry. However, legal issues arose due to opposition from local residents, under the group Hereford Waste Watchers, who made formal legal challenges until 2007[10]. These objections were eventually rejected the same year[11] and planning permission reapproved. However, Estech faced further issues as they struggled to secure a waste supply contract with the councils[12]. Talks eventually broke down, with the councils signing a contract for a 200,000 tpa EfW plant instead a few years later[13]. The primary issues voiced by the council related to 1) waste residues from the MHT, 2) the unproven nature of the technology and 3) the uncertain markets for its outputs.

Another early entrant to the market was *Sterecycle*, who in 2006 announced grand plans[14] to build 3 to 5 plants in the UK[15]. Planning permission was granted and private funding secured, avoiding the PFI process. The first of these came online in 2008 in Rotherham[16], accepting 100,000 tpa of MSW. In 2010, planning permission for a much larger plant (240,000 tpa) in Essex was granted, and in 2011 the capacity of the Rotherham plant was increased 75%. But Sterecycle then began to hit major problems. Not long after the capacity increase at Rotherham, there was an explosion at the plant, killing one worker and leading to some broad-brush bad press for the energy from waste industry[17]. Major financial difficulties followed, due to volatile prices of plastics and metals, lack of fibre end-markets (which was being given away), and expensive odour problems at the plant[18]. The local councils immediately arranged supply contracts with a local EfW plant instead.

Orchid Environmental were the final company to feature in DEFRAs early 2007 report. Funding was secured under DEFRA's *New Technologies Demonstrator Programme* for an 80,000 tpa plant, and this opened in Merseyside in 2008[19]. Two further plants, each of larger

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9 https://www.letsrecycle.com/news/latest-news/estech-looks-to-build-autoclave-in-worcestershire/
10 https://www.letsrecycle.com/news/latest-news/fresh-problems-for-hereford-worcester-autoclave-project/
11 https://www.letsrecycle.com/news/latest-news/challenge-to-herefordshire-autoclave-plant-thrown-out/
12 https://www.letsrecycle.com/news/latest-news/doubts-cast-over-herefordshire-autoclave/
13 http://www.worcestershire.gov.uk/info/20232/recycling_and_waste/1016/waste_contract/4
14 https://www.ft.com/content/25a31606-1ea2-11e0-a1d1-00144feab49a
15 https://www.letsrecycle.com/news/latest-news/autoclave-firm-secures-funds-for-ambitious-building-plan/
16 https://www.letsrecycle.com/news/latest-news/10-million-autoclave-plant-to-open-in-yorkshire/
17 https://www.thetimes.co.uk/article/fatal-blast-casts-doubt-on-power-from-waste-lzd6bpg0fzg
18 See https://www.letsrecycle.com/news/latest-news/sterecycle-goes-into-administration/ & https://www.letsrecycle.com/news/latest-news/sterecycle-ceases-operations-after-bdr-ends-contract/ & https://www.letsrecycle.com/news/latest-news/administrators-abandon-sterecycle-autoclave/
19 https://www.letsrecycle.com/news/latest-news/merseyside-opens-13m-demonstrator-plant/

capacity at 160,000 tpa, were planned for Shutton (North Wales) and Bexley (London) in 2008, and funding for the latter secured from the *London Waste and Recycling Board* in 2011[20]. The plants were intended to produce SRF. In 2011, the Rotherham plant was shut as the company promised to concentrate efforts on the two larger projects[21]. However, neither were ever built and, instead, Orchid began to focus on international markets and reopened the Rotherham plants[22]. This DEFRA subsidised plant remains the only one they operate in the UK.

DEFRA's 2013 updated report on MHTs detailed three further projects. The earliest and largest of these was from *Graphite Resources*, which received planning permission in 2005 to build a plant capable of processing 320,000 tpa of MSW in Gateshead, set to be the largest waste autoclave in the UK[23]. This was built in 2008, but only became operational after securing a waste supply contract in 2010. Planned outputs included RDF and fertilizer. After just three years, the company admitted major financial difficulties (at one point blamed on the need to fix odour problems) and closed down, making 70 local people redundant[24]. Fortunately, in 2016 the plant received further private investment and reopened as *Catfoss*, but the recycling firm's financial director noted that, given the *complicated, even niche* nature of the MHT technology, finance had been difficult to find[25].

A much smaller plant (75,000 tpa) detailed in the DEFRA 2013 report was planned by *Auto Thermal* to be built near Plymouth. This was expected to be the world's first integrated autoclave and advanced anaerobic digestion plant[26]. Planning permission was granted in 2011 and an opening date announced in 2013, but the plant appears to have not been built.

The most successful MHT project of those covered by DEFRA seems to be that of *Shanks Waste Management* in Wakefield. This is claimed to be the first fully integrated (waste and recycling) site for an entire local authority in the UK[27], with Autoclave (one of the UKs largest at 145,000 tpa capacity), anaerobic digestion, and other sorting technologies. Planning began around 2010 and, in a joined up, collaborative process, planning permission was granted in 2013 at the same time as a waste supply contract was signed and PFI finance secured (including a £33 mln grant from DEFRA). The plant was processing waste by 2015, and the integration of autoclaving for anaerobic digestion was helping the site produce biogas sufficient to supply 75% of its own energy needs[28].

Reviewing these UK MHT projects, many common themes emerge. First, there is a repeating pattern of grand claims, but a failure to deliver them. Financial problems can arise from the perceived risks of what is considered to be a complicated, risky technology with uncertain markets for its most voluminous output, i.e. fibre. These same perceptions can lead to issues securing waste supply contracts. However, if energy applications are indeed the most

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[20] https://www.letsrecycle.com/news/latest-news/london-waste-board-invests-4m-in-orchid-plant/
[21] https://www.letsrecycle.com/news/latest-news/orchid-shuts-formerly-defra-backed-mht-plant/
[22] https://www.letsrecycle.com/news/latest-news/orchid-in-hong-kong-as-london-plant-dropped/
[23] https://www.letsrecycle.com/news/latest-news/work-begins-on-uks-largest-steam-autoclave-plant/
[24] https://www.ft.com/content/9a5a843e-5c26-11e2-ab38-00144feab49a & http://www.thejournal.co.uk/news/north-east-news/jobs-axed-derwenthaugh-waste-plant-4408642
[25] https://www.mrw.co.uk/latest/mothballed-autoclave-plant-to-reopen/10009751.article
[26] https://waste-management-world.com/a/world-first-autoclaving-for-advanced-digestion
[27] http://www.wakefield.gov.uk/Pages/News/PR4863.aspx
[28] http://www.shanksplc.com/news-room/case-studies/super-service.aspx

appropriate destination for the fibres as indicated by the analysis of global megatrends, then risks due to market uncertainty may be significantly reduced; however, such claims require substantial further investigation of megatrends, markets, and a holistic assessment of technical, economic, social and environmental costs and benefits associated with the complete supply chain. When assessing investments into waste infrastructure in the UK, the frame of reference is EfW, a proven technology with an unambiguous market for its output. Planning and legal issues are not an issue, unless local residents' opposition is strong. But such local opposition is context-specific, such that, in, say, the ex-industrial North East, local residents are more likely to be perturbed by job losses if a plant is closed than by issues relating to developing the plant itself. In summary, MHT appear to face much of the same issues around financing and public sector support as any emerging technology attempting to integrate into a sector dominated by other technologies (particularly EfW), which, while they may be less effective at recovering resources, have a proven track record.

6 ECONOMIC ANALYSIS OF MHT SCENARIOS

6.1 INTRODUCTION

The main feature of the autoclave process is that an organic fibre stream can be created. The organic fibre stream has the potential of generating value-added products, subject to appropriate treatment and upgrading methods, and provided that the market of the product is available. The main objective of this analysis is to develop a better understanding on the feasibility of using the fibre in various applications and possible upgrading methods of fibre.

6.2 MASS AND ENERGY BALANCES

Figure 3 shows the mass and energy balances of an MHT plant for treating MSW, consisting of an autoclave process and a mechanical separation section. The capacity of the system has been assumed to be 150000 tonnes per year. Based on the work carried out by Garcia et al. (2012) [1], it has been estimated that 82050 tonnes per year of organic fibre (yield = 54.7%) can be produced from the plant, alongside 49305 tonnes per year (yield = 32.9%) of other recyclables (e.g. PET, ferrous and non-ferrous metals and plastics) and 18600 tonnes per year (yield = 12.4%) of rejects (e.g. textiles). The plant requires a total 36 GWh per year of energy (Steam: 19.8 GWh; Electricity: 14.2 GWh for autoclave and 1.9 GWh for mechanical separation). *Note: The results of the present case study should be treated as a hypothetical case.*

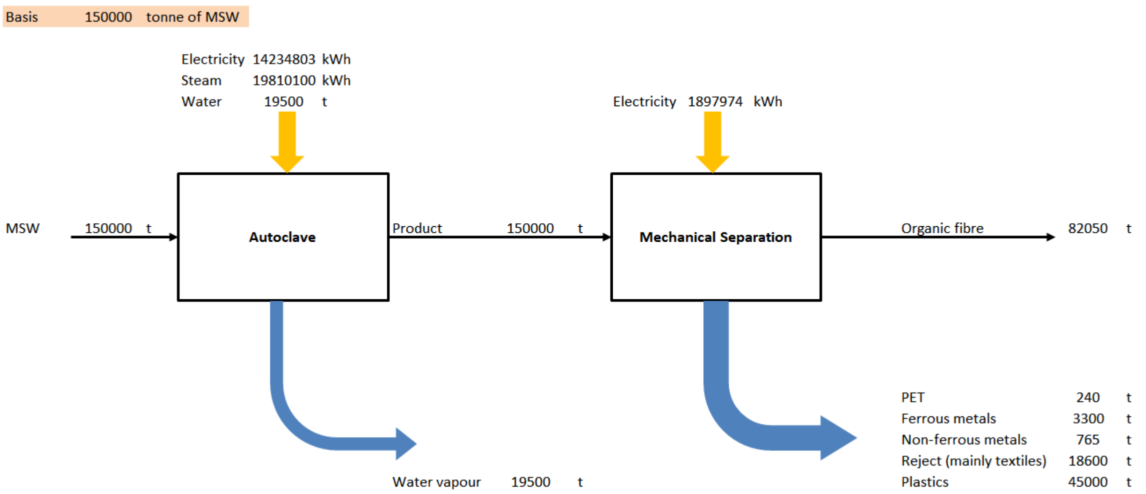

Figure 3: Mass and energy balances of an MHT plant for MSW treatment.

6.3 SCENARIOS

The current work presents 8 scenarios which are relevant to (a) the potential market application and upgrading of fibres from MSW (Base case, BAU1, BAU2, Upgrade 1, Upgrade 2 and Upgrade 3); (b) the potential of using waste materials other than MSW to produce fibres (Waste Substitute 1) and (c) the potential of using fibre instead of digestate for landspreading (Waste Substitute 2), summarised in Table 1.

Table 1: List of scenarios.

Scenario	*Description*
Base case	No market for fibre and hence it is disposed to landfill.
BAU1	Business-as-usual case 1: Fibre is converted into Torrefied Biomass Fuel Pellets (TBFP) and sold to the market.
BAU2	Business-as-usual case 2: Fibre is converted into TBFP and then used as fuel in combustion with CHP on site.
Upgrade 1	Fibre is upgraded to marketable compost-like output (CLO).
Upgrade 2	Fibre is upgraded to marketable digestate.
Upgrade 3	Fibre is converted to butanol, acetone and ethanol.
Waste substitute 1	Compost oversize as a substitute for MSW in producing fibres.
Waste substitute 2	Fibres are used for landspreading instead of digestate.

Methodology: The stream value approach has been adopted for analysing the economic feasibility of each scenario. The scenario analysis using this approach only considers the values of input and output streams, including feedstock, utility and products. The approach considers the trade-off between the cost and revenue of streams to obtain initial insights into the systems. This approach is useful for preliminary analysis and comparison of a series of scenarios. Detailed economic analysis considering capital (e.g. equipment etc.) and operating costs (e.g. personnel, maintenance etc.) is beyond the scope of the present analysis but it is desirable in future work. It should be reminded that the results from the analysis should be treated with caution due to the inherent subjectivity in the assumptions being made.

6.3.1 Base Case: No market for fibre and hence it is disposed to landfill

The base case scenario assumes that there is no market for the organic fibres from MSW and hence it is disposed of to landfill. Table 2 presents the stream value analysis of the Base Case. Cost for electricity consumption for the autoclave and mechanical separation processes has been estimated based on the energy balance in Figure 3. Landfill gate fees have been accounted for the organic fibre and rejects that are sent to the landfill. PET, ferrous and non-ferrous metals and plastics are sold to recycling facilities. The MHT facility receives gate fees for treating MSW. ***Based on the stream value analysis, revenue of £7.2 million/y is attainable for MSW treatment using MHT facilities, even with a disposal of 82050 tonne/y of organic fibres to the landfill.***

Table 2: Stream value analysis of Base Case.

Component	Price or cost (£/tonne or £/kWh)	Mass flow or energy flow (tonne/y or kWh/y)	Revenue or cost (£/y)
Utility cost			
Electricity (autoclave and mechanical separation)	-0.0816	16132776.35	-1316434.55
Product prices			
Organic fibre (to landfill)	-119.0	82050	-9763950
PET	90.0	240	21600
Ferrous metals	90.0	3300	297000
Non-ferrous metals	1433.3	765	1096500
Plastics	30.0	45000	1350000
External costs / Disposal costs / gate fees			
Rejects to landfill	-119.0	18600	-2213400
MHT	118.0	150000	17700000
Total			**7171315.45**

6.3.2 BAU1: Fibre is converted into TBFP and sold to the market

This business-as-usual case assumes that the organic fibre from MSW is converted into Torrefied Biomass Fuel Pellets (TBFP), which is obtained from fibre after drying, pelletisation, further drying and torrefaction, and then being sold to the market.

The net calorific value of the organic fibre is assumed to be 16.46 MJ/kg [2]. The total energy (electricity) requirement for the conversion of organic fibre into TBFP is 96.8 GWh, presented in Table 3 where it is estimated using the data given in [2].

Table 3: Energy balance for the production of TBFP from 82050 tonne of organic fibres.

Drying - first stage drying, pre-pelletisation	33391095.241	kWh
Pelletisation	3001446.763	kWh
Drying - second stage drying, post-pelletisation	15382414.661	kWh
Torrefaction	45021701.448	kWh
Total	**96796658.11**	**kWh**

Table 4 presents the stream value analysis of the BAU1 case. 82050 tonne/y of TBFP (assuming no loss of fibre in the conversion process to TBFP) is sold to the market at the price of £70 per tonne of TBFP [2]. The cost of electricity for preparing TBFP has also been accounted based on the results in Table 3. Other utility costs, product revenues, and gate fees are identical to the Base Case presented in **Error! Reference source not found.** 2. ***Based on the stream value analysis, revenue of £14.8 million/y is attainable for MSW treatment using MHT facilities, with 82050 tonne/y of organic fibres sold to the market as product. This case has shown a two-fold of revenue compared to the base case, however this is subjected to the market value of the organic fibres.***

Table 4: Stream value analysis of BAU1 case.

Component	Price or cost (£/tonne or £/kWh)	Mass flow or energy flow (tonne/y or kWh/y)	Revenue or cost (£/y)
Utility cost			
Electricity (autoclave and mechanical separation)	-0.0816	16132776.35	-1316434.55
Electricity (TBFP production from fibre)	-0.0816	96796658.11	-7898607.302
Product prices			
Organic fibre (sold as TBFP)	70.0	82050	5743500
PET	90.0	240	21600
Ferrous metals	90.0	3300	297000
Non-ferrous metals	1433.3	765	1096500
Plastics	30.0	45000	1350000
External costs / Disposal costs / gate fees			
Rejects to landfill	-119.0	18600	-2213400
MHT	118.0	150000	17700000
Total			**14780158.15**

6.3.3 BAU2: Fibre converted into TBFP and used as fuel in combustion with CHP on-site

This business-as-usual case assumes that the organic fibre from MSW is converted into TBFP, and then being used as fuel in combustion with CHP on site.

The energy balance for TBFP is the same as in Table 3. The cost and revenue analysis in this case, presented in Table 5, is similar to the BAU1 case presented in Table 4, except that the value of organic fibre is zero since it is generated and used on site and surplus electricity is generated through boiler and CHP using TBFP. It has been assumed that the boiler and CHP system has an efficiency of 30% [3] based on the net calorific value of 82050 tonne/y of TBFP, hence 112.55 GWh of electricity is generated. ***Based on the stream value analysis (Table 5), revenue of £18.2 million/y is attainable for MSW treatment using MHT facilities, with 82050 tonne/y of organic fibres (TBFP) used as fuel for electricity generation. This case has shown a 23% increase in revenue compared to BAU1 case, mainly attributed to the revenue obtained from exporting surplus electricity. However, it should be noted that the capital and operating costs for the boiler and CHP unit have not been accounted.***

Table 5: Stream value analysis of BAU2 case.

Component	Price or cost (£/tonne or £/kWh)	Mass flow or energy flow (tonne/y or kWh/y)	Revenue or cost (£/y)
Utility cost			
Electricity (autoclave and mechanical separation)	-0.0816	16132776.35	-1316434.55
Electricity (TBFP production from fibre)	-0.0816	96796658.11	-7898607.302
Product prices			
Organic fibre (TBFP used as fuel in boiler and CHP)	0.0	82050	0
PET	90.0	240	21600
Ferrous metals	90.0	3300	297000
Non-ferrous metals	1433.3	765	1096500
Plastics	30.0	45000	1350000
Electricity (generated from boiler and CHP using TBFP)	0.0816	112554253.6	9184427.1
External costs / Disposal costs / gate fees			
Rejects to landfill	-119.0	18600	-2213400
MHT	118.0	150000	17700000
Total			**18221085.24**

6.3.4 Upgrade 1: Fibre is upgraded to marketable compost-like output

This scenario assumes that the organic fibre from MSW is upgraded to compost-like output (CLO) through open windrows composting process. It has been assumed that the CLO is a marketable product and has met the associated regulations. In contrast to the BAU cases, the organic fibre does not need to be converted into TBFP prior to composting process.

Table 6 presents the stream value analysis of Upgrade 1 case. In this case, the electricity requirement for composting, the market value of compost and the corresponding gate fees for composting have been considered. The electricity consumption of the composting process is taken to be at 9.14 kWh/t of fibre [4]. It has been assumed that a yield of 58.9% (48302.8 tonnes/y) of compost can be achieved from 82050 tonnes/year of fibres [4]. ***Based on the stream value analysis, revenue of £20.7 million/y is attainable for MSW treatment using MHT facilities, with 82050 tonne/y of organic fibres converted into 48302.8 tonne/y of compost. This case has shown a 13.8% increase in revenue compared to BAU2 case. This is attributed to the lower cost of electricity requirement compared to BAU2 case, and higher revenue is obtained through selling compost as a product and the incentives from the gate fees for composting. However, it should be noted that the capital and operating costs for the composting process have not been accounted.***

Table 6: Stream value analysis of Upgrade 1 case.

Component	Price or cost (£/tonne or £/kWh)	Mass flow or energy flow (tonne/y or kWh/y)	Revenue or cost (£/y)
Utility cost			
Electricity (autoclave and mechanical separation)	-0.0816	16132776.35	-1316434.55
Electricity (composting of fibre)	-0.0816	750000	-61200
Product prices			
Organic fibre	0.0	82050	0
PET	90.0	240	21600
Ferrous metals	90.0	3300	297000
Non-ferrous metals	1433.3	765	1096500
Plastics	30.0	45000	1350000
Compost	24	48302.835	1159268.0
External costs / Disposal costs / gate fees			
Rejects to landfill	-119.0	18600	-2213400
MHT	118.0	150000	17700000
Composting	33.0	82050	2707650
Total			**20740983.49**

6.3.5 Upgrade 2: Fibre is upgraded to marketable digestate

This scenario assumes that the organic fibre is used in producing digestate and electricity through an anaerobic digestate (AD) and CHP processes, using organic fibre from MSW as the feedstock. It has been assumed that the digestate is a marketable product and has met the associated regulations. In contrast to the BAU cases, the organic fibre does not need to be converted into TBFP prior to AD process. In this case, the electricity requirement for AD (imported from the grid), electricity generated from biogas CHP (exported to the grid), the market value of digestate and the corresponding gate fees for AD have been considered.

The electricity generation and utilisation in the AD process is summarised in Table 7**Error! Reference source not found.**, derived from [4]. It has also been assumed that a yield of 56.86% (46653.6 tonnes/y) of digestate can be achieved from 82050 tonnes/year of fibres [4].

Table 7: Energy balance of electricity generation and utilisation in AD process, using organic fibres from MSW as the feedstock.

Electricity required for AD	96.89	kWh/t of fibre
Electricity generated from biogas	276.05	kWh/t of fibre
Electricity supplied from the grid to AD (import)	32.91	kWh/t of fibre
Electricity supplied from self-generation	63.99	kWh/t of fibre
Net electricity generation (export)	212.07	kWh/t of fibre

Table 8 presents the stream value analysis of Upgrade 2 case. ***Based on the stream value analysis, revenue of £21.7 million/y is attainable for MSW treatment using MHT facilities, with 82050 tonne/y of organic fibres converted to 46653.6 tonne/y of digestate. This case has shown a marginally 5% increase in revenue compared to Upgrade 1 case. This is***

attributed to the additional electricity generated from biogas CHP. However, it should be noted that the capital and operating costs for AD and CHP have not been accounted.

Table 8: Stream value analysis of Upgrade 2 case.

Component	Price or cost (£/tonne or £/kWh)	Mass flow or energy flow (tonne/y or kWh/y)	Revenue or cost (£/y)
Utility cost			
Electricity (autoclave and mechanical separation)	-0.0816	16132776.35	-1316434.55
Electricity (anaerobic digestion)	-0.0816	2700000	-220320
Product prices			
Organic fibre	0.0	82050	0
PET	90.0	240	21600
Ferrous metals	90.0	3300	297000
Non-ferrous metals	1433.3	765	1096500
Plastics	30.0	45000	1350000
Digestate	20	46653.63	933072.6
Electricity from biogas CHP	0.0816	17400000	1419840.0
External costs / Disposal costs / gate fees			
Rejects to landfill	-119.0	18600	-2213400
MHT	118.0	150000	17700000
Anaerobic digestion	32.5	82050	2666625
Total			**21734483.05**

6.3.6 Upgrade 3: Fibre is converted to butanol, acetone and ethanol

This scenario assumes that the organic fibre is converted into acetone, butanol and ethanol (ABE) through a biochemical process (fermentation). The yields of acetone (0.0424 t/t biomass), butanol (0.109 t/t biomass) and ethanol (0.03 t/t biomass) have been derived based on an ABE process using corn stover as the feedstock [5]. It has been assumed that the energy requirement in the ABE process is completely satisfied by the electricity generated from the on-site CHP system, and there is zero net electricity generation (i.e. no export of electricity).

Table 9 presents the stream value analysis of Upgrade 3 case. ***Based on the stream value analysis, revenue of £32.7 million/y is attainable for MSW treatment using MHT facilities, with 82050 tonne/y of organic fibres converted to 8984 tonne/y of butanol, 3478 tonne/y of acetone and 2450 tonne/y of ethanol. This case has shown the highest revenue among the three Upgrade cases. This is attributed to the high market values of acetone, butanol and ethanol as compared to compost and digestate. However, it should be noted that the capital and operating costs for the ABE process have not been accounted.***

Table 9: Stream value analysis of Upgrade 3 case.

Component	Price or cost (£/tonne or £/kWh)	Mass flow or energy flow (tonne/y or kWh/y)	Revenue or cost (£/y)
Utility cost			
Electricity (autoclave and mechanical separation)	-0.0816	16132776.35	-1316434.55
Product prices			
Organic fibre	0.0	82050	0
PET	90.0	240	21600
Ferrous metals	90.0	3300	297000
Non-ferrous metals	1433.3	765	1096500
Plastics	30.0	45000	1350000
Acetone	732.6	3478.2636	2548175.913
Butanol	1311.1	8984.035446	11778762.24
Ethanol	569.8	2450.312483	1396188.053
External costs / Disposal costs / gate fees			
Rejects to landfill	-119.0	18600	-2213400
MHT	118.0	150000	17700000
Total			**32658391.66**

6.3.7 Waste Substitute 1: Compost oversize as a substitute for MSW in producing fibres

This scenario assumes that compost oversize can be fed in the same way as MSW into the autoclave and MHT to produce organic fibres. Experimental studies have been done for MSW derived fibre by Garcia and co-workers [1], and the composition (normalised value) is shown in Table 10. The idea of this analysis is to predict the fibre quality derived from compost oversize. There is no literature or experimental studies carried out to date, so a linear extrapolation method is used for such prediction. The fibre derived from compost oversize has similar organic (94.6%), metals (0.17%) and plastics (2.84%) compared to the fibre from MSW, and there is no textile fraction. Glass does not appear in the analysis of fibre from compost oversize, however there might be a possibility of inclusion in the “Others” fraction. ***It has been hypothesised that the waste feedstock quality would have an impact on the fibre quality after autoclave and mechanical treatment, and thus would affect the market value of the fibre. Although there is no true market value for organic fibre to date (i.e. the application and upgrading methods of fibre is still under development), the variation of its value should not be significant as it can be seen from the predicted composition of fibre from compost oversize. However, this analysis has not taken into account the detailed analysis of contaminant (e.g. in the “Others” categories) which might have an impact on the market value.***

Table 10: Prediction of fibre quality from compost oversize based on the analysis of MSW case.

Component	Feedstock composition (wt%)		Fibre composition (wt%)	
	MSW [1]	Compost oversize [2]	Fibre from MSW [1]	Fibre from compost oversize (Predicted value)
Organics	64.80	65.38	93.75	94.60
Glass	5.12	0.00	1.53	0.00
Metals	2.80	2.44	0.20	0.17
Plastics	17.01	13.14	3.68	2.84
Textiles	3.18	0.00	0.00	0.00
Other	7.11	19.04	0.84	2.25

6.3.8 Waste Substitute 2: Fibres are used for land spreading instead of digestate

This scenario assumes that fibres are used for landscaping purposes as a substitute for digestate. The organic fibres can potentially be used for landscaping if it is mixed with microbes [6]. This is because the autoclave process has eliminated most of the microbes and the biological process will not be effective when the fibre is used for landscaping [6]. This also implies that organic fibre has to be processed either through composting or AD before it can be used for landspreading [6]. The CLO and digestate are considered as waste and will need to be comply with the Environmental Permitting regulations, the Compost Quality Protocol (CQP) and Anaerobic Digestion Quality Protocol (ADQP) [6,7].

In this scenario, the transportation cost of compost and digestate, assumed here as £3 per tonne of compost/digestate for 10 miles delivery plus £40-80 tonnes per hour for a hauled load, can be significant due to the high moisture content and bulky nature of the compost and digestate [7]. The cost of landspreading should also be considered and an average of £3.50 per tonne of compost/digestate is assumed [7]. A summary of transportation and spreading costs are summarised in Table 12 using the estimated amount of compost (48302.8 tonne/y) and digestate (46653.6 tonne/y) in Upgrade 1 and Upgrade 2 cases, respectively. ***Based on the transporting and spreading costs analysis, a total cost of £0.3 million/y + 40-80 £/h is incurred for both compost and digestate, derived from 82050 tonne/y of organic fibre.***

Table 11: Approximate cost for transporting and spreading compost or digestate.

Category of cost	Compost	Digestate
Cost for a hauled load (£/h)	40 - 80 depending on the number of hours	
Cost for 10 miles delivery (£/y)	144908.5	139960.9
Cost for spreading (£/y)	169059.9	163287.7

7 FURTHER RESEARCH

This report has shown that the adoption of MHT faces various challenges in the UK, including financial challenges due to high risk of deploying the technology, prevalence of serious accidents, uncertain end-markets for recovered fibres, and potential local opposition to planning consent. The economic analyses suggested that fibre converted to butanol, acetone and ethanol presents the best option to increase commercial returns under the current conditions.

Organic fibres have a wide range of potential applications and can achieve higher market value, subject to appropriate upgrading methods. Other potential uses of fibres include mixing with crushed shale and a resin to manufacture products (e.g. composite such as floor tiles), mixing with cement to produce building products, and washing the fibre to extract the long cellulose fibres suitable for paper-making or as insulation materials. These applications have not been covered in the present report but it is worth investigating in future works.

Another way of achieving higher value applications of the recovered fibres may be through the processing of segregated waste streams such as coffee cups. In theory this could result in a fibre of higher quality with more consistent characteristics. Instead of the current use of recovered fibres in energy applications, fibres recovered from a segregated waste stream of coffee cups could potentially be recycled back into new coffee cups, furniture and non-bearing construction materials. The additional benefit could be that the plastics recovered from coffee cups may be suitable for application in composite construction materials. In this way all materials in the coffee cups could be recovered, thereby achieving a higher aggregated recycling rate. The feasibility of these applications requires further research.

The separation of coffee cups from a mixed waste stream is likely to be associated with higher costs. These additional costs need to be offset by a sufficiently higher value generated through the application of fibres and polymers in components, when compared to the use of fibres recovered from MSW in energy applications. This involves market analysis in conjunction with investigating consumer acceptance and an insight into the technical characteristics required for materials used in potential end-markets (such as coffee cups-, furniture-, and construction materials manufacturing).

The technical characteristics of the recovered fibre and polymer from coffee cups via the autoclave system need to be analysed, in comparison to fibres and polymers recovered from MSW. This should include analysis of potential yields of fibre and polymer, tests regarding the suitability for energy applications such as calorific value and biogenic- and non-biogenic content of fibres, full analysis of ash content including trace metals, analysis of the types of polymers recovered from coffee cups, and fibre characteristics such as length and strength.

If there is a match between the technical characteristics of the recovered fibres and polymers and the materials in demand for the production of new components and products, then a detailed assessment of economic, environmental, social and technical values should be carried out to identify the optimum upgrading method and utilisation of the recovered resources. The Complex Value Optimisation for Resource Recovery (CVORR) approach can be applied[29] to assess which values are created and destructed along the supply chain.

The outcomes of the sustainability assessment with the CVORR approach can be used in the formulation of business models and in conversations with potential investors and regulators such as the Environment Agency in England. Moreover, disposable packaging such as coffee cups has been recognised as a particular issue in the UK[30,31]. Insight into the economic, social, environmental and technical costs and benefits of potential solutions ranging from waste prevention to recycling and energy recovery can support government decision-making on selecting the solution to the coffee cup problem that presents the best values for the UK.

29 https://www.sciencedirect.com/science/article/pii/S0959652617319893

30 https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/657/657.pdf

31 http://www.bbc.co.uk/news/business-42564948

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APPENDIX A: MHT INFRASTRUCTURE TIMELINE

Report	Plant	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Notes
Defra 2007 report	Estech[1] 100,000 t*	Planning submitted	Planning permission granted	Legal disputes with local groups Issues with waste supply contract	Planning permission granted again	Plans scrapped										The council decided to contract their waste to an EfW as they are proven/less risky, output less residual, and there are uncertainties about end markets for autoclave's recovered resources
Defra 2007 report; Defra 2013 report	Sterecycle Rotherham[2] 100,000 t			Project announced Funding secured	Planning permission granted	Plant opens	Plans to double capacity announced		Capacity increased 75% Explosion at plant	Financial difficulties, company enters administration & closes shortly afterwards						Financial difficulties arose due to volatile prices of plastics and metals, lack of an end market for the fibre (it was being given away), and expensive odour problems at the plant. Councils immediately arranged supply contracts with a local EfW plant
	Sterecycle Essex 240,000 t			Projects announced				Planning permission granted								
	Sterecycle S.Wales 240,000 t															
	Orchid Environment Merseyside[3] 80,000 t				DEFRA technology demonstrator funding secures planning	Plant opens Fire at site				Plant Shuts			Plant reopens			Company made big promises for big plants in the UK but they never materialised. They then attempted to move into foreign markets instead, and only continue to

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Notes
Orchid Environment London 160,000 t					Projects announced			Funding secured from London Waste Board		Plans scrapped					operate the DEFRA subsidised demonstrator plant
Orchid Environment N.Wales 160,000 t															
Graphite Resources North East[4] 320,000 t		Planning permission granted			Construction begins		Waste supply contract secured Plant opens			Mothballed due to financing issues			Plant reopens		Financing issues were partly caused by an odour problem. Securing finance to reopen was difficult due to, in the new investors words, the *complex and niche* nature of the plant and thus the perceived risks
Shanks /Babcock[5] 145,000 t							Planning announced			Panning permission granted; finance and waste supply contract secured		Plant opens			This was a very integrated and connected planning process and the result appears to have been resilient and successful
Aero Thermal[6] 75,000 t								Planning permission granted		Opening date announced					There have been promises of a plant being built but so far only research appears to have been carried out

*These values are in t of MSW treated per year

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APPENDIX B: BASIS FOR MSW COLLECTION AND TRANSPORTATION COSTS

Basis	10000	t/y MSW	(for Wilson case)
Lifetime of system	25	years	

Basis: (Estimated based on Doncaster centre region. Manipulated variables are in blue font while the rest are calculated values.)

Parameter	Value	Unit	Note
Truck loading capacity	26	t/truck	Mercedes Atego. Ref [1].
Average waste to be transported per day	27.4	t/d	This is estimated by dividing the total MSW to be processed by 365 days a year.
Number of rounds of transporting per day	2	rounds/d	This is an assumption.
Amount of waste transported per truck per day	52	t/truck-d	Estimated based on number of rounds of one unit of truck loading capacity.
Number of trucks needed	1	truck	Estimated by dividing the amount of waste to be transported per day by amount of waste transported per truck per day
Distance (single trip)	10	miles/single-trip	This is an assumption.
Distance (round trip)	20	miles/round-trip	Assuming the truck is travelling from the source to destination and return to the same source.
Total distance travelled per truck per day	40	miles/d	
Total distance travelled for all trucks per day	40	miles/d	
Total distance travelled for all trucks per year	14600	miles/year	This is a conservative estimate based on daily collection.
Number of refuse collectors per truck	2	persons	Estimation.
Total number of refuse collectors needed	2	persons	Assuming the same set of personnel working in each truck and each round for the whole year.

a) Diesel use

Parameter	Value	Unit	Note
Fuel consumption	0.4545	L/miles	Ref [1]. 10 mpg = 0.22 miles/litre.
Total fuel use	6635.7	L/y	
Unit cost of fuel	1.2059	£/L	
Total cost of fuel per year	8001.99	£/y	

b) Capital cost

Equipment	Cost per unit	Unit	Number of pieces of equipment	Unit	Cost (£)	Note
Truck (Refuse collection vehicle)	130000	£/unit	1	piece	130000.00	Cost per unit of truck obtained from Ref [2].

c) Personnel cost

Personnel	Number of personnel	£/person-y	Cost per year (£/y)	Note
Refuse collector	2	20000	40000	Average salary of refuse collector was taken from the National Career Service (https://nationalcareersservice.direct.gov.uk/job-profiles/refuse-collector)

d) Maintenance cost

Equipment	Replacement cost per unit (£/unit)	Lifetime (years)	Unit	No. of times of equipment replacement	Cost (£)	Note
Truck (Refuse collection vehicle)	130000	6	years	4	520000	Lifetime of vehicle obtained from Ref [2].

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Appendix C: Prices of digestate based on substitute products

1.3 Substitute materials

33 Digestate has two primary substitute products – soil conditioners (compost and mulches) and inorganic manufactured petroleum-based liquid fertiliser. Table 4 shows the current market values of these possible substitutes.

Table 4: Digestate substitutes and their associated market values [16, 26, 40]

Substitute	Example	Cost (£/ tonne)*	Cost (£/tonne) of active element (N, P K)
Fertiliser	Ammonium nitrate (NH_4NO_3)	133-199	378-568
	Phosphate (P_2O_5)	595–615	1,363–1,409
	Potash (K_2O)	235–245	283–295
	Sulphur	65–95	65–95
Agricultural and horticultural soil improver	PAS 100 compost	5–10	

* Given the diversity and volatility of the fertiliser market the range in these values is used later in the sensitivity analysis.

Ref [8]

APPENDIX D: PRICES OF SCRAP WASTE STREAMS FOR RECYCLING

Scrap waste	Prices (£/tonne)		Note
	min	max	
Plastics	10	50	Mixed plastics bottles, prices taken in October 2017 [1].
Aluminium can	950	1020	Baled or densified and strapped, prices taken in October 2017 [2].
Glass	4	12	Mixed glass, prices taken in October 2017 [3].
Metals (ferrous)	85	95	Light iron, prices taken in October 2017 [4].
Metals (non-ferrous)	550		Zinc mixed scrap, prices taken in October 2017 [5].
Metals (non-ferrous)	2500		Mixed brass, prices taken in October 2017 [5].
Metals (non-ferrous)	1250		Lead scrap, prices taken in October 2017 [5].

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