Towards Sustainable Energy and Fuels from Waste Pathways for the UK

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Abstract

Energy and Fuels from Municipal Solid Waste (MSW) and Commercial and Industrial (C&I) Waste can have an important role to play in the energy mix system and transition to the lower carbon economy towards the 2050 target. However, the co-existence of the Energy and Fuels from Waste (EfW) sector, the low carbon economy, and the circular economy (CE) are not obvious bedfellows. The EfW sector is seen by some stakeholders as an essential component of renewable energy policies, waste management policies and the development of sustainable integrated waste management systems. However, it also generates controversy among other stakeholders who see the sector as undermining the development of more sustainable waste management systems, the transition to a CE and lower carbon economy. Consequently, to date, there is still uncertainty about the long-term deployment strategy and role that the EfW sector can play in the national energy system and transition to a low carbon economy contributing towards UK net zero target by 2050. The aim of this thesis is to open up debate about the relative sustainability of six different EfW pathways; investigating the research question of *'How can energy and fuels from waste (EfW) technologies (Incineration, Gasification and Anaerobic Digestion) be integrated and contribute towards sustainable waste management and energy systems in the UK?'.* It does so by assessing and describing the perspectives and value-judgements of different stakeholders from UK Government departments, industry, academia and NGOs involved in the UK EfW sector. This research uses and further develops the elicitation approach called Multicriteria Mapping (MCM) to interview stakeholders, document and analyse their perspectives by gathering both qualitative and quantitative data around the relative sustainability of the six EfW pathways. The analysis brings to light the techno-economic, environmental, social and political uncertainties, divergent values and social priorities that shape the competing expectations of the sector and lead to differing conclusions about the sustainability and opportunities of waste management, EfW technologies and different energy outputs from EfW in the UK. The results show that there is potential for a symbiotic relationship between the EfW and waste management sectors and the CE, to help the UK achieve its net zero target by 2050. The thesis provides transparency on unresolved issues and existing barriers in the UK EfW sector, and on what the future opportunities of the EfW sector are according to the opinions of the stakeholder participants involved in the sector. A deeper understanding of these opportunities will lead to a better chance of EfW project deployment, and help the UK to develop a more sustainable and robust EfW sector, in line with sustainable waste management systems and the CE concept.

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List of Acronyms and Abbreviations

ACT	Advanced Conversion Technology
AD	Anaerobic Digestion
ATT	Advanced Thermal Technology
BAU	Business as Usual
BCS	Biofertiliser Certification Scheme
BEIS	Department for Business, Energy & Industrial Strategy
BMW	Biodegradable Municipal Waste
BSI PAS	British Standard Institution’s Publically Available Specification
CAPEX	Capital Cost
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CE	Circular Economy
CEWEP	Confederation of European Energy from Waste Plants
CfD	Contracts for Difference
CHP	Combined Heat and Power
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CV	Calorific Value
C&I	Commercial and Industrial
Decent AD HN	Decentralised Anaerobic Digestion for the decarbonisation of the heat sector
Decent AD TF	Decentralised Anaerobic Digestion for the decarbonisation of the transport sector
Decent Gasification HN	Decentralised Gasification for the decarbonisation of the heat sector
Decent Gasification TF	Decentralised Gasification for the decarbonisation of the transport sector
DEFRA	Department for Environment, Food & Rural Affairs
DfT	Department for Transport
DRS	Deposit Return Scheme
EA	Environment Agency

EfW	Energy and Fuels from Waste
EPR	Extended Producer Responsibility
ESA	Environmental Services Association
ETI	Energy Technologies Institute
EU	European Union
F4C	Future Fuels for Flight and Freight Competition
GHG	Greenhouse Gas
H_2	Hydrogen
HaFS	Hospitality and Food Service
HGV	Heavy Good Vehicles
ILUC	Indirect Land Use Change
LCA	Life Cycle Assessment
MCM	Multicriteria Mapping
MSW	Municipal Solid Waste
Mt	Million tonnes
MW	Megawatt
NGO	Non-Governmental Organisation
NIMBY	Not In My Back Yard
OPEX	Operational Cost
PFI	Private Finance Initiative
PM	Particulate Matter
R1	Energy Efficiency Criterion
RDF	Refuse Derived Fuel
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-Biological Origin
RHI	Renewable Heat Incentive
ROC	Renewable Obligation Certificates
RTFC	Renewable Transport Fuel Certificate
RTFO	Renewable Transport Fuel Obligation
RWS	Resources and Waste Strategy
TRL	Technology Readiness Level
TWh	Terawatt-hours

UK	United Kingdom
UKWIN	United Kingdom Without Incineration Network
WFD	Waste Framework Directive
WSR	Waste Shipments Regulations

Chapter 1. Introduction

The Paris Agreement adopted in 2015 (United Nations, 2015) aims to keep the global temperature rise well below 2°C, and contains the ambition to pursue efforts to limit the temperature increase even further to 1.5° C. While the exact amount of carbon emissions associated with global warming below a certain temperature threshold is uncertain, limiting global mean temperature increase at any level essentially requires global carbon emissions to become net zero by a certain point in the 21st century (IPCC, 2018). In June 2019, through the Climate Change Act, the UK became the first country to legislate for a legally binding net zero 2050 target (BEIS, 2019a; CCC, 2021). In the Climate Change Act, a set of "carbon budgets" which act as steppingstones towards the 2050 net zero target have been established. The first five carbon budgets have been legislated and run up until 2032. In December 2020, the UK Government announced an updated ambitious emissions target for 2030 (the fifth carbon budget), where rather than 57% reduction in greenhouse gas emissions (GHG) by 2030 compared to 1990 levels, the aim is now to achieve 68% reduction. The sixth carbon budget (2033 to 2037) with an emissions target of 78% reduction below 1990 levels by 2035 has been advised by the Committee on Climate Change (CCC), and is currently waiting for Government acceptance. This budget should be legislated by June 2021 by Parliament (CCC, 2021). The UK is currently on track with its third carbon budget period (2018 to 2022 with a target of 37% reduction below 1990 levels by 2020). According to the CCC (2021), in 2018 the UK emissions were 44% below 1990 levels. However, the UK is not on track to meet the fourth (2023 to 2027) or fifth (2028 to 2032) budgets. To meet upcoming carbon budgets and the net zero target by 2050, more challenging measures need to be introduced by the Government (CCC, 2021).

Reaching net-zero emissions in the UK will require all energy to be delivered in zero-carbon forms and to come from low carbon sources (CCC, 2019, 2020). Renewables such as wind, solar, hydrogen, nuclear, energy and fuels from waste (EfW) and biomass, with carbon capture and storage (CCS) represent critical options for the decarbonisation of the energy system (CCC, 2018, 2019, 2020; HM Government, 2020).

The UK energy in brief 2019 report from the Department for Business, Energy & Industrial Strategy (BEIS, 2019b) shows that the UK is on its way to achieving this net-zero objective. Results from the BEIS (2019b) report show that in 2018, about 19% of the total UK energy consumption came from low carbon sources, of which 7.4% was from biomass and wastes.

Biomass and wastes was the second largest component of low carbon source energy, after nuclear, accounting for the 37% of this total low carbon energy (BEIS, 2019b). According to the UK CCC (2018), EfW and biomass of relevance for this research, including wood waste and food waste (organic fraction of Municipal Solid Waste: MSW), could provide up to 15% of UK energy needs by 2050 (CCC, 2018). The CCC (2018) also highlights the important role of EfW technologies, such as gasification and AD, associated with CCS, for sequestering emission and for implementation in hard to decarbonise sectors such as heat and aviation, as well as for increasing recycling (CCC, 2018, 2019).

Energy and fuel recovery from MSW and Commercial and Industrial (C&I) waste, through thermochemical and biochemical conversion technologies, is seen as an essential component of renewable energy policies, waste management policies and the development of sustainable integrated waste management systems (Pan *et al.*, 2015; Malinauskaite *et al.*, 2017; DEFRA, 2018b; Ng *et al.*, 2019; Slorach *et al.*, 2019; Hussain *et al.*, 2020; Cross *et al.*, 2021). Underpinning the move to renewable sources for electricity generation, heat and in the transport sector, the production of EfW is seen as a potential element of the low carbon economy which could enable a cleaner, more sustainable and secure UK energy mix system (Jamasb and Nepal, 2010; DEFRA, 2011a, 2014, 2018b; BEIS, 2017b; Rhodes and Thair, 2017; Evans, 2017; CCC, 2018; DfT, 2018b; Ng *et al.*, 2019; Cross *et al.*, 2021).

Furthermore, provided that prevention, reuse, and recycling of waste are prioritized in the waste management cycle, turning waste into energy and fuels could be a key factor in the circular economy (CE) enabling the value of products, materials, and resources to be maintained on the market for as long as possible, minimising waste and resource use (Ellen MacArthur Foundation, 2014; Pan *et al.*, 2015; Malinauskaite *et al.*, 2017; DEFRA, 2018b; European Commission, 2018; Fagerström *et al.*, 2018; ERA, 2020; Hussain *et al.*, 2020). However, as ERA (2020) claims, EfW, low-carbon energy, and the CE are not immediately obvious bedfellows.

Ensuring the sustainability of waste supply chains towards a CE and the development of a low carbon economy, with an integrated sustainable development of the EfW sector, is a complex socio-technical issue and beyond the means of technical and financial solutions alone. There are multiple opportunities and barriers regarding the development of EfW technologies, which arise from political, technical, economic and social constraints (Thornley *et al.*, 2009; Welfle *et al.*, 2014a; Wright *et al.*, 2014; Waldheim, 2018). In recent years, the non-technical barriers have attained greater significance (Upham and Shackley, 2006;

Devine-Wright, 2009; Thornley and Prins, 2009; Purkus *et al.*, 2015; Cross *et al.*, 2021). Non-technical barriers are therefore also focused in this research.

The understanding of stakeholders perspectives plays an increasingly important role in achieving the sustainable development of supply chains (Thornley and Prins, 2009; Cross *et al.*, 2021). Direct and indirect stakeholders involved in the waste management and EfW sectors may perceive and value social, economic, technical and political opportunities and barriers differently (Devine-Wright, 2009; Upham *et al.*, 2009; Thornley and Gilbert, 2013; Cross *et al.*, 2021). Disagreement on opportunities and barriers, if not addressed on time, can result in not only public opposition towards EfW infrastructure, but also unsuitable points of departure from which inappropriate energy policies, waste management policies, waste management systems, and EfW systems, are then developed. Understanding reasons why different stakeholders agree and disagree with EfW pathways should help to inform policy decision-makers on the directions to take for achieving the development and deployment of sustainable EfW infrastructures, ensuring the sustainable integration of both the waste management and EfW sectors. Recognising and acknowledging stakeholder perceptions, attitudes, energy-related behaviours and practices is critical to achieving sustainability in energy decision-making.

There is growing amounts of literature endorsing and exploring the barriers and opportunities of the EfW sector, where emerging technologies are used to produce different energy outputs, such as electricity, heat, biofuels, chemicals and compost. However, despite broad agreement that EfW could make a significant contribution to waste management and energy policy goals, there are strong uncertainties and concerns about the feasibility, sustainable development, and robust energy transition that a future sustainable EfW market should pursue.

1.1 Aim and Research Questions

The overall research question is to investigate ‘How can energy and fuels from waste (EfW) technologies (Incineration, Gasification and Anaerobic Digestion) be integrated and contribute towards sustainable waste management and energy systems in the UK?’

The aim of this thesis is to open up debate about the relative sustainability of different EfW pathways by assessing the perspectives and value-judgments of different stakeholders and leading experts involved in the UK EfW sector. In this way, the thesis will make clear what interests, issues and uncertainties exist, bringing to light the technological uncertainties, divergent values and social priorities that shape competing expectations of the sector and lead to differing conclusions about the sustainability and opportunities of waste management, EfW technologies and energy outputs in the UK.

The thesis will answer the following research questions:

1) To what extent can Energy and Fuels from Waste pathways contribute towards more sustainable waste management systems?
2) To what extent can Energy and Fuels from Waste pathways contribute towards both more sustainable energy systems and achieving the UK´s net zero target?
3) What have been the contributions of using the Multicriteria Mapping (MCM) approach to explore stakeholder participants' perspectives on the sustainability of different Energy and Fuels from Waste pathways?

A comprehensive review of the literature has helped to design six pathways for responding to potential future pathways in the EfW sector in the UK. These pathways are the core of the investigation, around which the whole debate of this thesis takes place. A detailed explanation of the six pathways is provided in Chapter 3.

The project engages with a broad range of stakeholders and captures the technical, economic, environmental, social and political opportunities and barriers that different stakeholders perceive, value and prioritise for each of the pathways under appraisal. The project findings provide a comprehensive overview of the divergent stakeholder perspectives that bear upon decision making processes in the EfW sector. It brings transparency to unresolved issues and barriers for current project deployment, and leads to a better chance of success for the current projects, in addition to providing more knowledge on how to deploy future projects.

1.2 Thesis Structure

This thesis consists of eight chapters. Following this introduction, Chapter 2 reviews in more detail the current status of the waste management and EfW sectors in the UK. Drawing on academic literature and government reports, technical, environmental, economic, social and political opportunities and barriers associated with both the waste management and EfW sectors in the UK are highlighted. The chapter begins providing an introduction to the concept of the CE, and aims to highlight the role of the EfW sector within the concept. An overview of the waste management sector in the UK is then presented in the second section. It focusses on bringing to light the way in which the UK is managing waste, presenting both the main EU waste management policies, by which the UK is currently legislated, and also how the policies have been influencing the UK strategies of waste management, enabling development of the EfW sector. This section demonstrates the complexity of the EfW sector and how closely it intersects and depends on the waste management sector. The chapter then follows with an overview of the current status of the EfW sector in the UK. Technical and environmental opportunities and barriers associated with the different EfW technologies currently under debate for the decarbonisation of different sectors are identified. More complex social and political opportunities and barriers, which both drive and undermine development of the EfW sector in the UK are also highlighted.

Chapter 3 reports the research design and justifies the methods and processes used for the research. First, the selection of the Multicriteria Mapping (MCM) approach is justified and an overview of the MCM tool and its framing is presented. The methodological design is then presented, including elicitation, analysis, development of pathways for appraisal, and the adaptation of the MCM tool for the purposes of this research. The MCM process is explained with respect to participant scoping, recruitment, and conducting the interviews. Finally, the quantitative and qualitative methods of analysis used are described.

Chapter 4 is the first of the four chapters dedicated to analysis of the results of the MCM process. Here the criteria identified by participants are first analysed, resulting in three dimensions of sustainability: techno-economic, environmental, and social. Criteria related to each of these dimensions are further sub-divided into substantive 'issues' and weightings of criteria within each dimension are concluded. The chapter then provides an analysis of the final overall performance of the different pathways as perceived by participants.

Chapters 5, 6 and 7 are dedicated to the analysis and discussion of results of the MCM process. Each chapter is centred around the analysis of a sustainable dimension and associated identified issues. Chapter 5 considers the techno-economic dimension and issues, Chapter 6 the environmental dimension and issues and Chapter 7 the social dimension which encompasses social and political issues. Each chapter explores what the MCM process has shown about the sustainability of the six competing EfW pathways, by examining and discussing the most debated themes in participants' perspectives around the various issues of the techno-economic, environmental and social dimensions, respectively. Each chapter begins by identifying the dominant themes of the issues for the specific dimension under appraisal. The qualitative performance of each of the EfW pathways under each of the different themes, with the implications that emerged in participants' discussions, are then discussed.

Chapter 8 brings together the findings from the previous four chapters and presents conclusions and key insights from across the thesis. First an overview of the key findings and conclusions from Chapters 4, 5, 6 and 7 on the overall performance of the six core EfW pathways is presented to answer the main research question. The three research questions outlined in Chapter 1 are then addressed to further meet the research aim. The chapter concludes by discussing limitations of the research and future research directions.

Chapter 2. Literature Review

Introduction

This chapter describes a state of the art of the Energy and Fuels from Waste (EfW) sector in the UK. The EfW sector is a complex field interacting with multiple sectors, including the waste management sector. The aim of this literature review is to identify some of the opportunities for and also barriers inhibiting a sustainable development and deployment of the EfW sector in the UK, focusing on both technical and non-technical aspects.

Within the scope of this research, the feedstock materials of interest for energy and fuels recovery is Municipal Solid Waste (MSW), including Commercial and Industrial (C&I) waste. MSW is commonly known as refuse or rubbish and is a non-hazardous waste type consisting of everyday items that are discarded by the public. It covers household waste and household-like C&I (e.g., from offices or hotels) (DEFRA, 2014). It encompasses both recyclable materials such as plastics and papers, as well as residual waste from the ´black bag´. The residual waste is the waste that is left over when all the recycling possible has been done, and it is a mixture of different materials (DEFRA, 2014). Part of this residual waste will come from materials made from oil like plastics; other parts will originate from materials that are biodegradable – e.g. food, paper, wood etc. Consequently, materials of food and wood waste – which are organic material – can also be found in the residual waste of MSW and C&I waste streams (DEFRA, 2014; Letsrecycle, 2021). The availability of these feedstocks is directly linked to the industrial sector, such as the food, paper and plastics manufacturing sectors as well as the consumer sector. In the case of MSW, there is a clear relation between the income level and MSW generation of a country, i.e. as the income increases, the waste tends to have less organic content and more packaging material (Waldheim, 2018).

As MSW is generated across the domestic, C&I sectors, the EfW sector is closely related to the waste management sector. Front-end activities of production, segregation, sorting and processing of the waste streams as well as the other valorisation alternatives, such as exports, have a strong impact on the availability of these feedstocks for use in energy and fuels recovery. Consequently, this first chapter includes an overview of the waste management in the UK.

This literature review is divided into three sections. It first provides an introduction to the concept of the circular economy (CE), and aims to highlight the role of the EfW sector within this concept. The second section provides an overview of the waste management sector in the UK, and how the different political and market forces have been driving UK waste management decisions and consequently the EfW sector development in the UK. Drawing on academic literature and government reports, the technological, economic, social, environmental and political opportunities and barriers associated with the waste management sector in the UK are also highlighted. The third section aims to cover the current status of the EfW sector in the UK, to understand the technical, economic and environmental opportunities and barriers associated with the different technologies. Non-technical opportunities and barriers associated with social and political concerns are also identified, with an impact on the implementation and deployment of the EfW sector.

2.1 Circular Economy

The CE concept promotes the idea that instead of following a traditional linear economy of make, use and dispose of a material, the object is used as long as possible to optimize its value and, at the end of its lifetime, the material is recovered to generate new products (Ellen MacArthur Foundation, 2014). Figure 2.1 below shows the two material flows involved in the CE. The biological materials are those that are redesigned to re-enter in the circle; the technical materials are those helping to circulate and recirculate the biological nutrients. Both types of materials can, as the figure shows, return to the ecosystem. 'The CE is a system that is restorative by design' (Ellen MacArthur Foundation, 2014). This suggests that waste can be used as resources and should be conserved in a loop with the aim of reducing the use of raw materials and energy, and reducing the environmental burden associated with the extraction, production, consumption and disposal of materials. CE is thus a way to complement the waste hierarchy but with economic profitability.

In the present context, the circularity nature would mean that the current linear material economy of extraction-production-consumption-disposal pattern is reconfigured into a loop by returning the valuable fractions embedded in the waste streams into useful products such as energy and fuels that can be consumed.

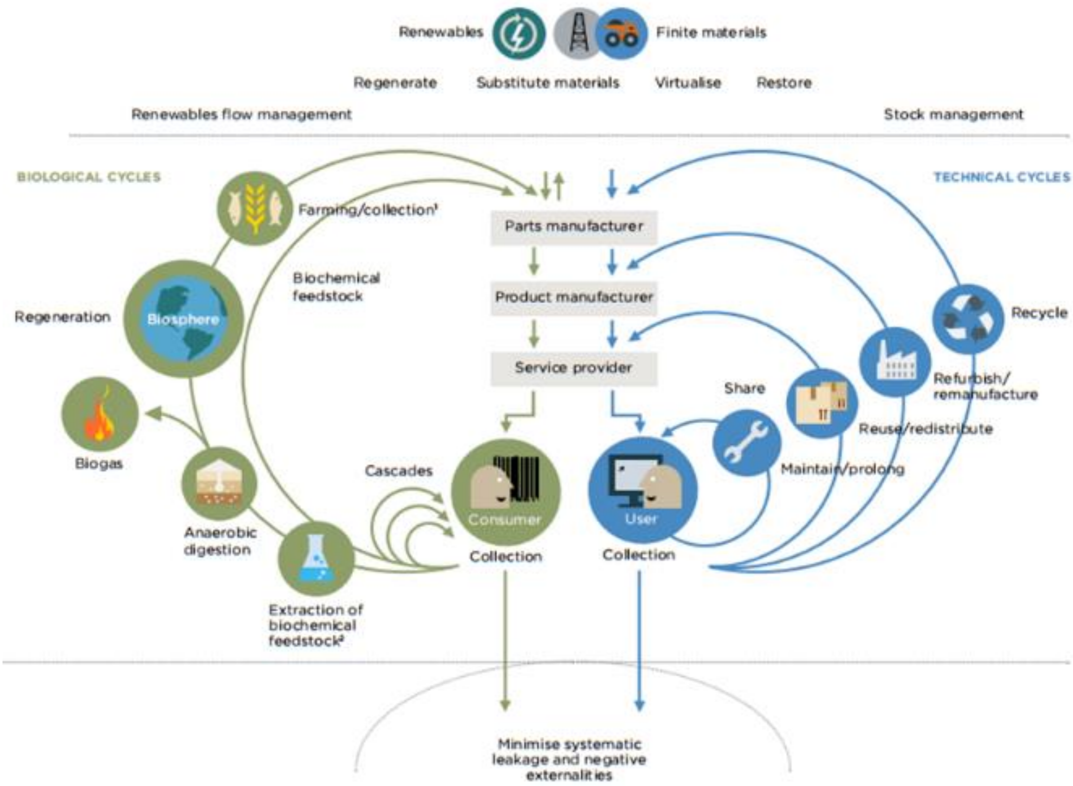

Figure 2.1. Circular Economy Diagram. Source: (Ellen MacArthur Foundation, 2014)

Whilst the CE idea is not new and it has been in academic literature for over 50 years (ERA, 2020), it has recently been adopted by the UK Government for implementation. The European Commission states: ‘It is only by respecting the waste hierarchy that waste-to-energy can maximise the circular economy's contribution to decarbonisation, in line with the Energy Union Strategy and the Paris agreement’ (European Commission, 2018, p.10). In other words, and as mentioned by Malinauskaite *et al.* (2017), provided that prevention, reuse, and recycling are prioritized in the waste management system, waste could play an important role in a circular economy. In 2018, the UK Government launched its Resources and Waste Strategy (RWS) which committed to move towards a CE. For this purpose, the RWS has set the priority overarching targets of zero avoidable waste by 2050, double resource efficiency by 2050, zero plastic waste by 2042, and zero food waste to landfill by 2030 (DEFRA, 2018b). The strategy concludes that EfW can play a role in achieving those targets and in the transition to a CE. This view, however, is not shared by some NGOs, such as United Kingdom Without Incineration (UKWIN) and Zero Waste Europe (Zero Waste Europe, 2016; UKWIN, 2021). Zero Waste Europe (2016) declares that conceptually speaking EfW does not have a place in the CE as the material loops are closed when “there is nothing left to burn”. Yet, this conclusion is made solely in the context of energy from waste via incineration.

The CE is opening the opportunity for the EfW sector to simultaneously address important concerns of energy demand, greenhouse gas emissions (GHG), waste management, resource efficiency and energy recovery. However, for this to happen, the current ‘linear’ economy, in which resources are extracted, turned into products, used once and then disposed or sent abroad, must be replaced. According to the RWS, growth in EfW and alternative residual waste treatment infrastructure will divert further waste from landfill, increase recycling and increase resource-efficiency (DEFRA, 2018b). However, as ERA (2020) states, the co-existence of EfW, the low carbon economy and the CE are not obvious bedfellows. An aim of this thesis is to contribute and extend current knowledge of this complex “jigsaw” (ERA, 2020) which the EfW sector in the UK has become, and to show that there is potential for a symbiotic relationship between them to help the UK achieve its net zero target by 2050.

2.2 Overview of the UK Waste Management Sector

2.2.1 EU Regulatory Framework and UK Waste Policy

As a result of the UK’s exit from the EU, officially consummated on January 31st 2020, new European environmental directives will no longer be transposed into UK law. Consequently, to retain the nature of the existing legislation, the UK has been developing its own plans and strategies in handling waste. Many of these remain in accordance with the provisions in the legislative frameworks of EU. It is therefore important to provide information on relevant policies at both a European and national level.

Over the years, the UK waste management policies have been influenced by a range of legislations from the EU. The most relevant policies and related targets for MSW and C&I waste are the 2008 Waste Framework Directive (WFD) that sets the target for recycling and preparing for reuse, and the Landfill Directive from 1999 that sets the landfill diversion targets for biodegradable municipal waste. Additionally, the 2006 Waste Shipment Regulation comprises a set of rules to supervise and control transboundary shipments and movements of hazardous waste and disposal between countries.

The EU WFD provides a set of legislations for waste prevention, collection, transport, recovery and disposal. The “waste hierarchy” is at the core of the strategy of the WFD (Figure 2.2). It encompasses a set of priorities for managing waste in the most suitable way. In theory, the prevention of all waste would be possible. However, due to practical, economic, political and social reasons, this does not happen. Hence, the waste hierarchy is useful for implementing more sustainable waste management practices in order to minimise the amount of waste generated. First of all, the generation of waste material should be prevented; if that is not possible and waste is unavoidable then try to re-use it; and if not, try to recycle it. Finally, when recycling is not possible, residual waste should go to energy recovery or, as a final resort, to landfill or incineration without energy recovery (European Commission, 2008; DEFRA, 2011b). Waste management is a devolved matter in the UK, and each administration is responsible for the development of its own waste strategy. The waste hierarchy has been incorporated into the UK legal framework through the Waste (England and Wales) Regulations 2011, the Waste Regulations (Northern Ireland) 2011, and the Waste (Scotland) Regulations 2012. With the aim of bringing current waste management policies under the same umbrella of one national plan, and to move relevant information of the WFD, and other EU policies into the UK Waste Regulatory Framework after Brexit, DEFRA published the Waste Management Plan for England (DEFRA, 2021b) in January 2021. The Plan, together with the policies to which it refers, is intended to deliver the objectives set out in the Waste (England and Wales) Regulations 2011, while also integrating the plans set out by the RWS, on moving England to a CE, and those set out in the 25 Year Environment Plan (HM Government, 2018), committing to leave the environment in a better state than we found it. In 2019, as a way of embedding EU waste management legislation targets into UK legislation, the Environment Bill was introduced to Parliament to fill the gap that would be left with new environmental legislature once the UK had left the EU (DEFRA, 2021b). Under the Environment Bill, currently on its passage through parliament, long-term legally-binding environmental targets, including resource efficiency and waste reduction, are being set. The targets set out in the UK´s own CE Package encompassed the targets of the Environment Bill, which includes the UK requirement to meet a minimum of 50% and 65% recycling targets of household waste by 2020 and 2035 respectively (DEFRA, 2020, 2021b; Letsrecycle, 2020b).

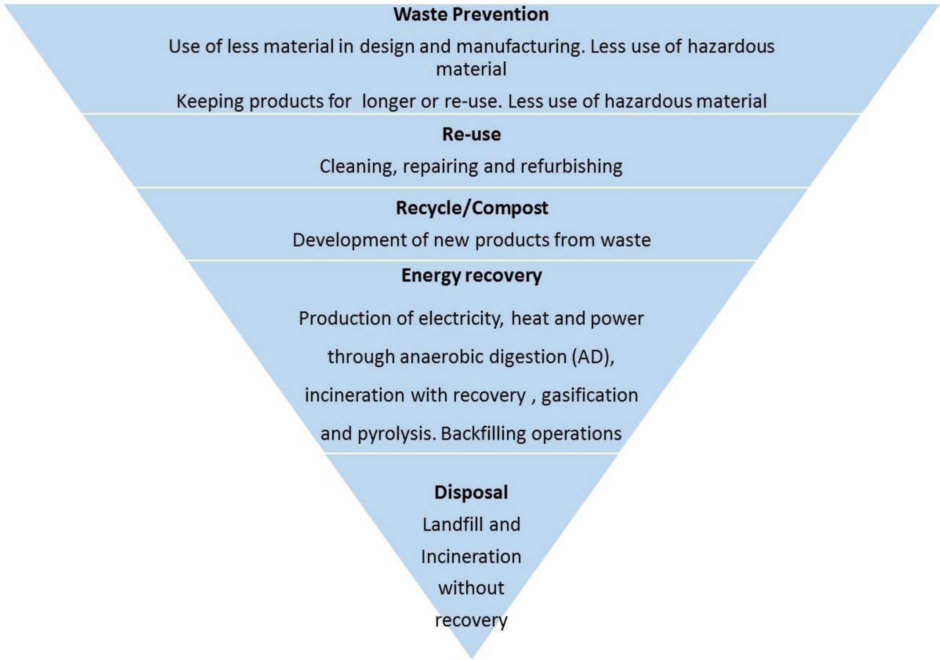

Figure 2.2. The Waste Hierarchy. Source:(DEFRA, 2011b)

A criterion of energy efficiency has been established in the WFD to promote the efficient use of energy generated from EfW plants. This criterion is known as "R1", often referred as to "R1 criterion". Activities of energy recovery and disposal are differentiated in the WFD in a list where different operations with different codes are identified. The classification for energy from waste operations is identified by R1 when waste is used as a fuel to obtain energy and by D10 when waste is disposed into landfill or burnt without energy recovery. The distinction between them lies in the fulfilment of the legal requirements of the R1 criterion. If the calculated criterion is above the specified required threshold, then the incinerator is considered to be R1, or in other words, incineration with energy recovery (European Commission, 2008; DEFRA, 2014). Within this R1 classification, other EfW technologies known as Advanced Thermal Technologies (ATT) and Advanced Conversion Technologies (ACT) are also included. Gasification and pyrolysis are some of these EfW thermal processes (DEFRA, 2014, 2021b).

The EU Landfill Directive aims to prevent and discourage landfilling waste, reducing the negative effects that disposing biodegradable municipal waste (BMW) into excavating pits has on the environment (surface and groundwater, soil, air) as well as on human health. BMW refers to any waste coming from commercial activities and householders that is capable of undergoing biological decomposition; food and garden waste, paper and cardboard fall within this definition (European Commission, 1999). Under this Directive, the UK is also required to meet the reduction targets of biodegradable MSW going to landfill of

75%, 50% and 35% by 2010, 2013 and 2020, respectively, with reference to the total amount of BMW produced in 1995 (DEFRA, 2020). In 2018, as part of the EU Circular Economy Package presented by the European Commission in 2015, the Landfill Directive was amended, and new targets were set. The UK is committed to limit the amount of municipal waste due to be landfilled to 10% or less by 2035. In 2020, this target was transposed into the UK´s CE Package (Letsrecycle, 2020b). The implementation of the two Directives (WFD and Landfill Directive) has brought changes in the waste management systems of the UK, such as an increase in recycling rates, energy recovery from waste, and waste exports as well as a reduction in waste disposal at landfills. These changes are revealed in more detail in the next section.

2.2.2 How Have Waste Policies Influenced UK Waste Management?

2.2.2.1 Disposal, Recycling and Energy Recovery

Due to the Landfill Tax introduced in 1996, with the "Landfill Tax Escalator", landfilling waste in the UK has come to be more expensive over the years. Starting in 1997 at £7 per tonne, the landfill tax is currently at £94.15 per tonne (HMRC, 2020). This tax appears to have been the main contributor over the last years towards achieving not just the landfill target, but also driving industries up on the waste hierarchy towards new ways of waste management such as recycling or waste recovery like EfW (DEFRA, 2014). The amount of BMW sent to landfill in 2018 was 7.2 million tonnes (Mt). This represents 20% of the 1995 baseline values (DEFRA, 2020). This means that the UK is already below the landfill target of the EU Landfill Directive (35% by 2020).

The UK generated 26.4 Mt of household waste in 2018 (DEFRA, 2020). Recycling rates in the UK have been increasing since 2000 (Smith and Bolton, 2018). However, since 2013, the rate has reached a plateau (DEFRA, 2018b; Smith and Bolton, 2018). In 2018, the UK recycling rate from household' waste was 45% (DEFRA, 2020). In 2018, Wales achieved a recycling rate of 54.1%, thus meeting the recycling targets. However, England, Scotland and Northern Ireland need to make significant efforts to improve their recycling rates to meet the target, with recycling rates of 44.7%, 47.7% and 42.8% respectively (DEFRA, 2020). Poor segregation of waste at source, inefficient collection of recyclable materials, increased occupancy of dwellings and ineffective policy levers are among the cited barriers to achieving a higher recycling rate (Smith and Bolton, 2018). Likewise, according to Ng and To (2020), these limitations to increasing recycling rates are due to a lack of appreciation at the domestic level of the concept of resource recovery from waste.

If the recycling rates remain unchanged, there might be a residual waste treatment capacity gap of 13 Mt by 2030 (ESA, 2017). In contrast, under a high recycling scenario (65% MSW and 78% C&I) the construction of additional EfW infrastructure would lead to overcapacity. If the waste exports from England are added to these estimations, the capacity gap estimates vary considerably. This leads to large uncertainties regarding the direction to take, which may also serve to discourage capital investment in the sector, either for infrastructure for recycling or for the treatment of residual waste (ESA, 2017).

Either way, there is a pressing need for government intervention through regulations and financial support to achieve further improvements in the UK recycling rates (Rhodes and Thair, 2017). However, already in 2014, Local Authorities reported that one of the main barriers to increasing recycling and improving collection systems was lack of budget (House of Commons, 2014) . This has remained the case over the last years, leading to little expenditures on improving waste management systems and new recycling infrastructure. Through the RWS, the UK Government has announced that separate collections will be funded. Subject to consultations, it has proposed to put in place legislation for mandatory separate food waste collections by 2023 and a core set of dry materials to be collected by all Local Authorities and waste operators (DEFRA, 2018b).

Additional plans set out on the RWS address the intention to invoke the “polluter pays” principle and extended producer responsibility (EPR) for packaging. The former puts a legal duty on producers of waste to pay full net-costs for the disposal of any packaging they place on the market. The latter mandates that industries manufacturing products harder to reuse or recycle will pay higher fees. Both policies aim to encourage manufacturers to design products which last longer and increase levels of re-use. Furthermore, plans to roll out new policies tacking plastic waste are also included within the strategy and as part of the UK Plastics Pact targets to be met by 2025. The UK Plastics Pact is a collaborative initiative to create a circular system that keeps plastic in the economy and out of the natural environment. Targets set out in the UK Plastics Pact are to eliminate problematic or unnecessary single-use plastic packaging, for 100% of plastic packaging to be reusable, recyclable or compostable, for 70% of plastic packaging to be effectively recycled, and for there to be an average of 30% recycled content across all plastic packaging. A deposit return scheme (DRS) from 2023 that will aim to increase the recycling of single-use drinks containers including bottles and disposable cups, and a plastics tax on packaging that uses less than 30% recycled content from 2022 aiming to stimulate demand for recycled materials in the UK are measures set on the Strategy to achieving those targets (DEFRA, 2018b).

Besides recycling, the other alternative to landfill disposal has been energy recovery, and more specifically incineration of waste, which has changed remarkably over the years in the UK. Driven by significant concerns over the insufficient capacity of landfills in the UK and the ability to cope with the rising amount of MSW, investments in EfW plants have gained traction. This is owing to EfW's ability to serve as a supporting treatment method for eliminating residual MSW and reducing the burden on landfills, while generating heat and electricity that supplies nearby communities (Rhodes and Thair, 2017). As of December 2019 there were 53 incinerators in operation or being commissioned, with a total capacity of 15.40 Mt. In addition, 11 EfW plants are under construction, with a total capacity of 3.10 Mt. The amount of residual waste sent to EfW facilities was 12.63 Mt in 2019, an increase of 9.9% from 2018 (Tolvik, 2020). This further corroborates the driving role played by the landfill tax and the strategic support that energy recovery activity seems to play in the management of waste in the UK. In the absence of better recycling rates, EfW capacity keeps increasing in the sector. This suggests that the UK is lacking in infrastructure for handling and sorting waste, required as part of the recycling process.

Through the Waste Infrastructure Delivery Programme, in 2006 the Government committed to spending £3bn by 2042 on developing new waste infrastructure, including infrastructure to help improve recycling. With its focus on the delivery of Private Finance Infrastructure contracts, one of the objectives of this programme has been to provide confidence in the private sector for investing into waste management projects (DEFRA, 2018b). The UK Government´s Private Finance Initiative (PFI) scheme, a mechanism to support large waste infrastructure projects underpinned by long-term contracts (typically 25 - 30 years), has stimulated the development of a number of large-scale facilities (HM Treasure, 2006; Ng *et al.*, 2021). EfW facilities have also been financed by the PFI scheme to enable the UK to meet the landfill diversion targets. However, this has generated controversy, as the investment in EfW plants via this scheme has created a technological lock-in into long-term contracts and has hindered optimum resource recovery (Hall, 2014). A total of 77% of incinerators are under this scheme and whilst PFI contracts are no longer granted (Rhodes and Thair, 2017), certain Local Authorities nowadays still remain in contract. Such is the case, for example, with

Kirklees' 25-year contract with Suez, a large waste management company, running until 2023 (Earnshaw, 2019). This means that the lock-in mechanism persists.

2.2.2.2 Waste Exports

The UK has relied heavily on waste exports over the years. The UK exports both recyclable materials that have been sorted separately, such as glass, plastics and paper, as well as residual waste, known as refuse derived fuel (RDF) (Malinauskaite *et al.*, 2017). RDF is waste from the ‘black bag’, that has been processed, to remove recyclable materials and moisture, compressed and wrapped to comply with certain standards (DEFRA, 2014). The UK Plan for Shipments of Waste, currently under development, but expected to be/generally in line with the EU Waste Shipments Regulations (WSR), dictates the requirements for waste exports and imports (DEFRA, 2021a).

The UK has been the leading exporter of RDF in Europe. The key UK end destinations of RDF are the Netherlands (main importer), Germany, Sweden, Norway and Denmark (Tolvik, 2015, 2016). It is interesting to note that the UK exports RDF to these countries for energy recovery (Malinauskaite *et al.*, 2017). This is to say, material which for the UK is still considered “nuisance” waste, in other countries is considered an energy resource. Exports of RDF have risen from zero in 2009 (DEFRA, 2013) to 2.71 Mt in 2019 (Creech, 2020). The increase in these exports has been economically driven, increasing in line with the rise in the UK Landfill Tax Escalator, and the market conditions and gate fees of the import countries of RDF with overcapacity of EfW (Tolvik, 2016; Malinauskaite *et al.*, 2017). A gate fee is the charge levied upon a given quantity of waste received at a waste processing facility (DEFRA, 2014). As EfW overcapacity emerged in the waste-importing countries, their gate fees plummeted drastically, meaning that other European waste generators found their market rates attractive and decided to export their material there. Detailed information on the gate fee trends of these waste-importing countries can be found elsewhere (Tolvik, 2015, 2016). However, the situation is changing and it is expected that UK waste exports will experience increasing challenges in the next few years. In 2020, the Netherlands and Sweden imposed an import tax per tonne of RDF of €32 and £6 respectively (Letsrecycle, 2019, 2020a). In the case of Sweden, the tax is expected to rise each year. This move is expected to increase the export costs of the UK gradually, which will consequently alter current waste management practices in the UK. Evidence of these changes from expected market pressures and risks in handling UK generated waste has already been reported. One such example can be found in

Essex Council, which at the end of 2019, after usually exporting their waste to the Netherlands but under pressures from the Dutch tax on waste, secured a landfill contract with Enovert for the landfilling of 200,000 tonnes per annum (Letsrecycle, 2020a). Following the waste hierarchy principles, however, landfill is the least desired alternative, so this solution in response to market influences does not help the UK meet its net zero emissions target, nor achieving better waste management systems and increasing resource efficiencies.

Additionally, the UK also exports recyclable materials like plastics. According to Greenpeace, in 2020, the UK exported 537,000 tonnes of plastic waste. The three main destination countries were Turkey (39%), Malaysia (12%) and Poland (7%) (Moore, 2021). In previous years, China was the major destination for UK paper, glass and plastics waste. However, in 2013 China introduced the first export ban known as the "Operation Green Fence" regulation, resulting in much stricter standards for the quality of imported waste (Associate Parliamentary Sustainable Resource Group, 2013). This has led to shift in waste exports to other countries, such as Turkey. Arguably, the lack of appreciation for the value of waste and EfW is even more evidence when trends in waste infrastructure development and exports are analysed (Ng and To, 2020). These trends could explain the previously reported lack of capacity for EfW as well as the plateauing recycling rate from lack of infrastructure for handling it. Driven by the market forces of the last ten years, the UK has found more attractive economic ways to manage and dispose of waste. Therefore, there has been no urgency to find solutions to manage UK waste at national level. However, this situation is changing, and the UK needs to find more sustainable solutions to make more efficient use of its own waste.

As can be seen, the UK waste export situation is in a state of flux. Countries with overcapacity seem to be handling UK waste and infrastructure, whether with their own resources or with better contracts. The favourable waste market, from which the UK has until now been benefiting, is undergoing changes in gate fees/tax variations of waste streams which could change the situation. Whilst exports are expected to continue to play a significant role in managing UK waste in the short and medium term, in the long term the UK domestic market must be expected to replace it (Rhodes and Thair 2017). Furthermore, the fact that the UK has exited the EU stresses even further the need to manage more sustainably the country´s own waste, where current waste exports are minimised and dependency on other countries is reduced. While the current waste exports situation is a barrier to cross-border economic activity, it should also be seen as a major opportunity to take control of the waste management sector and EfW sector in the UK. Moreover, evidence from Western European countries, such as Germany and the Netherlands, show that high rates of energy recovery and recycling with near elimination of landfill can co-exist. According to statistics from the Confederation of European Energy from Waste Plants (CEWEP), in 2017 Germany achieved 68% recycling and 31% energy recovery (1% waste was disposed) and the Netherlands managed to recycle 54%, recovered 44% and sent only 1% of their municipal waste to landfill. Meanwhile, the UK recycled 44%, recovered 37%, and still 17% of waste went to landfill (de Bruycker, 2019). The UK has a lot to do in terms of waste management, but if handled sustainably and efficiently, it could make better use of its own waste; as illustrated with other countries, both the waste management and EfW sectors can be sustainably integrated. From the perspective of the waste management sector, an increase in waste management and EfW infrastructure could contribute to the development of more sustainable resource-efficient systems. From the perspective of the energy system, EfW could contribute to the development of a low-carbon economy, helping with the transition of the decarbonisation of the energy sectors contributing to reaching the UK´s net zero emissions target by 2050.

This section has presented an overview of the waste management sector in the UK, and how the different political and market forces have been driving UK waste management decisions and consequently the EfW sector development in the UK. Opportunities and barriers associated with the waste management sector in the UK are also identified. The following section will provide an overview of the EfW sector in the UK. The main drivers and barriers for its development will be identified.

2.3 Overview of the UK Energy and Fuels from Waste Sector

2.3.1 Energy and Fuels from Waste Technologies: Opportunities and Barriers

EfW is a complex field. There are a wide range of feedstock varieties, conversion technologies and energy outputs. EfW interacts with other parts of the economy for example with agriculture, forestry, and with the waste management sector. EfW technologies include any waste treatment system that creates energy in the form of electricity, heat, transport fuels and/or chemicals from a waste feedstock (Yap and Nixon, 2015). These technologies can process many types of waste, including residues from MSW, C&I waste, agriculture and forestry, sewage and medical waste among others (Yap and Nixon, 2015; Scarlat *et al.*, 2019). However, as mentioned at the beginning of this chapter, the focus of this thesis is on MSW, which also includes C&I waste. A wide variety of waste materials falls in these categories, such as paper, card, plastics, wood, sanitary waste, glass, metals, food waste and garden waste, textiles, and shoes, among others. Detailed information on the materials and composition of MSW and C&I can be found elsewhere (DEFRA, 2018a). This thesis focuses specifically on plastic, paper, wood, and food wastes as feedstock for energy and fuels recovery. The reasons for selecting these feedstocks are discussed in further detail in Chapter 3.

There is a wide range of EfW technologies and pathways for the conversion of MSW into energy and fuels to accomplish low carbon objectives. There are three major waste to energy conversion routes – thermochemical, physicochemical and biochemical (Malinauskaite *et al.*, 2017). The compilation of available EfW technologies is shown in Figure 2.3. Of relevance for this thesis are the thermochemical and biochemical conversion routes.

The thermochemical processes (including combustion/incineration, gasification and pyrolysis) convert MSW into electricity, heat, liquid fuel and/or chemical products. They allow for the use of mixed waste streams. Of these thermochemical route, incineration is currently the most utilised technology for energy recovery of waste, for the generation of electricity and heat. Gasification and pyrolysis (ACTs) are alternative technologies for the production of liquid biofuels and chemical products from wastes (DEFRA, 2014).

Biochemical processes include advanced fermentation and anaerobic digestion (AD). They are typically used for the treatment of waste with high percentages of biodegradable organic matter and high moisture contents. In the case of MSW, the most relevant biochemical route is AD. Using the organic fraction of MSW, i.e., food waste material, AD enables the production of biogas (consisting mainly of methane and CO_2) and of a by-product that can be utilised as a fertiliser, known as digestate. The produced biogas from AD can be used for the generation of electricity and/or heat, through combined heat and power (CHP) or through a boiler. Alternatively, the biogas can be upgraded and cleaned into bio-methane for its injection into the gas grid, in the same way as natural gas, or transformed into methanol for use as liquid biofuel (DEFRA, 2011a; Fagerström *et al.*, 2018; Slorach *et al.*, 2019; Foster *et al.*, 2021).

These different technologies and processes are currently more or less developed. The most utilised processes for turning waste to energy and fuels are incineration, gasification and anaerobic digestion.

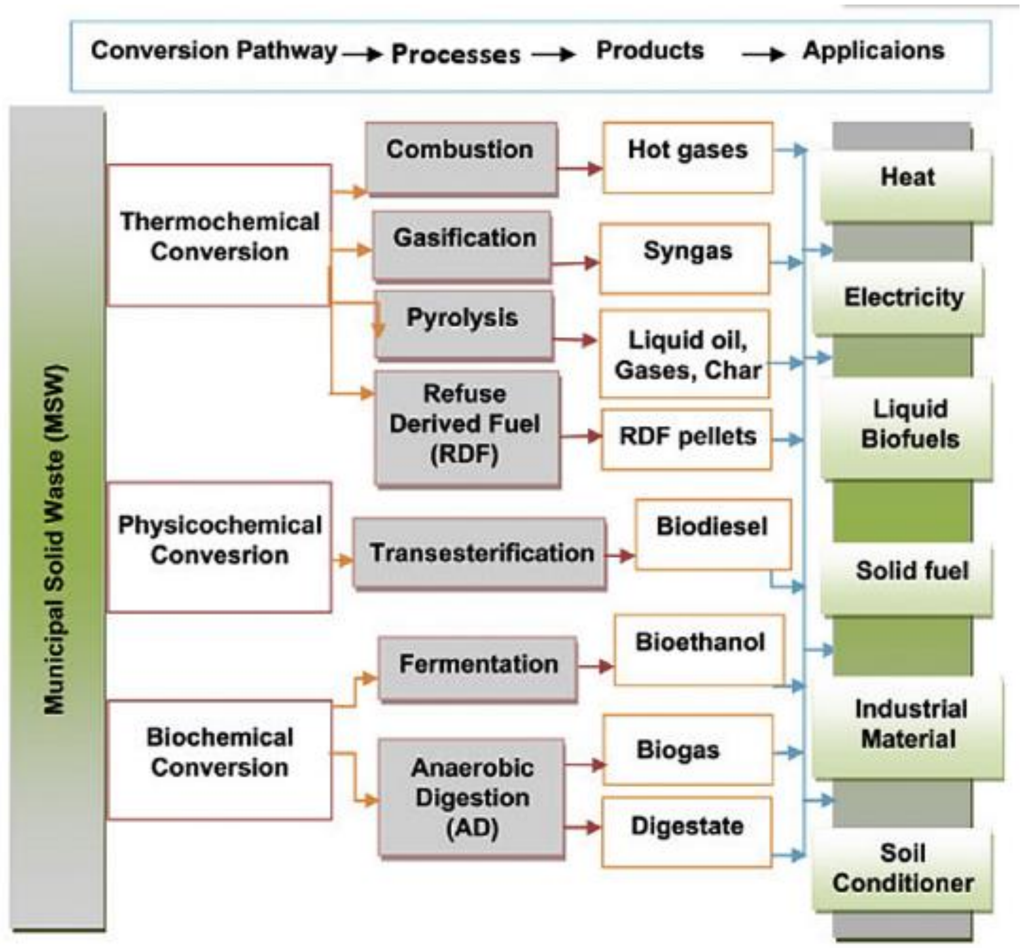

Figure 2.3. EfW technologies based on applied conversion process. Source: (Malinauskaite *et al.*, 2017)

2.3.1.1 Incineration

Incineration is the most used technology for EfW in the UK. One key advantage of incineration is its ability to deal with a diverse mixture of wastes, achieving up to a 90% volume reduction of MSW (Yap and Nixon, 2015; Foster *et al.*, 2021). The current status of this technology in the UK is at technology readiness level nine (TRL9) (see European Commission (2014) for details on TRL1 to TRL9), since the system is proven in an operational environment. According to Foster *et al.* (2021), it is foreseeable that the number of incineration facilities with energy recovery will increase over the next decade. The fact that incineration is a proven and mature technology, widely deployed, and with financially strong suppliers, makes it a much more attractive and bankable alternative to investors and a safer option for local decision-makers (Waldheim, 2018).

The RWS reports that in 2017, 3.4% of renewable energy was generated from incineration of biodegradable waste (DEFRA, 2018b). When biodegradable waste is combusted in EfW plants, the amount of CO_2 released can be assumed to be equal to that removed from the environment during the production of the original material. This effect is thus considered 'carbon neutral' as it has no impact on the environment over the product life cycle, and this is why energy from waste is considered a partially renewable energy source, sometimes referred to as a low carbon energy source (Jamasb and Nepal, 2010; DEFRA, 2014).

It is estimated that 2.3% of the UK's energy demand could be met through incineration with energy recovery should all the MSW that are currently sent to landfills be rerouted to incineration facilities (Jeswani and Azapagic, 2016). Not only would this have a positive effect on renewable energy generation in the UK, but also on GHG emissions released from landfills. As stated previously, legislation requires that the volume of biodegradable waste sent to landfill must be reduced significantly. This means that more MSW will be rerouted to other alternative waste management technologies, including incineration, resulting in more opportunity for energy recovery. However, the current stance of the UK Government is that although incineration plays an important role in waste management, the focus should be on prevention and recycling rather than landfills and incineration. Taxation on the incineration of waste is likely to increase over the next few years which may reduce the economic benefit of this waste management energy recovery alternative (DEFRA, 2018b).

Incineration can be a controversial form of low carbon technology. Whilst electricity from incineration has been reported to be environmentally better than conventional electricity generation from coal and oil (Jeswani and Azapagic, 2016), it has also been noted to have more adverse environmental impacts than conventional electricity generation from gas (Jeswani and Azapagic, 2016; Zero Waste Europe, 2019). Further evidence claims that the carbon intensity of energy produced through incineration is around two times greater than the carbon intensity of the current EU average electricity grid, which includes renewable energy from other technologies such as wind and solar (Zero Waste Europe, 2019). These are controversial points and barriers that technology currently faces if it is to be seen as a low-carbon energy technology. This calls into question the role that incineration can play in the production of renewable electricity in the long term. Further controversy arises from the emissions produced by fossil-based plastics contained in MSW, which is why Zero Waste Europe (2019, 2021) argues that incineration of MSW is a barrier to the transition to a low carbon economy.

Incineration can also be a controversial form of waste management. Proposals for new incineration facilities often face strong public opposition. Many environmental groups oppose incineration and there are specific campaign groups, including UKWIN (UK Without Incineration Network). UKWIN argues that, among other things, incineration is a barrier to a CE, preventing resources from being reused, that it depresses recycling, is a nuisance and gives rise to air pollution concerns (UKWIN, 2021).

Apart from CO_2, emissions from incinerators also contain other pollutants, including particulate matter (PM), SO_x and NO_x (Yap and Nixon, 2015). These can be significantly reduced through the use of appropriate pollutant control systems (Yap and Nixon, 2015). However, there has also been concern about the impact of air pollution from waste incinerators on human health, particularly in respect of PM. Under such concerns, UKWIN argues that the taxation of incineration is already a must (UKWIN, 2018b).

Several studies agree that achieving the full potential of EfW requires developing the delivery networks that are necessary for the use of electricity and heat from CHP plants with EfW (Jamasb and Nepal, 2010; Wright *et al.*, 2014; Jeswani and Azapagic, 2016). CHP is defined as '… the simultaneous generation of usable heat and power in a single process' (Wright *et al.*, 2014, p.3). From a technical point of view, EfW plants "producing electricity only" have the lowest energy efficiency criterion (R1), and EfW plants producing CHP achieve the highest energy efficiency criterion (R1) (Foster *et al.*, 2021).

Heat networks (also known as district heating) supply heat from a central source to consumers, via a network of underground pipes carrying hot water (BEIS, 2018b). The potential in using EfW with CHP, with the main objective of using the heat via a heating network, has been echoed by other authors (ERA, 2020; Cross *et al.*, 2021), who strongly support the need to look at how the Nordic countries are managing decarbonisation of the heat sector, and follow a similar strategy. The Netherlands, Denmark and Sweden typically use their waste heat to supply district heating. For example, the city of Copenhagen is almost entirely (97%) served by district heating (C40 Cities, 2011). This, however, seems to be challenging in the UK as out of the 53 incinerators in the UK, only ten EfW facilities produce heat for beneficial use alongside electricity (Tolvik, 2020), and only 2% of domestic and non-domestic buildings are connected to district heating (Wright *et al.*, 2014; ERA, 2020). This makes heat from the processes largely unusable and is wasted. Consequently, the efficiencies and emissions of the process are worse compared to a combined use of electricity and heat.

Average emissions from UK incinerators are four times higher than those of Nordic countries (ERA, 2020). Considering the uncertainty about the role that electricity generation from EfW might play in the future, the use of incinerators for electricity-only is being questioned (ERA, 2020; Cross *et al.*, 2021).

It is well recognised that the decarbonisation of heat is one of the biggest energy challenges for the UK (CCC, 2016; ETI, 2018; ERA, 2020; Cross *et al.*, 2021). The use of heat in domestic and non-domestic buildings in the UK accounts for around half of all energy use and around one third of carbon emissions. It has been reported that nearly half of the UK heat demand could be met by heat networks, while reducing national decarbonisation costs by £3 billion (ETI, 2018). Furthermore, the Committee on Climate Change (CCC) estimates that around 18% of UK heat will need to come from heat networks by 2050 if the UK is to meet its carbon targets in a cost effective way (BEIS, 2017a). The UK is at present a net importer of natural gas (ETI, 2018). This is likely to become a factor that generates further interest in district heating as a means of providing greater energy security. Heat networks are particularly attractive in high-density areas such as city centres, universities and new build developments (CCC, 2016; BEIS, 2018b). With their capacity to connect to multiple buildings and scale flexibility – with an expansion in capacity when required – heat networks are seen as a way to tackle fuel poverty and reduce consumer bills. Additionally, as they grow and connect, their efficiency and carbon-saving potential increases (BEIS, 2018b; ETI, 2018). However, for this to happen, many barriers need to be overcome. The reduced number of heat networks in the UK, the remote location of EfW plants from high heat demand, the public opposition to EfW plants, the low prices of heat in comparison to electricity as well as the capital costs of heat network deployment and a lack of skills, have been cited as barriers to deployment (Wright *et al.*, 2014; ETI, 2018; ERA, 2020; Cross *et al.*, 2021). Moreover, the fact that heat networks involve multiple stakeholders who may have different priorities, interests and values, is considered as an additional barrier, increasing the complexity of their development and deployment (Wright *et al.*, 2014; ETI, 2018). Additional information on both the multi-stakeholders involved in the supply chain and an explanation of the opportunities and barriers in the deployment of EfW with CHP and district heating can be found elsewhere in Wright *et al.* (2014) and ETI (2018) studies.

To encourage uptake of heat networks, the UK Government has launched several investment programmes. In 2016 the government announced the Heat Network Investment Project (HNIP), committing £320 million to deliver heat network projects in England and Wales. The aims are to solve the lack of heat networks in the UK, to deliver carbon savings and to create the conditions necessary for a sustainable heat network market to develop. There is also the Heat Networks Delivery Unit (HNDU) programme, introduced in 2013, that provides support through the early stages of heat network development to Local Authorities in England and Wales (BEIS, 2017a). In March 2020, through the Green Heat Network Fund (GHNF) scheme the Government proposed £270 million of new funding to enable new and existing heat networks to adopt low carbon heat sources (DEFRA, 2021b). However, ERA (2020) considers that these investments are not enough to achieve the CCC targets and has recommended an increase of £3 billion for heat network support.

2.3.1.2 Gasification

Gasification is an advanced thermochemical treatment process that allows the generation of a clean syngas. The process, which includes a gas cleaning step, is also known as "true gasification" (Evans, 2017; Waldheim, 2018). The clean syngas consists of a mixture of carbon monoxide [CO], hydrogen [H_2] and methane [CH_4]. It can be used as energy for electricity and heat, and it can further be upgraded into higher value products such as liquid fuels and/or chemicals (Yap and Nixon, 2015; Evans, 2017; Foster *et al.*, 2021).

However, direct upgrading of MSW into these products, without prior extraction of recyclable materials is not sustainable (Evans, 2017; Waldheim, 2018; Foster *et al.*, 2021; Ng *et al.*, 2021). The consistency and handling of feedstock are two strong technical barriers related to gasification technology (Waldheim, 2018). From a waste availability point of view, this could be a clear drawback when compared to incineration. Likewise, the composition of syngas varies depending on the waste composition and physical properties (Arena, 2012) and it is difficult and expensive to condition and clean the syngas to meet end-use requirements or limit emission values (Waldheim, 2018; Cooper *et al.*, 2019). Altogether, these factors increase the complexity of the process, which increases the costs, making gasification costlier than incineration (Arena, 2012; Waldheim, 2018), and its economic viability a challenge (Cooper *et al.*, 2019).

Gasification plants have numerous advantages in comparison to incineration. Due to its feedstock flexibility (as it allows a wide range of waste feedstocks), syngas application versatility/output flexibility, scalability and energy efficiency and environmental performances (Arena, 2012; Evans, 2017), it has been increasingly proposed as an alternative to incineration (BEIS, 2017b; CCC, 2018; DEFRA, 2018b; DfT, 2018b; Waldheim, 2018). In addition, as with incineration, the possibility of combining gasification with carbon capture and storage (CCS) technology has been recognised (BEIS, 2017b; Evans, 2017; CCC, 2018).

Efficiencies of gasification have been reported to be higher than with incineration (Arena, 2012; Yap and Nixon, 2015; Foster *et al.*, 2021) and CO_2 emissions have been reported to be lower. The latter is related to the ability of achieving higher conversion efficiencies (Yap and Nixon, 2015; Waldheim, 2018). In addition, NO_x and SO_x from gasification have also been reported to be lower than in incineration. Furthermore, it produces lower volumes of gases, which means that smaller treatment and cleaning systems of the syngas can be utilised (Foster *et al.*, 2021). As for the incineration process, bottom ash can be treated for utilisation in the construction sector (Arena, 2012), which means, that secondary products from the conversion process can have a second life usage.

The size and land requirement for a gasification plant is comparable to a conventional incineration plant (Yap and Nixon, 2015). However, gasification has also been reported to be able to be delivered at a smaller scale and scaling up is possible if desired (Arena, 2012; Johansson and Warren, 2016; Evans, 2017; Ng *et al.*, 2019). This is because gasification plants are often modular, which allows the possibility to modify the capacity of solid waste treatment and they are also quicker to build (Arena, 2012). Moreover, gasification has been identified as playing an important role in decentralised distribution as a technology that helps to foster environmental and social community benefits (Evans, 2017; Ng *et al.*, 2019). Ng et al. (2019) evaluated the energy recovery of food waste and mixed waste streams from supermarkets and households via AD and gasification, for the production of electricity and transport fuels. The study assessed different levels of distribution, including centralised and decentralised. The decentralised concept was studied where the plants were co-located with a supermarket, hence reducing transport miles. The results showed that recovering food waste and mixed waste at community level, partially or fully decentralised, enables production of cleaner and more affordable energy for the local community.

According to research by the Energy Technologies Institute (ETI) assessing the scale of the waste to energy opportunity in the UK, there is potential for around 50-100 town scale plants in the UK, each processing waste in the range of 50,000 to 200,000 tonnes/year (approximating to 5-20 MWe) (Evans, 2017). While large scales come with the advantages of economics of scale, the uncertainty in securing feedstock supply might be also factor to consider. Given the demographic situation of the UK, and the need to decarbonise the different sectors, small scale plants are gaining interest as better alternatives to ensure energy supply (Johansson and Warren, 2016; Evans, 2017). The use of small-scale gasification plants allows efficient operations, with the waste heat generated being readily available for use in district heating networks to provide heat and power (Wright *et al.*, 2014; Evans, 2017).

There are a number of advantages to locating waste treatment plants close to energy generation points. First is the reduction in transport distances and an associated reduction in emissions. Additionally, there is the inclusion of local actors in the supply chain, which incentivises the local economy and the generation of jobs (each town plant could provide25-40 jobs according to ETI). There is also the possibility of connecting the plant to the heat network, enabling the delivery of low-carbon heat and helping to tackle fuel poverty. There are lower perceived negative health and visual effects from the community associated with the deployment of small-scale plants, reducing public opposition. (Jamasb and Nepal, 2010; Johansson and Warren, 2016; Evans, 2017). Notwithstanding the above, a recent study from Supergen, where different stakeholders engaged in the identification of barriers and research needs for gasification, reports there were uncertainties about which scale would be the most appropriate (Cooper *et al.*, 2019). The UK could once again learn from its European neighbours by anticipating problems of overcapacity.

There are a number of successful gasification plants in other countries such as the Lathi II (Kymijärvi II) plant in Finland (Waldheim, 2018). Detailed information on some gasification projects deployed around the world, technicalities, and their progress can be found elsewhere (see Waldheim, 2018). However, the use of MSW, is not readily applied in the UK.

In 2019, operation of the UK's first MSW gasification plant located in Wednesbury commenced (Bioenergy Insight, 2019; ETI, 2019). This is a 1.5MWe Waste Gasification Commercial Demonstration Plant, built in partnership with the company Kew Technology and with the financial support of the ETI. To date, the plant has run three separate tests on wood waste and RDF feedstock – in April and July 2019 (wood waste) and October 2019 (RDF). All three tests have been successful in the production of syngas and the generation of electricity which was fed into the grid network. Due to COVID-19, the plant shut down during 2020. The plant reopened in 2021, and is planning to enter continuous operation in late May (direct communication). (NB. Kew Technology and the ETI were industrial sponsors of this study. Their relationship to this thesis will be discussed in Chapter 3).

This is not the first gasification plant constructed in the UK for the processing of waste. Several such facilities have been built in the past, and have failed (Ernsting, 2015; UKWIN, 2016a; Waldheim, 2018).

One such example is a gasification plant established in the Isle of Wight in 2009 by Energos Ltd. The plant made use of refuse derived fuel (RDF) and clean wood waste for the production of electricity (designed to provide 1.8 MWe power). However, the company went into administration in 2016; the cause was a failure to deliver on gasification contracts (UKWIN, 2020). After this failure, in 2017 a variation of the permit was granted by the Environment Agency. The gasification technology has since been switched to incineration for the production of electricity (Letsrecycle, 2017a, 2017b).

Another failed example is the company Air Products Ltd and its Tees Valley plants (TV1 and TV2). The two plants were supposed to convert RDF into gas for the national grid. The gasification TV1 plant began construction in 2012, and in 2015, at the latest stage of commissioning it was announced that the plant was not functioning well. TV2 was under construction on the same site. Due to technical difficulties, related to design and operation, of TV1, both plants were put on hold (ENDS Waste & Bioenergy, 2016a; UKWIN, 2016b, 2017; Waldheim, 2018).

The syngas cleaning process complexity, the increasing number of failures undermining their reliability, the reliance on technologies that are not well established, the increasing development times and high capital and operational costs for operators (Garnett *et al.*, 2017), are some of the major challenges for gasification plants (Yap and Nixon, 2015; Waldheim, 2018; Cooper *et al.*, 2019). Gasification´s feasibility has been questioned for many years; moreover, it has been identified on occasion as a niche technology, e.g. suitable for supermarkets, with little expectation of reaching the levels of commercialization and performance of incineration (Rhodes and Thair, 2017).

Hence, from technological and economic points of view, these failures and challenges stain gasification´s implementation and development feasibility, as well as its ability for attracting investment to increase its TRL and become financially viable (Waldheim, 2018). Based on DEFRA´s RWS, government incentives for the development of advanced conversion technologies, such as gasification of municipal waste, may receive more attention in the next decade (DEFRA, 2018b).

Gasification is unique compared to other thermochemical conversion processes in that the products can be chemicals and/or liquid biofuels (also known as “high value products” and “advanced biofuels”) and the process can be classified as material recovery and not as energy recovery only when power and/or heat is the output (Waldheim, 2018). This means that as material recovery, the production of liquid biofuels and/or chemicals from gasification could be seen as contributions to the CE. In the past, when reducing waste and avoiding landfill were the main drivers, this unique conversion feature was not seen as very important. However, as there is an increasing drive towards decarbonisation of the transport and biochemical sectors, this unique ability of gasification has become increasingly attractive (BEIS, 2017b; CCC, 2018; DfT, 2018b). The benefits of using wastes have already been recognised in the updated Renewable Energy Directive (RED II) in the EU. The introduction of ”recycled carbon fuels” in parallel to “advanced biofuels” means that both the fossil and biogenic part of fuels produced from waste streams, can be incentivised by the member states through transport targets and support schemes, thereby enhancing resource efficiency. However, this has generated controversy in terms of waste management as it might discourage the mechanical treatment and sorting of waste streams; the real contribution that fuels derived from fossil waste make as low-carbon energy/fuel to the decarbonisation of the energy system has been questioned (Zero Waste Europe, 2021).

The UK currently has some gasification projects producing liquid biofuels, such as the Velocys Altalto project in Immingham and the Kew Technology Ltd. project in Wednesbury, which may help the UK enter the gasification technology and high-value product markets. The Velocys Altalto project is developing a commercial plant, with the support of industry partners, including BA and Shell Aviation, and the Department for Transport (DfT), to make jet fuel from MSW and C&I waste. In January 2021, Shell Aviation withdrew from the Joint Development Agreement (Altalto, 2021). The UK Department for Transport (DfT), under the Future Fuels for Flight and Freight Competition (F4C), awarded funds of £0.9 million to the Velocys Altalto and £20 million to the Kew Technology project. Kew Technology have also secured a share of £6.5 million with Rika Biogas Technologies (AD for liquid bio-methane production) to provide fuel for heavy goods vehicles (HGV), as well as researching the production of low carbon aviation fuel (DfT, 2018a, 2019; Kew Technology, 2019b). In 2019, Kew Technology was awarded further funding from the Department for Business, Energy & Industrial Strategy (BEIS) to explore waste to hydrogen (Kew Technology, 2019a; Kew Technology and BEIS, 2019).

The UK has an extensive gas grid network, and according to the CCC a large-scale shift to a hydrogen gas supply is technically feasible for existing gas distribution networks (CCC, 2016). Together with the deployment of the heat networks, the injection of hydrogen into the gas grid could be an additional strategy contributing to the decarbonisation of the gas grid. Nonetheless, the production of hydrogen in a low-carbon way at the necessary scale would require CCS (CCC, 2016). As previously noted, the possibility of combining gasification with

CCS technology has been recognised (BEIS, 2017b; Evans, 2017; CCC, 2018). This means that gasification as a technology capable of producing hydrogen, could be a key technology in the transition to a low carbon heat in the UK.

Nonetheless, there have also been some failures of gasification for the conversion of waste to liquid biofuels in the UK. The GreenSky London project, a joint project between British Airways and Solena Ltd. established in 2012, aimed to build a first of its kind alternative fuel plant in London to convert MSW and C&I waste into aviation fuel for use in British Airways flights from London airports (Letsrecycle, 2014). As a result of Solena's bankruptcy in 2015, the project was put on hold (Bioenergy International, 2015).

On account of the flexibility of inputs and end products, it is not surprising that there has been an increase in interest and exploration of gasification by different statutory advisors and government departments. Given its requirement for feedstock pre-treatment and flexibility in outputs, from a CE point of view, gasification could affect not just the energy recovery sector and waste management strategies but also could provide a broader market of commodities which could be sold locally, nationally and internationally. However, just as with incineration, gasification can also be a controversial form of waste management and low carbon economy, often facing strong public opposition (Ernsting, 2015; UKWIN, 2016a, 2018a). Nonetheless, gasification appears to be less controversial than incineration (Garnett *et al.*, 2017). Social perspectives, opportunities and barriers on EfW plants are further discussed in Section 2.3.2.

2.3.1.3 Anaerobic Digestion

As with incineration, AD is a well-established, widely deployed (TRL9) process within the EfW sector for the treatment of organic wastes. Dating back to the 1800s, it is one of the oldest energy from waste processes (Foster *et al.*, 2021).

Any organic matter can be fed into AD, as the process works on the decomposition of organic matter aided by microorganisms that digest/eat the feedstock to produce biogas. Biogas is predominantly composed of methane (50-70%), and carbon dioxide (30-50%) along with other minor components making up the remainder (Fagerström *et al.*, 2018). After the process, a by-product known as digestate – a nutrient rich product that can be used as a fertiliser – is left (Foster *et al.*, 2021). This makes the process of AD fully compliant with the CE, as it turns food waste – as well as other organic feedstock falling outside of this thesis scope – into a product that restores nutrients to the land (Fagerström *et al.*, 2018; Slorach *et* *al.*, 2019; ERA, 2020). Results from Röder´s (2016) study on stakeholders' perceptions of AD in the UK showed that the production of digestate from the AD operations was perceived as an important driver for AD deployment, e.g., reducing the need of fertilizers, contributing to soil nutrient management, as well as generating an additional income if sold. While Röder´s (2016) study is centred around the deployment of AD to manage farm residues, the benefits above exposed from producing digestate from AD could be extrapolated to the use and management of food waste as feedstock. However, whilst digestate is potentially a valuable AD by-product, the quality of digestate remains a concern (Garnett *et al.*, 2017; Fagerström *et al.*, 2018; ERA, 2020). This creates market uncertainty, despite standards such as PAS110 established to promote product quality. Consequently, some plants in the UK are giving it away to farmers for free (Garnett *et al.*, 2017; ERA, 2020).

The biogas produced can be combusted in a CHP plant for the production of electricity and heat (the most common use of biogas), or it can be upgraded to pure methane/bio-methane (the main constituent of natural gas) for use as transport fuels in cars, or it can be injected into the gas grid (Fagerström *et al.*, 2018; Foster *et al.*, 2021). There are currently 661 AD plants operational in the UK (Foster *et al.*, 2021), supplying the national grid with bio-methane (102 plants), electricity (583 plants) and providing local heating (42 plants). The feedstock varies widely and includes agricultural waste, the organic fraction of MSW and C&I waste and sewage sludge. A total of 161 AD plants use the organic fraction of MSW and C&I waste (Foster *et al.*, 2021).

Several studies have assessed the environmental and economic sustainability of the current food waste treatment routes over the past decade (Ng *et al.*, 2019; Slorach *et al.*, 2019, 2020)**.** The majority of studies which included AD as a waste treatment routes conclude that AD had the lowest negative environmental and economic impacts (Slorach *et al.*, 2020). For example, focusing on the UK context, Slorach *et al.´s* (2019) results showed that if all of the food waste was incinerated, £103m and 360 kt CO_2 eq./year could be saved compared to current waste management. Even further environmental and economic benefits would be obtained if all food waste was sent to AD, which could annually save £251m and 490 kt CO_2 eq. in comparison to the current situation. A later study from these same researchers (Slorach *et al.*, 2020) evaluating the most sustainable future scenarios for the household food waste management in the UK, concludes that scenarios with the highest share of AD are the most sustainable, both in terms of environmental and economic assessment. Slorach *et al.*´s (2020) is the first study internationally to assess the environmental and economic impacts of future scenarios for treating household food waste. Furthermore, exploring the sustainability impacts of using organic sources from households and supermarkets for the production of electricity and liquid biofuels, Ng *et al.* (2019) concludes that the adoption of decentralised strategies with the use of waste at the local level through AD could bring multiple benefits to the community, including reductions in emissions and energy costs. However, the majority of these studies do not integrate a holistic approach of analysis where together with the issues of technical and economic matter, wider systemic issues of social and political matter are also taken into consideration. The one that comes closest to a holistic view, is the study from Ng *et al.* (2019); these researchers claim that a more integrated, circular and advanced technological approach in waste management should be undertaken as it could lead to a wider range of socio-economic and environmental benefits to the local community, which is of essential need in the UK.

AD is considered a key process for achieving a CE, increasing resource-efficiency and for the bio-economy as a whole (CCC, 2018; Fagerström *et al.*, 2018; Ng *et al.*, 2019; Slorach *et al.*, 2019; ERA, 2020). Despite these reported environmental and economic advantages, the implementation of AD for energy and fuels recovery using food waste remains a challenge, with associated wider environmental, societal and political barriers. Although the compulsory segregation of food waste is currently under consultation with potential implementation by 2023, there is currently no legal requirement in UK law stipulating the provision of separate food collections (DEFRA, 2018b). This has been reported as a key political barrier to AD deployment (Ng *et al.*, 2019; Slorach *et al.*, 2020). Other barriers reported are more closely related to the practical uptake of separate food waste collection; these include uncertainty of recuperating the cost of food waste collection, insufficient funding to support the collection services, and low participation rate of households, among others (Ng *et al.*, 2019).

The security of supply and sustainability of feedstock have been identified as potential barriers to future uptake of EfW and biomass projects (Thornley and Prins, 2009; Thornley *et al.*, 2009; Welfle *et al.*, 2014a, 2014b; Wright *et al.*, 2014). Although these feedstock studies refer to biomass, the barriers identified could be extrapolated to MSW, as the availability of waste for energy recovery depends on multiple factors. Factors include the waste management policy at both local and national levels, the composition of residual waste, the availability of infrastructure for waste treatment and processing, the cost of waste treatment as well as markets for residual waste and recyclables. It could be expected that the policy on separate collection (under consultation), recycling rates and schemes such as the EPR will reduce the amount of waste potentially available for EfW processes. This may be an additional factor of uncertainty, in terms of decisions to be made regarding the deployment of the EfW sector in the UK.

Successful implementation of EfW conversion technologies depends considerably upon the efficiency of the process which, in turn, depends on the quality of the waste feedstock and the conversion technology (DEFRA, 2014). The different composition and properties of the feedstock materials have an impact on the treatments and technologies to be used. Their chemical and physical composition, with their associated parameters, such as energy content (technically known as calorific value (CV)), moisture and ash content, may influence the processes to which they can be submitted, whether by changing the feedstock composition; or by making changes to the technological designs (Arena, 2012; DEFRA, 2014). As discussed in the previous section, gasification and AD technologies are sensitive to feedstock properties, requiring pre-treatment of waste before feeding it into the process. The heterogeneous nature of MSW (feedstock quality, composition and properties) as well as its availability over time (feedstock supply) poses challenges in both the selection of the technology and the feasibility and reliability of the process (DEFRA, 2011a; Waldheim, 2018).

The variability in waste both over time and in terms of its heterogeneity, has been identified as one of the main characteristics and challenges of using waste as feedstock. The variability stems from many factors, such as seasonal variations, socio-economic levels and cultural differentiations as well as collection practices (DEFRA, 2014; Evans, 2017; Waldheim, 2018). The changing context of the waste hampers the possibility of achieving consistency of feedstock and the production of good quality gas. For instance, Waldheim (2018) presents a chemical composition comparison between different samples of MSW from Germany, RDF from Sweden and RDF from the UK imported to Sweden. Results show that there are wide variations in the net calorific value as well as in the moisture and ash content. These variations in the composition of the raw material together with the conversion technology used will influence the final energy performance.

Furthermore, some feedstock may have restricted applications or specific standards to follow so that a particular conversion process is applied. This means that end-use requirements and environmental standards may also be taken into consideration when selecting the process. Such is the case for example with the British Standard Institution’s Publically Available Specification known as BSI PAS 110, for the digestate produced from AD, with the aim of generating a market for the AD by-product. This standard provides a baseline quality specification for digestate, ensuring that it is safe and reliable to use. PAS110 includes requirements about how food waste and other materials can be processed, and is one of the fundamental pillars of the Biofertiliser Certification Scheme (BCS) (DEFRA, 2011a; WRAP, 2021).

Considering these factors, defining long-term infrastructure with the amount of waste which could be produced in the future and the potential to generate renewable energy from that waste, becomes challenging. This inevitably increases the uncertainty regarding the potential future role that EfW could play in responding to energy demand and the low-carbon economy in the UK. There are a wide variety of technologies and a wide variety of energy outputs. Each of these technologies and energy outputs have, in turn, their own opportunities and barriers to implementation, which may overlap with each other, making the sector extremely complex to understand. Furthermore, according to Thornley and Gilbert (2013), the sustainability of a particular biofuel is inextricably linked to non-technical aspects, such as societal values and ethical judgments, for which an understanding of stakeholders' perspectives, their knowledge, interests, values and priorities becomes relevant to achieve sustainable development and integration of the waste management and EfW sectors.

In addition to technological and environmental opportunities and barriers of EfW technologies, previous studies have attempt to understand social – especially social acceptance and public opposition – and political opportunities and barriers on EfW technologies and deployment. The following sections provide a brief outline of the main social and political concerns identified in the literature towards EfW infrastructure development.

2.3.2 Public perceptions and acceptance: Opportunities and Barriers

Academic studies assessing public perceptions and acceptance towards EfW projects are limited. Most of the studies found in the literature have either looked at public perceptions and acceptance in relation to the bioenergy sector with the use of biomass as the main feedstock, or assessed public perception more generally regarding the location of renewable energy technologies. Drawing on these studies, the following lines bring to light different conflicts and factors identified which can be extrapolated to the EfW public perceptions field. Many of the studies although assessing a different type of feedstock, have considered similar EfW technologies.

The literature suggests that if local people fail to understand the bioenergy technology – this includes EfW technologies – they will be unwilling to support or engage in any energy development. In such a situation, public perceptions differ from the experts' views, scientists and developers, industries and governmental organizations (Upreti, 2004; Thornley and Prins, 2009; Upham *et al.*, 2009). Researchers have identified that aspects such as the risk perception of the unfamiliar technology and degree of communication, awareness and understanding play key roles in public acceptance or opposition to local energy projects (Upreti, 2004; Thornley and Prins, 2009; Upham *et al.*, 2009; Evans and Newton-Cross, 2016). Evans and Newton-Cross (2016) researched public perception of bioenergy, including EfW, in the UK and found that it was well supported (80%), but that targeted efforts to raise public awareness would benefit the sector. The study revealed that respondents with more knowledge, understanding and awareness of the bioenergy, including EfW, sector were more likely to support its deployment than those who said they knew nothing about it. Consequently, this suggests that promoting public awareness and understanding is essential to public positive perception and public acceptance.

When considering conflict surrounding the location of new infrastructure, the concept and phenomenon of NIMBYsm (Not In My Back Yard) has commonly been used to explain public opposition to new developments near homes and communities, particularly arising from energy technologies (Devine-Wright, 2009). The type of technology, scale of the project and environmental beliefs have also been highlighted as factors influencing public opposition. Among these categories, arise concerns regarding location and proximity of the plant to the residential area, appearance/aesthetic appreciation of the plant, nuisance and odour, transport congestion, and environmental impacts of emissions from transport and processes (Upreti, 2004; Upham and Shackley, 2007; Upham *et al.*, 2009; Jeswani and Azapagic, 2016). These concerns lead to a perceived unreasonable loss-to-public benefit ratio, i.e., the conclusion of the public that the development brings more losses than gains to the community.

Additional cited reasons for public opposition to renewable energy technology are lack of trust, lack of public engagement, lack of communication between local people and the rest of the stakeholders, such as developers, energy companies and policy makers; and lack of personal connection to the local area (Upreti, 2004; Upham and Shackley, 2006, 2007; Devine-Wright, 2009). The latter includes processes of place attachment and place identity which according to Devine-Wright (2009) are key founders of public opposition and NIMBYSm (Devine-Wright 2009). Moreover, expanding further on the concept of place attachment, Devine-Wright and Batel (2017) showed that depending upon the strength of attachment to a place, people experience different infrastructure beliefs and attitudes. Consequently, understanding the level of place attachment in the area together with the beliefs and views of local people should be seen as a priority, likely to help anticipate potential public opposition activities.

Research findings also show that the general public in the UK trust environmental NGOs and pressure groups more than policy makers, industries and public bodies. This is directly linked to the lack of communication between policy makers, industries, developers and the local public. Devon's biomass gasifier, the North Wiltshire Biomass Power Plant (gasification plant) in Cricklage, and Elean Power Station (incineration plant) in Ely are examples of the generalised mistrust of the local individuals towards the different organization and stakeholders of the projects (Upreti, 2004; Upham and Shackley, 2006). In these projects, one of the main conflicts of all three biomass plants was the weak public relation strategy between developers and local communities. Furthermore, the communication and language used between different supply chain stakeholders have also been reported as a significant barrier to uptake of AD projects (Röder, 2016). Of course, it is very likely that these barriers also exist between stakeholders in other supply chains of other types of projects. Results from Röder´s (2016) study reported that stakeholders from the same sector might not have a complete knowledge or understanding of what, how and why an activity is being undertaken which, in turn, may create mistrust and misunderstanding, and may lead to issues of social acceptability from the community.

Notwithstanding the above, studies also point out that people would welcome opportunities for greater involvement in energy project developments and the boost of more local community energy initiatives (Upreti, 2004; Upham and Shackley, 2006, 2007). Some of the strongest evidence comes from the studies of local opinion in the Devon biomass gasifier and the Elean Power Station projects. In the case of the Devon gasifier, the first surveys undertaken after an intensive local campaign and the refusal of planning permission showed that most people were in favour of the decision. Nonetheless, when a second survey was undertaken later, results revealed that around 69% of the local population would support a smaller project, if it was controlled by the community (Upham and Shackley, 2007). Furthermore, several researchers (Upreti, 2004; Welfle *et al.*, 2014a) have for a long time recommended learning from other EU members, where public opinions are less hostile. For example, in the case of Ely's Elean Power Station, in response to the reasons for rejection from the formed localised pressure group of opposition, the developers revised the proposal and engaged on a fact-finding mission into the Netherlands to find out about local residents' benefits from biomass projects. They came back, convinced the residents, and the second application for planning permission was accepted (Upreti, 2004). Educating local populations about community benefits of plants and direct local energy benefits such as district heating, and reassuring about air pollutant regulations can all help to reduce public opposition (Welfle *et al.*, 2014a). Although it might seem obvious, communities have different priorities, and their concerns need to be addressed for developments to succeed.

2.3.3 Policy Framework: Opportunities and Barriers

The UK Government has put in place a set of energy policies and measures that create interest in renewable energy production. EfW development has principally been supported in the UK through "Renewable Obligation Certificates" (ROCs- for electricity), the "Renewable Heat Incentive" (RHI) and the "Renewable Transport Fuel Obligation" (RTFO). In 2015, the UK has shifted its support for Renewable Electricity from ROCs to "Contracts for Difference".

The rationale for these government interventions was to stimulate renewable energy deployment when the technologies were immature, and costs were high. The aim was to ensure market access for the technologies, to offset the higher costs of the energy produced, and to reduce GHG emissions. The most cited policy drivers to the bioenergy development are GHG emission targets, energy efficiency and consumption targets, and renewable and bioenergy targets (Welfle *et al.*, 2014a; Purkus *et al.*, 2015; Cross *et al.*, 2021). Today, the aim for these policies still remains/stands in the EfW sector, however it includes additional priorities associated with imposing tighter sustainability constraints. This can be exemplified, by the increase in targets set out in the RTFO. The RTFO obliges suppliers of road transport fuel to introduce a steadily rising fraction of renewable fuel. The rates for 2020 stands at 9.75% and must increase to 12.4% by 2032. Of relevance for the EfW sector as well, are recent amendments in the EU RED, such as: 1) The introduction of definitions for wastes and residues, i.e. a "development fuel" is defined as a fuel made from certain sustainable wastes, residues or renewable fuels of non-biological origin (RFNBO)s. Several new fuel types are now made eligible for support under the RTFO including aviation fuel, hydrogen and other RFNBO. 2) Renewable fuels derived from certain waste or residue feedstock, including food waste, are awarded double the renewable transport fuel certificates (RTFCs) per litre or kilogram supplied; and 3) In line with the amendments to the Directive 2015/15132 ("Indirect Land Use Change (ILUC) Directive") biofuels derived from wastes are considered to meet the land use criteria required by the RTFO (DfT, 2018b). Moreover, land used for feedstock generation such as energy crops, which are a concern on the bioenergy sector, is no longer an issue if using MSW feedstock.

The Contracts for Difference (CfD) is the main government policy instrument supporting low carbon electricity generation. ACT and AD with and without CHP can be eligible for CfD contracts (BEIS, 2020). However, given the lack of district heating infrastructure in the UK, it can be difficult to find government intervention opportunities for these combination of technologies in the UK.

At the same time, renewable heat is also supported through the Renewable Heat Incentive (RHI). The RHI policy aims to increase deployment of low-carbon heat in the UK. RHI supports a wide range of renewable heat technologies, including bio-methane injection and energy from solid biomass contained in waste (with CHP) (Ofgem, 2018). RHI is due to end on the 31st March 2022 (Ofgem, 2021). However, beyond 2022, there is no commitment to fund new projects in renewable heat. Likewise, no other government support interventions have been announced. This uncertainty and instability about future government support for renewable heat is seen as a strong barrier, which hinders the development of future projects for CHP and AD projects (ERA, 2020; Cross *et al.*, 2021). Additional concerns associated with the availability, feasibility, and public perception of heat networks in the UK have also been identified as concerns to policy development and implementation (Cross *et al.*, 2021). While it is true that due to the lack of district heating infrastructure in the UK, the success of the bio-heat sector in the Nordic countries would have limited transferability to the UK at present, the political will to maintain support policies is critical. The success in sustained long-term policy has been identified as another key advantage of Nordic countries in EfW development (Cross *et al.*, 2021).

The awards of policy instruments are well recognised as essential for the developments of EfW projects. According to Cross *et al.* (2021), there is a clear positive correlation between the number of policies that are created to support the bioenergy sector, including EfW, and the level of energy that is generated over time. However, the political instruments available for EfW development in the UK have also been a subject of debate. The effectiveness of policy instruments for the sustainable development of the bioenergy sector in different countries, including the UK, has been an important theme for analysis by researchers and for debate by stakeholders (Thornley and Cooper, 2008; Thornley and Prins, 2009; Purkus *et al.*, 2015; Cross *et al.*, 2021)

The uncertainty and lack of continuity in energy policies, the support scheme timescale, the reduced capacity of adaptability of energy policies to the contextual needs, as well as the inadequate type of support – largely dependent on the technology's readiness level of commercial maturity – have been identified as political barriers to EfW development. Additional concerns related to the lacklustre behaviour from the government to manage the policies have also been identified. This includes the time taken by the government to make changes in the policies, and the unclear vision from the government on the direction to be taken (Thornley and Prins, 2009; Purkus *et al.*, 2015; Röder, 2016; Cross *et al.*, 2021).

Several researchers maintain that the focus of policy intervention needs to be aligned with the technology's stage of commercial maturity; otherwise, the technology and market's development would be at risk (Thornley and Prins, 2009; Purkus *et al.*, 2015). Technologies should be supported at early stages with investment subsidies, and then at medium and late stages with other initiatives such as funding (Thornley and Prins, 2009). Furthermore, policy makers use specific incentives to steer technology and feedstock choices or leave them neutral and allow market actors to make the choices. Studies such as those by Thornley and Cooper (2008) and Purkus *et al.* (2015) contribute towards understanding these differences and how political instruments and uncertainties develop a sector in a certain way. These studies carried out comparative evaluations of bioenergy policies in different countries, including the UK, and analysed their implications on the sector. For example, in the case of the UK, driven by supports such as the ROCs, the bioenergy sector has been managed through market forces, where the price was not regulated. Since the price was not regulated, EfW producers looked for lower cost technologies ensuring they complied with environmental obligations. Since, lower costs are usually achieved by the larger producers who can play with economies of scale, this enabled the establishment of large-scale plants. The system was boosted by commercial motivations and regulation compliances set by the government (Purkus *et al.*, 2015). Hence, this explains the centralised distribution of EfW large-scale plants in the UK (Cross *et al.*, 2021).

Likewise, findings from studies have also corroborated that influences are not so much from the policy instruments in place, although incentives are essential for bioenergy and EfW development, but related to the policy design of a nation, which is strongly linked to the culture and history of the nation, i.e., the national context (Purkus *et al.*, 2015; Cross *et al.*, 2021). The study from Cross *et al.* (2021) evaluated the progress in development of the bioenergy sector in the UK and Nordic countries, and concludes that ´Given that different countries have unique policy landscapes and market contexts, the changing dynamics of the energy landscape in one country may have a different collective impact on the renewable sector compared to a similar change in another country´ (Cross *et al.*, 2021, p.11). Additionally, Cross and colleagues (2021) also highlight that policy alone does not drive increased energy generation, but that it is the relationship between energy generation and wider independent variables that collectively characterise the energy, economic and environmental landscape of the countries. In other words, it is the interactions between technological, environmental, economic, social, and political factors that shape the direction of the sector.

Conclusions

This chapter has identified some of the opportunities and barriers driving and undermining EfW development in the UK, focusing on both technical and non-technical aspects. The EfW sector interacts in a complex way with the waste management sector and the CE; an improved understanding of these interactions is key to envisaging the potential contribution that the EfW sector can have in the energy transition to a low carbon economy.

The CE is opening up opportunities for the EfW sector, which could simultaneously address concerns over energy demand, GHG emissions, waste management, resource efficiency, and energy recovery. However, for this to happen, the current linear economy, in which resources are extracted, turned into products, used once and then disposed or sent abroad, must be replaced. The UK must find a way to integrate, in a sustainable way, both the waste management, and EfW sectors. Gasification and AD technologies seem to have more opportunities for integration within the CE; however, for this to happen, several technological, economic, social and political barriers will need to be overcome.

The EfW sector is intrinsically linked to the waste management sector and this, in turn, is largely influenced by legislation on waste management at a national and international level. Due to the WFD and Landfill Directive, over the last years, the UK has been increasing its recycling rates, and energy recovery infrastructure, to a point that EfW has now become an important waste management alternative. Moreover, the literature suggests that while recycling rates in the UK have been plateauing in recent years, the EfW has continued to increase. This suggests that there is a lack of infrastructure for handling and managing the waste in accordance with the upper stages of the waste hierarchy. Limitations for greater recycling are due to multiple technological, economic, social and political factors, which are not only associated with the waste management front-end activity of handling and sorting, but also with the interdependency/interactions of the waste management sector with the EfW sector. These factors, in turn, are also interrelated, bringing to light the interactions between both technical and non-technical aspects, and providing greater complexity to the topic. Furthermore, led by market forces, the UK has become the main exporter of waste (RDF to European countries, and recyclables to non-European countries), and while the UK seems to see the waste as a nuisance, European countries receiving the RDF often see the waste as a resource providing them with energy. However, the export situation is changing. Countries are putting in place political restrictions and market pressures on the importation of waste. It is expected that the UK will experience difficulties stemming from this in the future. The UK is under pressure to find more sustainable solutions and make a more efficient use of its own waste. For this, there must be a clear direction set up, which with such an array of opportunities and barriers becomes complex. Clear and comprehensive studies and/or data will help to build a better understanding and aid advancement in the field. This thesis aims to contribute to this need.

The EfW sector is highly complex on its own and influenced by a wide range of opportunities and barriers that may themselves be equally complex. There is a wide variety of technologies as well as a wide variety of energy outputs. Consequently, there are many possible pathways and each would contribute to the decarbonisation of the specific energy sector. The technologies under evaluation are: incineration, gasification and AD. Each of the technologies has its own technology, economic, environmental, social, and political opportunities and barriers, which may themselves also interrelate between each other.

The decarbonisation of the heat sector is seen as challenging in the UK. The full potential of the EfW sector lies in the ability to use the heat from the process, but this requires development, and deployment of heat networks, which are currently scarce in the UK. This has been associated in the literature with different technological, economic, social, and political barriers. The need to look into the Nordic countries´ experiences in the use of heat has been widely emphasised in the literature. Furthermore, given the demographic situation of the UK, and the need to decarbonise the different sectors, small scale plants are also seen as better alternatives to ensure energy supply, and enable the full potential of the EfW process with the waste heat generated being readily available for use in district heating networks. However, this also has technical and non-technical factors.

There is strong uncertainty about the direction to take in the EfW. This is due to:

- Interaction/interdependency of the EfW sector with the waste management sector and strategies: the lack of clarity about what will happen to the recycling rate in the future, whether it will increase or stagnate, and whether or not exports will cease.
- Controversial thoughts in terms of the environmental impacts associated with some EfW technologies and the role that these technologies should have in the transition to a low carbon economy.
- Unclear political strategy of support of technologies and energy outputs by the UK Government.

Overall, the literature has shown that the impacts of the EfW sector extend far beyond techno-economic and environmental factors, and due recognition must be given to the full range of social, political, environmental, and techno-economic impacts in any assessment.

When taking into account opportunities and barriers identified in the literature, it is important to note that the development of EfW becomes contested: there seems to be substantial support for development from some groups, such as those of the government departments and industry which are investing in the deployment of these technologies and developing policies for their implementation. However, others, such as NGOs, and the public, seem to consider their impact to be environmentally and socially negative and believe, therefore, that further development should cease. As discussed in this chapter, this is partly due, to differences between stakeholders' interests, values and priorities. If EfW is to be developed to its potential, it is necessary to understand the perspective of stakeholders involved in the EfW sector.

Furthermore, considering the strong interrelation of the waste management sector and the EfW sector, addressing the issues of the waste management and EfW sectors independently, without a holistic view of the interactions between the sectors and the different factors, may lead to unsustainable development and potential losses of opportunities to manage and use the waste in the most efficient way. Consequently, an improved understanding of these interactions would help to visualise the impact of the EfW sector in the UK, identify the direction that it should take, to commit to a sustainable development and deployment of it, in line with the waste hierarchy, the CE and the development of a low carbon economy, thus contributing to the 2050 net zero target.

The following Chapter 3 presents the research design and methods implemented in this research.

Chapter 3. Research Design and Methods

The previous two chapters have provided the contextual foundation for this thesis, presenting an extensive review of the Energy and Fuels from Waste (EfW) sector in the UK. The aim of this chapter is to outline the Multicriteria Mapping (MCM) methodological process that will be implemented in this research.

In Section 3.1, the selection of MCM is justified and an overview of the MCM tool and its framing is provided. Section 3.2 outlines the methodological design of the process including elicitation, analysis and development of options/pathways for appraisal, and the adaptation of the MCM tool for the purposes of this research. In Section 3.3, the MCM process is explained with respect to participant scoping and recruitment and the conduct of interviews. Finally, the quantitative and qualitative methods of analysis that will be used are described in Section 3.4.

3.1 Multicriteria Mapping

In this section, the choice of methodology is justified with reference to the origin and baseline of the project in question. This discussion will be followed by a detailed description of the Multicriteria Mapping (MCM), i.e., the social appraisal method that has been selected for this research.

3.1.1 Selection of Method

There is a wide variety of methods for sustainability valuation and appraisal (Stagl, 2007; Dodgson *et al.*, 2009). Depending on the type of valuation and level of participation, sustainability valuation methods can be classified into different categories. These include Monetary Valuation techniques, Multi-criteria Analyses (MCA), Multi-criteria Evaluation (MCE), Multicriteria Mapping (MCM) and Participatory and Deliberation approaches (Stagl, 2007; Gerber *et al.*, 2013; Coburn and Stirling, 2014). These MCA, MCE, MCM and Participatory and Deliberation approaches have been defined by Coburn and Stirling (2014) as “social appraisal” methodologies.

Narrow technical assessment processes, based on risk assessment such as monetary valuation techniques like cost-benefit analysis (CBA) and cost-effective analysis (CEA), have been extensively used in policy analysis, such as transport, health and safety, energy, technology and environmental problems, including climate change and waste management. Some of these expert-based quantitative approaches, however, have a bias in common: they treat the concept of risk as an objectively determined quantity and, consequently, they look for a single result, by identifying the "best" solution out of a series of options (Stirling *et al.*, 1999). However, focus on a single solution often fails to reflect the wide complexity of the topic in question. Technological, societal, ethical, cultural or environmental aspects are often very much present at the moment of decision-making and might have different dimensions of value. In fact, when dealing with complex systems, there is not one sole, rational way to aggregate different dimensions of value along a single metric (Stagl, 2007). These narrow approaches make it difficult to understand the conflicting interests that reflect a diversity of choices, solutions, and viewpoints.

To overcome these shortcomings, a wide range of methods that combine the use of participatory techniques and multicriteria analysis have emerged (Stagl, 2007). The aim of such approaches is to provide a tool for decision making that takes conflicting interests and multiple criteria into account. Methods such as the MCA, MCE, MCM and Qualitative Participatory Deliberation (QPD) allow measurement of conflicting impacts in different units (monetary and non-monetary) and in different ways (quantitatively and qualitatively). In addition, as participatory techniques, they are characterised by different levels of participation. Multicriteria analysis approaches tend to involve experts only, leading to a more closed decision making process, while participatory and deliberation methodologies allow for a higher level of stakeholder engagement (including non-experts' participation), transparency and social learning, opening up the decision making process (Stirling, 2008; Coburn and Stirling, 2014). Direct and indirect stakeholders (experts and non-experts) involved in decision-making, may perceive and value conflicting interests differently. Under these circumstances, it seems that both quantitative and qualitative approaches are important and that recognising and acknowledging stakeholder perceptions, attitudes, behaviours and practices is critical to increase legitimacy and sustainability in decision-making.

The multicriteria process consists in identifying and selecting different alternative pathways in relation to specific objectives. After consideration of the different stakeholders in the decision-making process, a set of values and preferences are established to assess the extent of the objectives (Stagl, 2007; Dodgson *et al.*, 2009). The mainstream of multicriteria approaches share a four-part framework (Stagl, 2007; Dodgson *et al.*, 2009; Coburn and Stirling, 2014) consisting of:

- 1) identification of a set of alternative ways ("options" or "pathways") to achieve a specific aim – the terms "options" and "pathways" are used interchangeably along this research;
- 2) development of a set of "criteria" to reflect the relevant factors that affect the appraisal of options;
- 3) evaluation of each option through numerical scores to reflect their performance under each criterion;
- 4) assignment of a quantitative "weighting" to each criterion, to reflect its relative importance under a specific viewpoint.

The result of these four steps is the calculation of an overall performance rank for each option under all the criteria taken into consideration for a particular viewpoint.

MCM is a multicriteria decision analysis tool, named "Multicriteria Mapper", developed by Stirling (1997). It was originally conceived to allow stakeholders to explore different options/pathways under different circumstances, with the aim of developing a sensitivity map that charts the technology and policy choices preferred by different individuals, constituencies or agencies at a certain moment (Stirling, 1997). In the words of Stirling, 'the aim of MCM is to explore the ways in which different pictures of strategic choices change, depending on the view that is taken – not to prescribe a particular "best choice"' (Coburn and Stirling, 2016 p9).

The MCM takes into account policymakers' need to have a clear, in-depth understanding of different stakeholders' viewpoints. This understanding is important, not only in helping policymakers decide which measures to introduce, when to introduce them, and how to sustain them. It can also provide foresight into potential problems that may arise and this can, in turn, permit the development of anticipation actions (Stirling *et al.*, 2007).
To this end, the mapping methodology must take into account a range of dimensions, including the different stakeholders, the types of options available, the criteria to be considered, both individually and collectively. The results of this process can provide, based on stakeholders' inputs, a ranking of options and priorities. The process helps to address several questions. For instance, it helps to identify the most and least supportive options and criteria, and to assess the relationship between priorities and the type of stakeholder. In addition, it opens the path to judgements and uncertainties shown by participants along the process, through the meanings, selection, understanding, and prioritization of options and criteria (Stirling *et al.*, 2007).

3.1.2 Origin and Baseline of the Research Focus

This project was initiated with the support of the Energy Technologies Institute (ETI), which is now closed. It is based on the ETI's waste gasification project (*Homepage | The ETI*, 2021) led by Kew Technology Ltd. Kew Technology Ltd was funded by the ETI to develop and build a 1.5 MWe advanced gasification demonstration plant in Wednesbury in the West Midlands. The operational plant is designed to process about 40 tonnes per day of Municipal Solid Waste (MSW) and Commercial and Industrial wastes (C&I) which are very similar in composition, coming from the local areas. Wastes are treated to become refuse derived fuel (RDF) and converted, in the gasifier, into a clean syngas. First, unwanted contaminants are removed and the gas is made as clean as natural gas. Next, the syngas is converted to electricity and heat in a gas engine. It is expected to produce enough electricity and heat for 2500 homes and 1000 local centres, respectively.

Both ETI and Kew Technologies Ltd. were interested in assessing the perceptions and interests of the different stakeholders involved in their gasification technology plant. When they were introduced to the MCM approach, they were especially interested in its ability to provide comparisons between pathways involving different technologies of the Energy and Fuels from Waste (EfW) sector. They saw this as a potentially useful tool to review the competitiveness of the sector and to assess the consequences of previous and forthcoming decisions. Both ETI and Kew Technologies Ltd. acknowledged that being able to identify and assess interests and values of different stakeholders, when it comes to selecting competing technologies in advanced gasification, could provide them with highly valuable information and significantly facilitate future decision-making processes, in the short and long term. Hence, instead of focusing only on their gasification technology and the Wednesbury plant, they suggested to broaden the scope of the project by including other technologies of the EfW sector. This led to selecting the MCM as a suitable method for this research project.

3.1.3 An Overview of MCM

The MCM approach is a software-based tool that allows to build a "map" of the debate surrounding any issue that may be concerning, slowing down or influencing the decision-making process of a complex topic. Within the same assessment framework, it allows for inclusion of multiple public perspectives (opinions, interests, and concerns) from multidisciplinary arenas. The MCM tool gathers both quantitative and qualitative information, and this provides a balance between the precision of numerical approaches and the arbitrariness of methodologies that rely on subjective decisions and public participation. As such, it can provide an illuminating, pluralistic, reliable, and transparent reflection of the issues, understanding, knowledge, and still unresolved gaps that might help policymakers to find a better approach to decision-making (Stirling *et al.*, 1999; Stirling, 2008; Coburn and Stirling, 2016).

This MCM approach has been used in the fields of energy, technology and climate change (McDowall and Eames, 2007; Hansen, 2010; Bellamy *et al.*, 2013, 2014; Raven *et al.*, 2017), food and agriculture (Stirling and Mayer, 2001; Thompson, 2009; Harriss-White *et al.*, 2019), health and nutrition (Davies *et al.*, 2003; Lobstein *et al.*, 2006; Stirling *et al.*, 2007; Holdsworth *et al.*, 2015; Lubogo and Orach, 2016; Greffeuille *et al.*, 2019) , biomedical technologies and lifestyle (Jones, 2010; White and Stirling, 2013).

The main difference between the MCM and other multi-criteria techniques is that the MCM does not impose meanings, options, criteria or weightings, but it is the participants who generate these meanings, options, criteria and weightings along the process. In addition, as the MCM analysis framework is not fixed, the participants can add elements along the different stages as they wish, going forwards and backwards at any time. This provides flexibility when evaluating the problem.

The researcher can either establish an initial set of options, to which participants are free to add further ones, or, alternatively, options can be entirely defined by the interviewees. This approach is available also when it comes to defining criteria. In addition, results can be analysed from different perspectives: by individual viewpoints or stakeholder categories or by most or least supported criteria. Further, rather than emphasising the stakeholders' points of view, the focus can also be on the resulting maps of options performing across perspectives, or on the scoring and weighting part where documented "judgements" and "uncertainties" have been gathered through quantitative and qualitative methods (Stirling *et al.*, 2007). Hence, the strengths of the MCM are its flexibility and capacity to broaden the scope of appraisal to include multiple framings and perspectives, thereby opening up the debate. Further, the quantitative data is accompanied by rich qualitative data, and this helps to obtain a better understanding in terms of uncertainties and divergent values surrounding the topic in question.

By contrast, the perceived weaknesses of MCM are related to its capacity of opening up debate, which may lead to over-interpretation. This might adversely affect the justification of certain decisions and have the effect of destabilising closure. The latter therefore implies a rigorous analytical exploration of the different aspects (Jones, 2010; Bellamy, 2013; Coburn and Stirling, 2014). Further, a critical point raised by Hansen (2010) is that MCM provides a snapshot of participants' perspectives at the time of the study, but it does not necessarily reflect the actual situation once the study has been concluded. In other words, the MCM allows participants to gain further understanding of points of views and to acquire knowledge about technical, economic, environmental, societal and political issues. This understanding, in turn, might or might not change their perspective after further reflection.

A brief overview of the method is outlined in the following subsection; further details are available from the MCM Manual (Coburn and Stirling, 2016). Figure 3.1 below shows the four-step structure with an overall ranking chart, which can reflect the point of view of one single participant, of a specific group of participants, or can represent the overall point of view of all the interviewed participants.

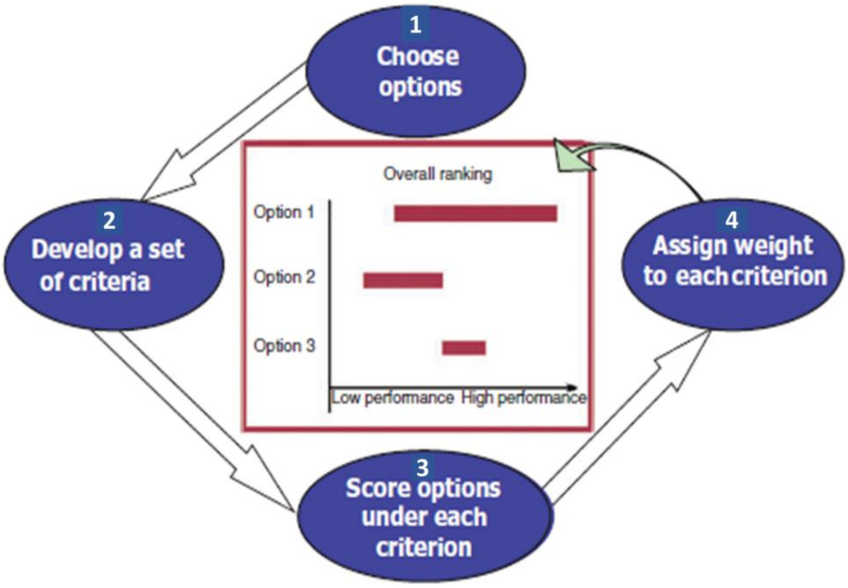

Figure 3.1. Four-stages procedure used in MCM, from Stirling, Lobstein and Millstone (2007)

3.1.4 The MCM Four-Stage Process

This section outlines the MCM process, which consists of four stages plus a final overview stage. The one-to-one interviews with stakeholders, which take two to three hours, are conducted through the "Multicriteria Mapper" software tool (Coburn and Stirling, 2016).

Before the implementation of the four MCM stages, three additional pre-stages were needed in order to adapt this methodology to my research project. These were the identification and recruitment of participants, the ethical approval procedure, and the definition of options/pathways to be appraised (coherently with my decision to define a set of options/pathways from the start), as will be explained in Section 3.2. In other instances, the MCM approach may be undertaken with nil pre-defined options, in which case options for appraisal are entirely provided by participants.

3.1.4.1 Stage 1: Choose Options/Pathways

The first stage consists in the selection of options to be evaluated. Three types of options may be identified: “core options”, “discretionary options”, and “additional options”. The “core options” are the main alternatives, that are the mandatory pathways that must be assessed by all participants. Because they are evaluated by everyone, it is the core options that allow for the systematic and structured comparison between all the interviewees. Usually, these are set by the researcher/s, who may spend months or years gathering information on the topic, either through individual research or through collaborations with specialists, before the actual MCM process implementation starts. Occasionally, however, the definition of options is left entirely to participants at the start of the MCM procedure.

In addition to the core options, the MCM approach allows for the inclusion of “discretionary options” by the researcher and/or by participants. They are called “discretionary options” when the participants can choose whether to evaluate them or not. “Core options” and “discretionary options” are also defined, collectively, as “pre-defined options” (Coburn and Stirling, 2016).

Thirdly, there are “additional options”, which are included if the participant feels that none of the predefined options captures an aspect that they believe important to discuss.

Once core and discretionary alternatives are defined, they are explained to the participants. The explanation needs to be as objective as possible, so that researchers’ opinions will not influence the points of view of participants along the process. Once the options are understood, participants are asked to include further alternatives, if they consider them to be relevant for the evaluation process. Good examples of this procedure are found in the studies done by Bellamy et al. (2013, 2014); Hansen (2010); A. Stirling & Mayer (2001) and Thompson (2009).

3.1.4.2 Stage 2: Criteria Definition

The second stage consists in the creation and definition of criteria. Individually, each participant elaborates a list of criteria that they consider relevant for evaluating the objective, or the group of options that target the same objective. The MCM allows for the specification of two types of criteria, which are classified into criteria and principles, a distinction that can appear confusing but that is based on the concept of trade-off. Criteria are factors that can be traded off, when choosing and comparing the pros and cons of the different options against each other. Conversely, a principle reflects an ethical or institutional point of view, which cannot be traded off (Hansen, 2010; Coburn and Stirling, 2016).

The diversity of participants with their individual perspectives, interests, understanding, knowledge and attitudes towards the issue under evaluation will result in the definition of a wide number of criteria. Criteria, as noted above, must be defined by participants at all times to make sure that a clear understanding of the context given by each participant is gathered. This results in the collection of qualitative data. In addition, by allowing participants to identify and define their own criteria, the MCM approach is sensitive and inclusive to individual perspectives, which would not be possible if criteria were defined by the researcher in advance. For example, Stirling, Mayer and Vine´s (1999) study on genetically modified (GM) crops allowed each participant to provide up to 12 criteria, which resulted in a total of 117 criteria.

Alternatively, a set of criteria can be initially defined by the research team, if there are specific factors that need to be assessed. For instance, Hansen (2010) applied what could be called a “half-definition” criteria process, because it started off with a set of 66 criteria identified through literature review, and then allowed MCM stakeholders to narrow them down to 24 criteria.

Once defined, criteria are usually grouped into broader categories, which enables researchers to qualitatively represent the major issues identified by stakeholders.

3.1.4.3 Stage 3: Assessing Scores and Explore Uncertainty

The third stage is the scoring stage and consists in evaluating the relative performance of the different options (selected in stage 1) under each of the different criteria (identified in stage 2). In the evaluation, participants are asked to give a pessimistic and optimistic score for each option on a scale chosen by the participants themselves (usually a 10-point or 100-point scale), with high scores indicating good performance and low scores indicating poor performance. The aim is to capture how well or poorly an option performs when judged under a particular criterion.

Then for the optimistic score: if everything went well, how well could an option perform when judging it by a particular criterion? For the pessimistic score: if everything did not go well, how poorly could an option perform when judging it by a particular criterion? Participants are also asked to explain the reason behind the scores. The interval between the optimistic and pessimistic scores given to the option under a specific criterion captures the degree of uncertainty and variability around the performance of the option, in accordance with the criterion under evaluation. The data collected in this stage are primarily quantitative, but they also include qualitative information on the perspectives of each participant (Stirling and Mayer, 2001; Dodgson *et al.*, 2009; Hansen, 2010; Coburn and Stirling, 2016).

However, in case an interviewee has also defined one or more principles, the assessment process does not involve a numerical score, and each option is simply classified as either "acceptable" or "unacceptable" under that principle (Coburn and Stirling, 2016: 40). If an option is unacceptable, it will be ruled out from evaluation for the participant interview.

3.1.4.4 Stage 4: Assigning Weights

The fourth stage is about assigning weights to each of the criteria in order to rank their relevance. Each participant can express the relative importance they attribute to each criterion, which enables the identification of different interests and priorities. In the MCM software, weighting is done using a 100-point scale, and the weights are then normalised. This stage combines quantitative data, obtained from the scoring, with qualitative data, since the prioritisation of criteria will be highly subjective for each participant (Stirling and Mayer, 2001; Dodgson *et al.*, 2009; Hansen, 2010). As in the previous stages, the qualitative data is obtained from the reasons and explanations that the participants provide as they report the scores and weights they assign to each of the criteria, and the reasons why they give it. The MCM software enables notes boxes where the qualitative data can be included as the interview is happening. Additional qualitative data from recordings or transcripts can also be loaded into the MCM software after the interview.

3.1.4.5 Stage Overview: Final Ranks and Reflect on Outcome

Once scores and weights are established, the final performance rankings of the options under the various criteria can be visualised on the computer screen. In this last stage, the software multiplies the scores of each criterion by its weightings score and, for each of the options under appraisal, each graph shows the overall ranking. The extension of the horizontal bars shown in Figure 3.1 reflects the option's overall performance under a particular perspective. The rank's extremes reflect the pessimistic and optimistic value attributed by the participant in question to that particular option. This provides a useful indication of the option's uncertainty: the greater the length, the greater the uncertainty. In addition, the further to the right, the better the performance (Coburn and Stirling, 2016). At this stage, participants are shown the overall picture that their appraisal has produced, and they are asked if they are happy with the final ranks or if there is something that surprises them, and they want to explore further. If so, it is possible to return to an earlier MCM stage and make changes, if desired. If changes are made, they will be recorded quantitatively and qualitatively.

3.2 Preparation Phase: Adapting the MCM to the Research Project

Whereas the previous section has provided an introduction to the general MCM methodology, this section will turn to the specific approach undertaken in this project. As mentioned in Section 3.1.4, three essential pre-stages were needed to adapt this methodology to my research project, before the MCM process could be implemented. As I personally developed the options to be appraised, one of the pre-stages consisted in defining these options. As mentioned earlier in this chapter, the terms "options" and "pathways" are used interchangeably along this research. From now on I will stick to the term "pathways", when referring to the "options" term of the MCM approach (see Section 3.1.4.1 Stage 1: Choose Options/Pathways).

Previous applications of the MCM approach have involved the appraisal of technological pathways. As an engineer by background, the project by McDowall and Eames (2006, 2007) focusing on the appraisal of long-term hydrogen futures in the context of a back-casting exercise was of particular interest and relevance to my own. I found the extrapolation of the back-casting exercise of McDowall and Eames (2006, 2007) project to the context of EfW pathways an effective way for capturing and assessing perspective between competing EfW technologies. The back-casting exercise for this project is explained in Section 3.2.1. The pre-stage consisting in the definition of pathways was followed by the identification and recruitment of participants and the ethical approval procedure, to finally reach the stage of MCM implementation.

Hence, the methodology developed for this research comprises the following pre-stages: 1) scope of process and pathways development; 2) stakeholder participant identification and recruitment; 3) ethical approval, as explained in detail below.

Figure 3.2 below illustrates the overall MCM process as it was adapted to this research, with the pre-stages incorporated into the diagram.

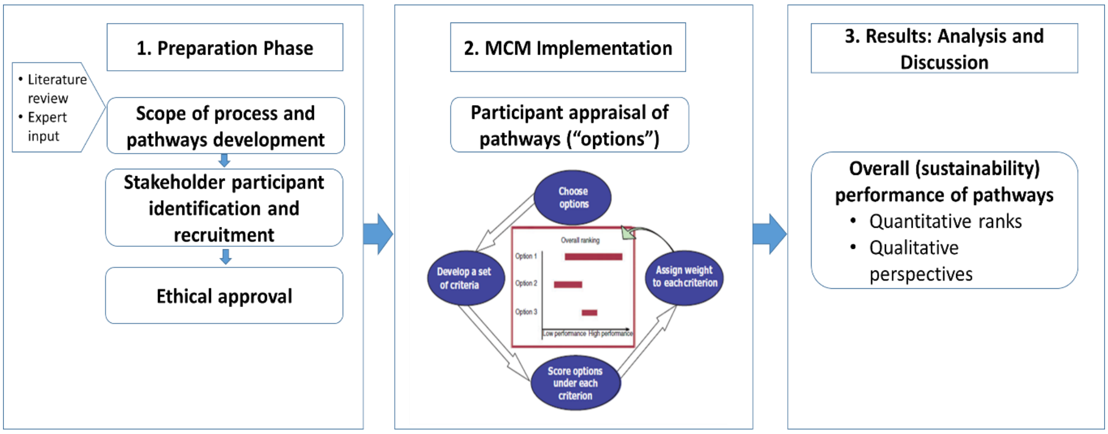

Figure 3.2. Overall Multicriteria Mapping (MCM) process

3.2.1 Pre-stage 1: Scope of Process and Pathways Development

The aim of this first pre-stage was to create a set of different plausible and consistent end points that strike a balance between the particularities of the pathways and the coverage of the EfW sector with its potential contribution to the different energy demand sectors in the UK.

The scope consisted in the implementation of the technologies of incineration, gasification and anaerobic digestion (AD) for the production of different energy outputs, through the use of MSW and C&I waste streams.

Six core pathways were developed. These were: 1) Business as Usual (BAU); 2) Centralised Gasification for the decarbonisation of the transport sector; 3) Decentralised Gasification for the decarbonisation of the heat sector; 4) Decentralised Gasification for the decarbonisation of the transport sector; 5) Decentralised Anaerobic Digestion for the decarbonisation of the heat sector; and 6) Decentralised Anaerobic Digestion for the decarbonisation of the transport sector. The full pathways can be found in *Appendix 1.1*, as part of the *"Expert Booklet"*. Each pathway differs in relation to the waste streams used as feedstock, the technology deployed and the degree of centralisation or decentralisation of the pathway, the energy output (whether power, heat, liquid biofuels, synthetic natural gas and bio-methane) with the degree of production and contribution to the UK total energy demand.

The pathways were initially developed through a comprehensive review of the literature. Afterwards, a series of scoping face-to-face and telephone conversations with ETI helped to map the expectations on the future of these technologies. In order to outline the structure and narrative of the pathways, their development was divided into three stages, which will be described in more detail in the following section. Such stages were: 1) selection of technologies for conversion and energy outputs; 2) waste availability in the UK to consider as input for the energy pathways; 3) contribution of the pathways to UK total energy demand.

3.2.1.1 Selection of Technologies for Conversion and Energy Outputs

The first stage of pathway development consisted in identifying the technologies to take into consideration for pathway appraisals.

The decision to include incineration, gasification and AD in the different pathways in order to enable a comparison was the result of in-depth discussions with representatives of the ETI, Kew Technology Ltd, and academic and industrial supervisors in 2016 and 2017. The decision to use these technologies was not a simple one but was the result of an ongoing series of decisions and considerations taken to frame the scope of the project. These considerations were related to both the type of feedstock and the energy outputs that were of interest to include within the pathways for its appraisal.

To give context to these considerations, as mentioned in Section 3.1.2, the ETI and Kew Technology Ltd. developed a 1.5 MWe advanced gasification commercial demonstration plant in Wednesbury, in the West Midlands. The operational plant is designed to process about 40 tonnes per day of MSW and C&I waste sourced from the local area which will be treated to become RDF and converted into a syngas. This syngas is subsequently made as clean as natural gas prior to its use in a gas engine to produce electricity and heat. The plant is expected to produce enough electricity and heat to supply approximately 2500 homes and 1000 local centres, respectively. Both ETI and KEW Technologies Ltd. were interested in assessing and acknowledging the perceptions and concerns of the different stakeholders regarding their gasification technology plant. When the MCM approach was explained to them, ETI and Kew Technology Ltd. were interested in its ability to provide comparisons between pathways that could include different technologies of the EfW sector. They saw this as a potentially useful tool to review the competitiveness of the sector, and to assess the consequences of previous and forthcoming decisions. Both expert organisations (ETI and Kew Technology Ltd.) acknowledged that being able to identify and assess interests and values of different stakeholders, when it comes to assessing competing technologies in advanced gasification, could significantly facilitate future decision-making processes in the short and long term. Hence, instead of focusing only on their gasification technology and the Wednesbury plant, they suggested to broaden the scope of the project and include other technologies of the EfW sector.

At this stage of the pathway development process, the range of technologies to consider was too broad since there are various methods to process waste. It was necessary to draw a line in terms of the number of technologies to investigate within the time constraints of the project, while ensuring exploratory research. As discussed in the literature (Section 2.3.1), EfW conversion processes can be grouped into two main categories: thermochemical (for example, incineration, gasification and pyrolysis for the production of electricity, heat, fuels and/or chemicals), and biochemical (for example, composting, advanced fermentation to produce for example, ethanol, and AD to produce methane).

The selection of technologies to be included was driven by a series of technical considerations, along with the interests expressed by the two industrial supporters of the project. The series of technical considerations and discussions, which led to include incineration, gasification and AD, highlighted the following main points:

- Based on the characteristics of the type of fuels used and energy outputs produced by the Wednesbury plant, two reference points for the selection of technologies were established. These were: 1) the use of different energy recovery routes for MSW and C&I and 2) the use of different energy routes for MSW and C&I which enable the production of power, heat, liquid biofuels and chemicals as energy outputs.
- There is competition between well-established waste incineration technologies and the emerging gasification technology. Both technologies enable the production of heat and power, but gasification also enables the production of liquid biofuels and chemicals. Kew Technologies Ltd and ETI expressed an interest in understanding the opportunities and barriers that the different stakeholders identified in the choice between incineration and gasification technologies. Hence, incineration and gasification technologies were included.

- The biological route of AD is an interesting alternative for the utilization of the organic fraction of MSW. Incineration and gasification also use the organic fraction of MSW as feedstock. This means the three technologies are competing for the same feedstock.
- Currently, there is considerable debate on whether the MSW should be used for the production of power, the decarbonisation of the heat sector or the decarbonisation of the transport sector. One of the aims of the pathways appraisal was to explore the perspectives, interests and thoughts of participants in terms of what energy output these technologies should be targeting. Outside the conventional thermal conversion of wastes, the policies for decarbonisation of the transport sector have recognized the potential for utilizing wastes for the production of transport fuels (Waldheim, 2018). For this application in the UK setting, gasification is a key technology. In addition, AD technology enables the production of biogas which could be used for the decarbonisation of both the heat and the transport sectors. It also produces digestate which has the potential to be used as fertilizer.

The combination of the three different technologies selected with the different energy outputs that these technologies allow enabled to establish the creation of the six potential alternative pathways (see Table 3.1 below) to assess with the MCM. Four of these conversion pathways were thermochemical, whereas two were biochemical.

Table 3.1. The six core pathways of Energy and Fuels from Waste

Pathway	Technology	Energy Outputs
Pathway 1. Business as Usual. Centralised Incineration EfW Pathway.	Incineration	Power
Pathway 2. Centralised Gasification EfW Pathway. Displacement of incineration.	Gasification	Power or liquid biofuels
Pathway 3. Decentralised Gasification EfW Pathway. Decarbonisation of the heat sector.	Gasification	Power and heat or synthetic natural gas to gas grid
Pathway 4. Decentralised Gasification EfW Pathway. Decarbonisation of the transport sector.	Gasification	Liquid biofuels
Pathway 5. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the heat sector.	Anaerobic Digestion	Power and heat or bio-methane to gas grid
Pathway 6. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the transport sector.	Anaerobic Digestion	Bio-methane for transport

Pathway 1. Business as Usual (BAU). Centralised Incineration: The UK EfW sector is focused on conventional incineration technologies for the production of electricity. This electricity is supplied to the domestic and non-domestic sectors. Limited recovered heat is used for industrial facilities closely located to the plant. The heat that could be supplied to the domestic sector via heat network deployment is not a widely available option: heat network deployment over large distances from energy recovery facilities to houses and city services involves high investment costs as well as important changes on planning and design. Therefore, gas for heat for industrial, commercial and domestic use continues to be supplied by the national gas grid, and possibly in the future more electrical heating (for example through heat pumps). Gasification remains a niche technology, which struggles to come to commercial scale deployment due to weak support from government, few financial incentives for new demonstration plants, poor performance of existing demonstration plants, absence of technology-specific policy and lagging market developments. Figure 3.3 shows the conversion process for Pathway 1. Business as Usual (BAU). Centralised Incineration.

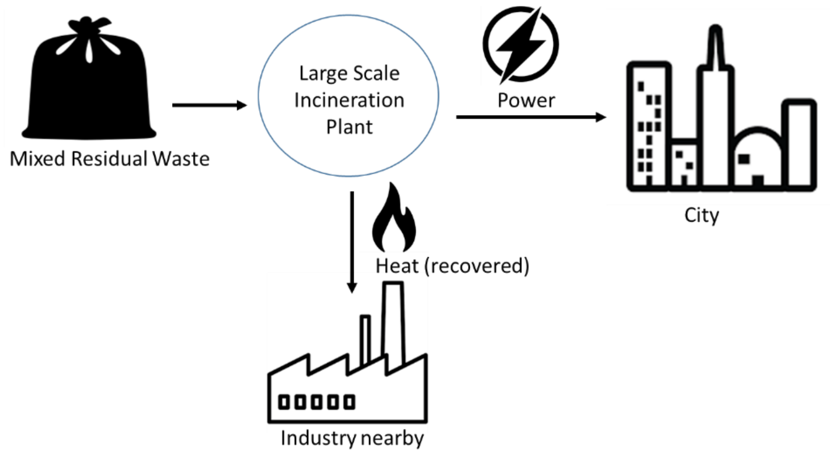

Figure 3.3. Pathway 1. Business as Usual. Centralised Incineration

Pathway 2. Centralised Gasification: Large and medium-scale gasification plants located outside cities, displace large incinerator plants, producing electricity as well as higher value liquid biofuels for the road, air and marine transport sectors and chemicals of high commercial importance including plastics precursors, cosmetics, agricultural chemicals, paints and adhesives.

Gasification contributes to the production of electricity for domestic and commercial services. Heat for industrial, commercial and domestic use is supplied by the natural gas grid. Figure 3.4 shows the conversion process for Pathway 2. Centralised Gasification.

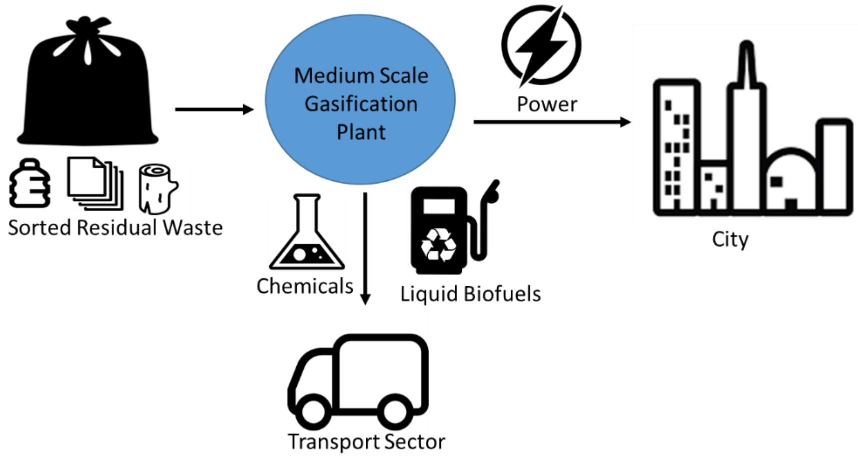

Figure 3.4. Pathway 2. Centralised Gasification

Pathway 3. Decentralised Gasification. Decarbonisation of the heat sector: The decarbonisation of heat is seen as a high priority by the UK Government. Local heat networks enable the use of local renewable energy sources at a larger scale. Fuels and heat generated at Energy from Waste facilities are a key element contributing to this decarbonisation goal. This drives strong and rapid investment in small-scale urban gasification plants, which allow the adaptability of scale to local planning needs, embedding them within cities.

The clean syngas produced from the gasification is combusted on-site to generate heat and electricity. The heat is used locally in an integrated district heating network. This entails the construction of district heating infrastructure to make use of the heat produced. As an alternative, the clean syngas can be upgraded to synthetic natural gas and/or hydrogen for its use as a natural gas renewable equivalent, injected and stored into the gas grid.

Small-scale gasification plants provide electricity and heat to domestic and non-domestic services such as universities and colleges, leisure, arts and community sectors; contributing to meeting the energy demand in the local areas. Figure 3.5 shows the conversion process for Pathway 3. Decentralised Gasification. Decarbonisation of the heat sector.

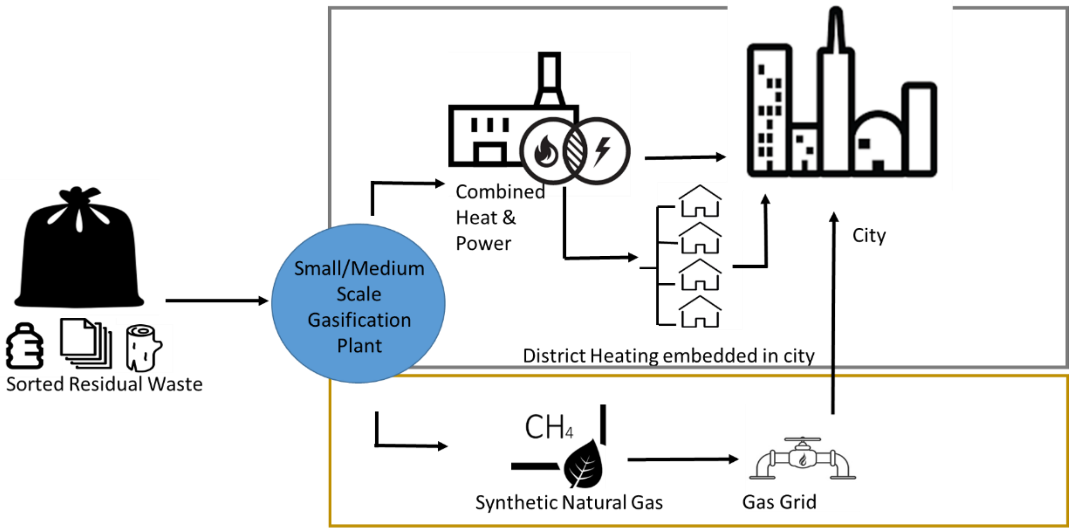

Figure 3.5. Pathway 3. Decentralised Gasification. Decarbonisation of the heat sector

Pathway 4. Decentralised Gasification. Decarbonisation of the transport sector: Gasification is exploited as a technology for the production of transportation fuels and/or higher value chemical products from waste. Liquid transportation fuels derived from waste are used within the road, aviation and marine transportation sectors. Deploying medium-scale gasification plants embedded within cities enables the recovery and use of the waste heat in district heating networks while also reducing potential transport constraints that would be associated with larger scale facilities. Large waste incineration plants located on the fringes of cities, with limited heat recovery, contribute to the supply through the generation of both electricity for domestic and non-domestic areas and heat supplied only to buildings near the plants.

Heat and power for industrial, commercial and domestic use continues to be supplied by electricity and the natural gas grid.

Figure 3.6 shows the conversion process for Pathway 4. Decentralised Gasification. Decarbonisation of the transport sector.

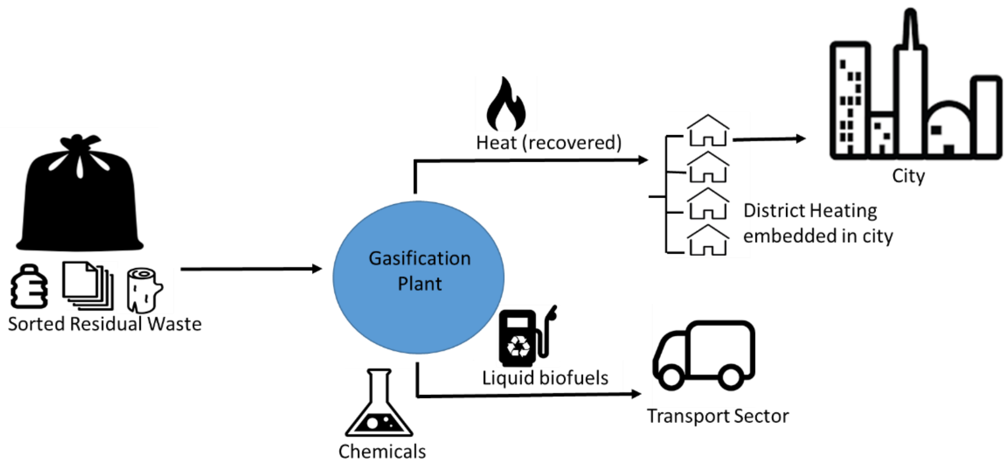

Figure 3.6. Pathway 4. Decentralised Gasification. Decarbonisation of the transport sector

Pathway 5. Decentralised Anaerobic Digestion. Decarbonisation of the heat sector: The biogas produced is used locally for the generation of electricity and/or heat for the domestic and non-domestic sector. With an integrated district heating network, the biogas is burned in a combined heat and power (CHP) process, producing electricity and heat which is then exported to the grid. This entails constructing district heating infrastructure to make use of this heat. Alternatively, the biogas can be upgraded to bio-methane for its use as a natural gas renewable equivalent, injected and stored into the gas grid. Figure 3.7 shows the conversion process for Pathway 5. Decentralised Anaerobic Digestion. Decarbonisation of the heat sector.

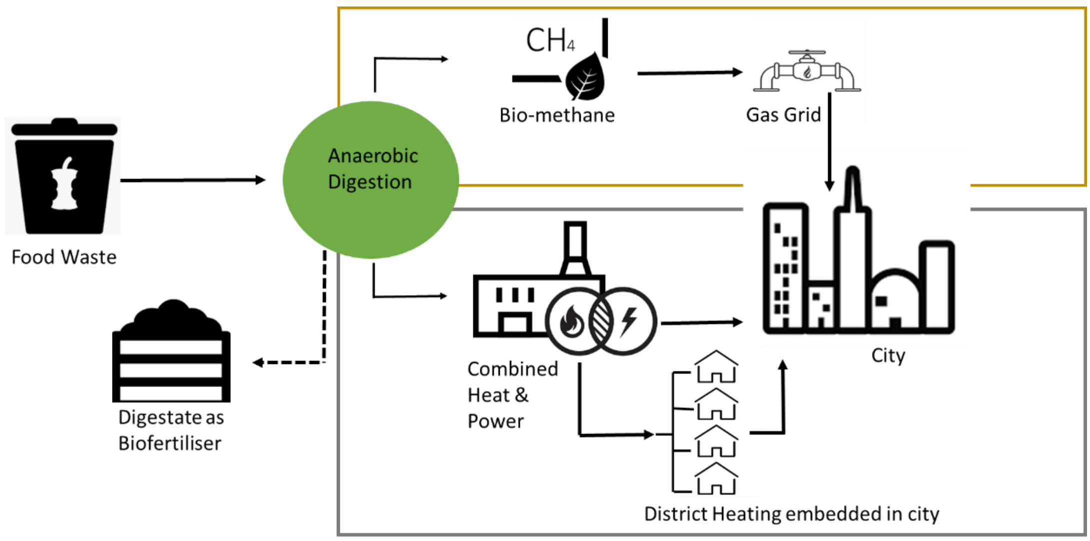

Figure 3.7. Pathway 5. Decentralised Anaerobic Digestion. Decarbonisation of the heat sector.

Pathway 6. Decentralised Anaerobic Digestion. Decarbonisation of the transport sector: The biogas obtained from the AD process is upgraded in to bio-methane for its use as transport biofuel. The deployment of AD around urban areas is dedicated to the decarbonisation of the transport sector. Figure 3.8 shows the conversion process for Pathway 6. Decentralised Anaerobic Digestion. Decarbonisation of the transport sector.

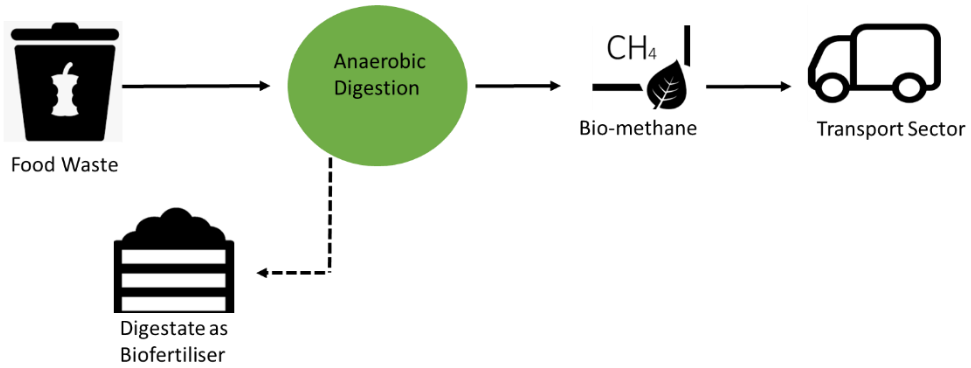

Figure 3.8. Pathway 6. Decentralised Anaerobic Digestion. Decarbonisation of the transport sector

3.2.1.2 Waste Available for Energy Recovery in the UK. Quantities and Energy Content of Different Waste Streams

The second stage in the pathways development process consisted in calculating the amount of waste available for energy and fuel recovery in the UK. This involved making assumptions on the quantities and energy content of different waste streams that could be used for the technology conversion under scope identified in the previous stage. This in turn would enable the assessment of how much energy (TWh) could be generated each year from the different energy and fuels from waste technologies.

For this purpose, a process of data collection and assessment were undertaken, with a focus on MSW and C&I waste generated in the UK. Both sector waste streams were included in the research scope because C&I waste is mixed with MSW in the waste processing industry. Therefore, most commonly, operational plants are treating both sectors' waste streams together, rather than separately.

Only specific types of waste streams from these two sectors were, however, considered for the calculation of waste availability for energy and fuel generation. On the one hand, the waste streams considered for the development of the thermochemical conversion pathways were those of high calorific value or, in other words, with high energy content, suitable for energy recovery. These were plastics packaging, paper and wood. On the other hand, the waste stream considered for the development of the AD conversion pathways was food waste from domestic, commercial and industrial facilities. This is due to the fact that whereas thermochemical processes such as incineration and gasification work most efficiently with dry wastes, AD can only process food wastes (including waste oils and food wastes from restaurants, supermarkets, and kerbside collections).

Information sources

Data on waste streams quantities were obtained from different governmental documents from WRAP (WRAPa, 2016; WRAPb, 2016; WRAP, 2010; WRAP, 2018) (RECOUP, 2017) and DEFRA (DEFRAa, 2017; DEFRAb, 2017; DEFRAc 2017), as well as from industry reports from Veolia (Veolia, 2018), the Confederation of Paper Industries (CPI, 2016), among others.

These data included total waste streams of plastic packaging, paper, wood and food within MSW and C&I waste. Depending on the waste streams, the baseline figures used are drawn from the years 2014, 2015, and 2016. Different calculations and assumptions were made regarding the conversion technologies under investigation, the quantities and energy content of waste streams, UK and European Union recycling and landfill targets, and UK waste export. These are explained in the following subsections. This permitted to establish the first figures in the pathways, which report the amount of waste input that is fed into each pathway. It is important to emphasise that the estimates of the waste stream are indicative values, aiming to provide the participants with an idea of magnitude. They are intended to be used as reference points to provide a better understanding of the different pathways in terms of both, conversion technologies' efficiencies and energy and fuels output quantities that the different pathways could potentially generate and their contribution in the UK total energy demand.

The estimation of proportions of waste streams involved several stages. The first focused on calculating the total amount of waste stream generated in a year. This was considered the baselines figure, to which different assumptions, and calculations were applied depending on the pathway under consideration. The objective of these calculations was to obtain the amount of waste going into energy recovery. Business as Usual pathway looks at the current state of energy recovery via incineration technology with heat recovery. Once baseline waste stream figures were calculated, different status quo energy recovery rates for each waste stream were retrieved. This permitted the calculation of the total amount of waste going into energy recovery for the Business as Usual pathway. The other pathways represented medium to long term potential future scenarios, employing gasification and AD as the main technologies. Different assumptions based on projection in waste stream availability, EU recycling rates and waste exports were made to estimate the total amount for energy recovery for each pathway. The baseline waste stream figure is discussed below, along with the analytical procedures and the assumptions made. The estimation of waste streams was carried out in 2017. At this stage, no updated figures were available.

Estimations on waste streams availability

1. **Plastic packaging waste**

Overall UK plastic waste in 2014 was estimated to be either 3.7 million tonnes or 4.9 million tonnes, depending on the source (WRAP, 2016; Eunomia, 2018b).

Plastic from packaging is the main source of plastic waste generation in the UK (67% of the UK plastic waste stream). The remaining plastic waste comes from non-packaging household waste as well as waste from the automotive, agricultural, construction and demolition sectors, among others (Eunomia, 2018b). As the pathways represent energy recovery from MSW and C&I waste streams, it was decided to use only the plastic packaging waste stream for the calculation of the plastic waste available.

Following the assumptions made in the aforementioned reports, the amount of plastic packaging put on the market in one year was considered equivalent to the quantity of plastic packaging waste generated. Official statistics estimated a total amount of 2.26 million tonnes of plastic packaging waste across the UK in 2014/2015 (WRAP, 2016; Eunomia, 2018a). Around 1.5 million tonnes of this waste were produced in the consumer sector: more than a third was estimated to be bottles (594,000 tonnes), another third other rigid waste such as pots, tubs, and trays (PTTs) (525,000 tonnes), and the remainder consisted of films (414,000 tonnes). The remaining 0.7 million tonnes were produced in the non-consumer sector (RECOUP, 2018), which included commercial and industrial (C&I), construction and demolition (C&D) and agriculture (WRAP, 2016).

However, according to a more recent report from Eunomia (2018a), the total amount of 2.26 million tonnes would only be a subset of the real plastic waste, merely representing the amount collected by Local Authorities, to which another 1.4 million tonnes of plastic packaging waste should be added from the commercial and industrial sector.

Following this report, a total amount of 3.7 million tonnes of plastic packaging waste, generated from both MSW and C&I waste streams, has been included in the pathways.

Plastic packaging going to energy recovery in Business as Usual

In 2014, 23% of UK plastic packaging was recycled (Eunomia, 2018a). Following WWF estimates, it was considered that out of the non-recycled waste, a small fraction was littered (1%) and the remaining was sent to residual disposal (76%). From the total amount of disposal waste, 23% went into energy recovery (Eunomia, 2018b).

This means that of the total of 3.7 million tonnes of plastic packaging waste, 0.65 million tonnes went into energy recovery.

2. Paper and cardboard waste

In 2017, 7.8 million tonnes of recovered paper were collected in UK waste streams (Confederation of Paper Industries, 2017). This figure refers to the total amount of recovered paper in the UK, which includes graphics, corrugated case materials, parent reels of tissues, packaging paper and boards, which, in turn, are included in the C&I and MSW waste sectors.

Paper and cardboard waste going to energy recovery in Business as Usual

Assumptions on paper and cardboard waste availability for energy recovery drew on a separate document, which made estimations for the year 2014 (DEFRA, 2017). Based on the data reported by paper and card flow, 71% of consumer paper and card packaging and 64% of non-consumer paper and card packaging were recycled in 2014. For the purposes of our calculations, the same percentages were assumed for 2017. Since 7.8 million tonnes includes both MSW and C&I waste, the medium of the two percentages (67.5%) was estimated to be the recycling rate of paper and cardboard waste. The remaining 32.5% was assumed to be sent to residual disposal directly into energy recovery.

This means that, out of the 7.8 million tonnes of paper and cardboard waste produced, 2.5 million tonnes went into energy recovery.

3. Wood

The Wood Recyclers' Association (WRA) estimated a total of 5.1 million tonnes of waste wood available for recycling and recovery in 2016-2017 in the UK. Out of this amount, 3.1 million tonnes were recycled or reused; 1.7 million tonnes went to UK energy recovery plants and the remaining 300,000 tonnes were exported (Wood Recyclers' Association, 2018). There was no need to make assumptions on wood waste availability for energy recovery because the WRA provided the estimated waste wood going to energy recovery.

4. Food waste

According to WRAP (2018a), 10.2 million tonnes of food and drink were thrown out in 2015 in the UK. Of this quantity, 7.1 million tonnes were from household waste and the remaining

3.14 million tonnes came from the supply chain (retail, manufacture, hospitality and food service (HaFS)).

Food waste going to energy recovery in Business as Usual

Based on data from WRAP (2018b), 4.7 million tonnes, out of the 10.2 million tonnes of food waste, were assumed to go to energy recovery in 2015. Of this amount, 2.7 million tonnes derived from MSW and the remaining 2 million tonnes from C&I sectors, which include hospitality and food service, retail and wholesale, and manufacturing.

Additional assumptions

Concerning the other pathways, several assumptions were made to determine the amount of each waste stream available for energy recovery in the medium to long term (2025-2030). These assumptions are the following:

- Increase in waste stream generation by 2025-2030. According to WWF, generation of plastic packaging waste is projected to increase by 22% by 2030 (Eunomia, 2018b). Data could not be retrieved in the case of paper and wood and, therefore, the same baseline quantities of waste streams were assumed. Concerning food waste production, WRAP (2018a) estimates a reduction of 24% by 2025.
- EU waste management recycling targets for the different waste streams reached by 2030. Concerning the waste streams under the research scope, the EU envisages the following targets for 2030: 55% for plastics, 85% for paper and 30% for wood (Letsrecycle, 2018). These targets were considered in the case of plastic packaging and paper. The recycling rate for wood waste was not considered as, according to Wood Recyclers' Association (2018), wood waste is already over the 30% recycling rate.
- The remaining percentage in each waste stream was considered to equal the amount going to residual waste. In turn, the amount of residual waste going to energy recovery from each waste stream was estimated by relying on two assumptions: first, that by 2030 no more than 10% of MSW should go to landfill in the EU, as stated by the Landfill Directive (this percentage was assumed for all waste streams); secondly, that waste exports will be drastically minimised.

Table 3.2 below shows the amount of waste stream available by 2025-2030.

Table 3.2. Amount of waste stream available for 2025-2030

Waste stream	Million tonnes pa
Plastic packaging waste (2016)	3.7
Increase by 2030 (22%)	4.5
Recycling target 2030 (55% plastics)	2.5
Residual waste 2030 (45% plastics)	2
of which:	
- Landfill (<10%)	0.2
- Energy recovery (90%)	**1.8**
Waste exports	0
Paper and card waste (2017)	7.8
Increase by 2030	NA
Recycling targets 2030 (70% paper)	5.5
Residual waste (30% paper)	2.3
of which:	
- Landfill (<10%)	0.2
- Energy recovery (90%)	**2.1**
Waste exports	0
Wood waste (2016)	5.1
Increase by 2030	NA
Recycling targets 2030	3
Residual waste 2030	2.2
of which:	
- Landfill (<10%)	0.2
- Energy recovery (90%)	**2**
Waste exports	0
Food waste by 2025	10.2
Reduction by 2025 (24%)	7.6
of which:	
- Landfill (<10%)	0.8
- Energy recovery (90%)	**6.8**

Total amount of waste going to energy recovery

Business as Usual: Under *Business as Usual*, it is assumed that waste disposal rather than waste valorisation remains the priority, due to the large amount of waste generated and the low recycling rates. In this pathway, incineration is the main technology. This technology is not sensible to feedstock and is suitable for all types of waste (Yap and Nixon, 2015; Foster *et al.*, 2021). There is no segregation of waste streams, which means that the four waste streams under the research scope (plastic packaging, paper and card, wood, and food waste) are mixed up and sent to energy recovery. The total amount of waste estimated as going to energy recovery in this pathway was obtained by summing all proportions of each waste stream going to energy recovery at the current state. This resulted in a total of **8.1 million tonnes (Mt) of residual waste going into energy recovery**. New calculations suggest that this amount has been underestimated by 17%, which would result in a total of 9.5 million tonnes. Moreover, during the interviews some participants argued that the amount of waste going to energy recovery is probably higher than estimated, although it is difficult to know by how much because data reported is not reliable enough.

Gasification pathways: Under the pathways of gasification, it is assumed that there is a strong change of mentality in the management of waste, and a more efficient use of the national and local waste. The EU waste management targets are met and national waste exports are drastically minimised.

Rather than waste disposal, under these pathways, waste valorisation in terms of energy content and efficiency, end-products generation, flexibility and adaptability to contextual needs, becomes the priority. Under these pathways it is assumed that the high calorific value waste streams (plastics, paper and wood) are sorted and processed individually in the gasifiers, to maximise the energy outputs. Food waste is compulsory segregated at all Local Authorities and businesses and sent to Anaerobic Digestion. The resulting figure estimates **5.9 million tonnes (Mt) going into energy recovery**.

Anaerobic digestion (AD): The segregation and collection of waste food in separated bin becomes mandatory at a household level. Commercial and Industrial food waste is also collected separately from the rest of waste streams. Food waste is no longer going to landfill or incineration plants. Food waste is used as feedstock on anaerobic digestion plants for the production of biogas. **This results in a total of 6.8 million tonnes (Mt) going into energy recovery for the AD pathways.**

In summary, in the pathway of Business as Usual, similar residual waste quantities as the ones that are currently produced were considered to be sent to incineration with heat recovery for the production of power and, in some cases, heat (as reported in the two subsections 3.2.1.1 and 3.2.1.2). In the case of Centralised and Decentralised Gasification pathways, as this technology requires a much more homogenous and clean feedstock, the only waste streams considered as inputs for the gasifiers have been plastics, papers and wood, which are the highest calorific value waste streams. The pathways on the deployment of gasification at different scales, present the possibility of producing power, heat, chemicals and liquid biofuels. Finally, the analysis of waste production in the domestic and industrial sectors enable to appreciate the large amount of food waste currently send to landfill and incineration and, at the same time, to acknowledge that few Local Authorities to date have incorporated segregated food waste collection into their waste management. Hence, in the case of AD, it had to be assumed that segregated collection of food streams in the household has become compulsory for all Local Authorities, and that all food waste is sent to anaerobic digestion for the production of power, heat, and bio-methane.

The following stage involved estimating the contribution that each technology and pathway could make to national total energy demand.

3.2.1.3 Contribution to UK total energy demand.

In order to develop plausible and consistent end points, a final stage was dedicated to estimating the contribution of each pathway to the total UK energy demand. These estimates were calculated on the basis of the calorific values of waste streams and end energy products, the different efficiencies of the technologies, and the current total energy demand of the different outputs in the UK.

Calorific value & energy content per waste stream

The energy content of different waste streams was obtained by multiplying the estimated quantities of waste available for energy recovery by the calorific value of the waste streams used as input in each technology. Table 3.3 below shows the calorific values used for the different waste streams and the total amount of waste energy content (MJ) estimated to go into the technologies. It goes without saying that an increase in the total tonnage available for energy recovery would also result in an increase in the total energy content.

Table 3.3. Waste stream calorific value, from World Energy Council (2016)

Technology	Waste stream	Net Calorific Value (MJ/Kg)	Waste available (million tonnes)	Energy content (MJ)	
Incineration	Residual waste	10	8.1	8.1E+10	8.1E+10
Gasification	Plastics	35	1.8	6.3E+10	1.2E+11
	Paper	16	2.1	3.4E+10	
	Wood	14	2	2.8E+10	
Anaerobic Digestion	Organic material	4	6.8	2.7E+10	2.7E+10

Technical efficiencies

The technology efficiencies were inferred from discussions with technology experts, which took place before the interviews, and from studies on each technology. Table 3.4 presents, for each pathway, the technology efficiencies in the production of different outputs.

Table 3.4. Technical efficiencies, from DEFRA (2014); Saveyn *et al.* (2016); IEA Bioenergy (2018)

Net efficiencies (%) per energy output			
Pathway	**Electricity**	**Heat**	**Liquid Biofuels**
Pathway 1. Business as Usual. Centralised Incineration EfW Pathway.	20-30	<10	
Pathway 2. Centralised Gasification EfW Pathway. Displacement of Incineration.	22.5		22.5
Pathway 3. Decentralised Gasification EfW Pathway. Decarbonisation of the heat sector.	25-40	35-40	
Pathway 3. Decentralised Gasification EfW Pathway. Decarbonisation of the heat sector.		55-65	
Pathway 4. Decentralised Gasification EfW Pathway. Decarbonisation of the transport sector.		30-40	40-45
Pathway 5. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the heat sector.	35-40	50-55	
Pathway 5. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the heat sector.		68	
Pathway 6. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the transport sector.			68

Energy potentially available from each pathway

Multiplying the energy content of the total waste estimated to go into the different technologies by the different efficiencies resulted in the total energy and fuels potentially available (TWh per year) from the different pathways (see Table 3.5).

Table 3.5. Energy potentially available from each pathway

Net Energy Values (TWh per year)			
Pathway	**Electricity**	**Heat**	**Liquid Biofuels**
Pathway 1. Business as Usual. Centralised Incineration EfW Pathway.	7	2	
Pathway 2. Centralised Gasification EfW Pathway. Displacement of Incineration.	8		8
Pathway 3. Decentralised Gasification EfW Pathway. Decarbonisation of the heat network.	12	14	

Pathway 3. Decentralised Gasification EfW Pathway. Decarbonisation of the heat network.		22	
Pathway 4. Decentralised Gasification EfW Pathway. Decarbonisation of the transport sector.		14	15
Pathway 5. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the heat network.	3	4	
Pathway 5. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the heat network.		5	
Pathway 6. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the transport sector.			5

Contribution of EfW

Proportions of total energy demand which could be met with the different pathways were calculated (see Table 3.8) on the basis of the energy demand figures reported in the Digest of United Kingdom Energy Statistics 2018 document from BEIS (2018) (see Table 3.6).

While electricity, natural gas and electricity and heat demand from CHP were easily retrievable from the Digest of United Kingdom Energy Statistics 2018 document from BEIS (2018), additional calculations had to be made to estimate total transport demand. Multiplying the consumption (in million tonnes) of road transport (petrol and diesel) and jet fuels estimated by the report by their respective calorific value (45 MJ/kg, 43 MJ/kg and 43 MJ/kg) yielded the total transport fuels demand associated to jet transport, heavy good vehicles (HGV), and all transport vehicles (see Table 3.7).

Table 3.6. 2017 UK Total Demand per energy output

Energy Output	UK Total Demand 2017 (GWh, GJ)
Electricity	353,838
Natural gas	875,000
Electricity from CHP	21,638
Heat from CHP	42,238
Jetfuels transport (GJ)*	507,400,000
Heavy good vehicles (GJ)*	278,640,000
All transport vehicles (GJ)*	2,104,600,000
Natural gas + heat from CHP	917,238
* indicates that additional calculations were required to obtain this number	

Table 3.7. Estimated

Transport fuel	Consumption 2017 (Million tonnes)	CV (MJ/kg)	Energy content (MJ)	Energy content (GJ)
Petrol	11.7	45	526,500,000,000	526,500,000
Diesel	24.9	43	1,070,700,000,000	1,070,700,000
of which:				
- Heavy good vehicles	6.5		278,640,000,000	278,640,000
- Jet fuels	11.8	43	507,400,000,000	507,400,000
		Total	2,104,600,000,000	2,104,600,000

Table 3.8. Estimated contribution (%) to energy demand by each pathway

Contribution (%) to energy demand			
Pathway	**Electricity**	**Heat/synthetic natural gas/bio-methane**	**Liquid biofuels**
Pathway 1. Business as Usual. Centralised Incineration EfW Pathway.	2%	0.25%	
Pathway 2. Centralised Gasification EfW Pathway. Displacement of incineration.	2%		- 10% (in heavy good vehicles) - 6% (in jet fuel transports) - 1% (in total transport fuel demand)
Pathway 3. Decentralised Gasification EfW Pathway. Decarbonisation of the heat sector.	3.5%	1.5%	
Pathway 3. Decentralised Gasification EfW Pathway. Decarbonisation of the heat sector.		2.50%	
Pathway 4. Decentralised Gasification EfW Pathway. Decarbonisation of the transport sector.		1.50%	-19% (in heavy good vehicles) -10% (in jet fuel transports) -2.5% (in total transport fuel demand)
Pathway 5. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the heat sector.	0.80%	0.40%	
Pathway 5. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the heat sector.		0.70%	
Pathway 6. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the transport sector.			-6.7% (in heavy good vehicles) -0.9% (in total transport fuel demand)

Under the assumption that demand for power and heat remains much as it is today, each pathway is expected to contribute the following percentages:

Pathway 1. Business as Usual would contribute 2% and 0.25% of UK power and heat respectively.

Pathway 2. Centralised Gasification would contribute 2% and 1% of UK power and liquid fuel for transport respectively. The contribution to the transport sector becomes more significant in relation to heavy good vehicles and jet fuels, resulting in 10% and 6% respectively.

Pathway 3. Decentralised Gasification. Decarbonisation of the heat sector would contribute 3.4% and 1.5% of UK power and heat, respectively. Alternatively, 2.5% of heat demand could be met via injection of synthetic natural gas (SNG) in the gas grid.

Pathway 4. Decentralised Gasification. Decarbonisation of the transport sector would contribute 1.5% and 2.5% of UK heat and liquid fuel transport respectively. The contribution to the transport sector becomes more significant in relation to heavy good vehicles or jet fuels, resulting in 19% and 10% respectively.

Pathway 5. Decentralised Anaerobic Digestion. Decarbonisation of the heat sector would contribute 0.8% and 0.4% of UK power and heat respectively. Alternatively, 0.7% of heat demand could be met via injection of bio-methane in the gas grid.

Pathway 6. Decentralised Anaerobic Digestion. Decarbonisation of the transport sector would contribute 0.9% of UK liquid transport fuel.

As a consequence, each pathway description comprises: a narrative of the configuration of energy production, technology and infrastructure required; quantitative indicators to provide a sense of scale of both, the pathway deployment and the contribution to the UK energy demand implied; and diagrams providing representations of each pathway. The full description of pathways can be found in *Appendix 1.1. Expert Booklet*.

The pathways are not intended as predictions, but rather as potential future EfW pathways. Even though they have been presented individually, the technologies they comprise could be configured into wider systems/scenarios, and therefore several pathways can be combined to become hybrid EfW systems/scenarios. The pathways are intended to cover a range of possibilities in the most simplistic way so that clear and detailed information on opportunities and challenges can be identified by the participants and gathered with the MCM. The results should not be seen as supporting any one of the pathways alone. In fact, the aim of the project is not to identify or predict the most sustainable EfW pathway, but to use the study and results as tools for learning about important perceptions, issues and uncertainties surrounding the EfW debate.

The full description of pathways presented to stakeholders can be found in *Appendix 1.1. Expert Booklet.*

3.2.2 Pre-stage 2: Stakeholder Participant Identification and Recruitment

Stakeholders engaged in participatory processes are of major importance to the legitimacy of the outcomes. For this reason, it is critical to identify and engage with stakeholders who have a relevant knowledge or interest in the field under appraisal. The aim of this stage was to map the relevant stakeholders to identify suitable participants for the study. Stakeholders were identified through discussions with the industrial and academic supervisors. There was a first mapping exercise regarding stakeholders' identification before the development of pathways, in which a first framework regarding the type of stakeholders interested in being included in the research in order to open up the debate on Sustainable EfW pathways, were identified. I was interested in ensuring representation from the government, industry, academic and civil society embedded within the supply chain of the pathways, whether on the waste management, the energy recovery and technologies, and/or the energy production, distribution and/or end-use. This first stakeholders mapping exercise helped in the design framework and description of the pathways. The complex conversion processes and technologies were described in an easy-to-understand language, since we were interested in engaging with a wide range of professionals from multiple disciplinary backgrounds and we had to make sure the pathways developed were relatively easy to understand for all the stakeholders. The idea of doing a back-casting exercise was already in mind.

Once pathways were developed, a second stakeholder mapping exercise was carried out, in which specific people from the different sectors of government, industry, academia and civil society were identified through a snowballing technique, i.e., the interviewees were asked to identify other key stakeholders.

A total of 25 potential interview participants were initially identified through a range of methods and contacted via email. Some were identified through references having worked previously in the fields of both public perceptions and behaviour analysis in relation to energy technologies development and deployment, and/or bioenergy and EfW. Other participants were identified via their institutions and their professional roles, e.g., working in a large company of EfW as technology commercial, or in a government department as energy policy maker. As previously mentioned, however, most participants were identified via the snowballing effect.

In the email that invited them to participate, the research topic was introduced and reference was made to their field of expertise. If the individual had been referred by somebody, this information was also included within the email. From the total of the 25 contacted individuals, three rejected to participate because of lack of time in their schedule; seven did not reply; the remaining 15 accepted. Several emails followed their reply to set a suitable time and place to undertake the interview. Previous to the interview, these 15 participants were provided with the *Expert Booklet*, which explained in detail the MCM interview methodology and the six EfW pathways that would be asked to assess. A copy of the *Expert Booklet* can be found in *Appendix 1.1*.

All the stakeholders who accepted were interviewed. Interviews started in mid-March 2019 until November 2019. Participants were interviewed one-to-one at their place of work, except for one interview, which was undertaken via Skype, in which screen sharing ensured that the participant could see the MCM software screen. In this case, the interviewee was already familiar with the MCM software. Each interview lasted between two and four hours. The interviews were conducted using the computer software packaged "Multicriteria Mapper". Participants were guided though the four stage multicriteria process described in Section 3.1.4 and were asked to complete the interview in their personal capacity.

The MCM identifies groups of participants as "perspectives"; and under the basis of the MCM analysis they allow to display certain features. Participants were grouped under four different perspectives: Government, Industry, Academia and Civil Society. Table 3.9 below shows the list of interviews undertaken. For reasons of confidentiality, each participant is anonymised and identified by a code with the letter signifying their sector (G1 to G6 for government, I1 to I3 for industry, A1 to A4 for academia and CS1 and CS2 for civil society); or by pseudonym associated to their professional expertise, while still keeping their anonymity. Pseudonyms included the organisation names when participants had no issues with this information being disclosed and authorised its use in their consent form. In order of appearance in the table: BEIS – Department for Business, Energy and Industrial Strategy; DfT – Department for Transport; DEFRA – Department for Environment, Food and Rural Affairs; EA – Environment Agency; ESA – Environmental Services Association; UKWIN – United Kingdom Without Incineration Network.

Table 3.9. Interviews undertaken. Stakeholder participants' identification per perspective, code and pseudonym

Perspective	Code	Pseudonym
Government	G1	BEIS Energy Engineer Expert
	G2	DfT Advanced Biofuels Policy Maker
	G3	DEFRA Economic Advisor
	G4	Waste & Resources Specialist Consultant
	G5	Local Authority Waste Management Officer
	G6	EA Waste Management Planning and Strategy Regulator Advisor
Industry	I1	Energy from Waste Industry Sales Manager
	I2	ESA Executive Director
	I3	Energy from Waste Industry Managing Director
Academia	A1	Sustainable Bioenergy Expert
	A2	Waste Management Process Engineer Scientist
	A3	Public Perceptions of Energy and Sustainability Scientist
	A4	Waste Management Policy Advisor
Civil Society	CS1	UKWIN Environmental Campaigner
	CS2	Sustainable and Strategy Developer

3.2.3 Pre-stage 3: Ethical Approval

As this project involved human participants, before conducting any research study and communication with key stakeholders, I had to submit to the University of Nottingham an application for ethical approval. The Ethics Committee checked my study proposal to see that I had given full consideration to ethical issues and that I will provide participants with suitable and satisfactory information.

A "Participant Consent Form" for the participants was developed to be administered prior to the interview. This form was included as part of the Ethical approval (see *Appendix 1.2.* for a copy of this form).

3.3 MCM Implementation

Before starting the interviews, all participants were asked to read and sign the participant consent form. Most participants had read the *Expert Booklet* prior to the interview meeting. Some had skimmed through it and obtained an overall picture of the interview process and pathways for appraisal. Others had read it thoroughly, had prepared a set of notes or questions for clarification and, in some cases, even come up with a list of initial criteria. In all cases, the pathways were explained to them in detail before the interviews took place.

As part of the first stage of the MCM, participants were encouraged to ask questions about the pathways and MCM approach, in case further clarification was needed. They were also asked if they wanted to include and define any additional pathway. Three of the 15 participants chose to do so, making for a total of four additional pathways. These were:

- Add1. Centralised Advanced Combustion, identified by participant I1;
- Add2. Small Scale CHP Combustion, identified by participant A1;
- Add3. and Add4., identified by participant CS1.

The description of each of these additional pathways given by the particular participant identifying each of them, can be found in *Appendix 2.1*. The following Chapters 4, 5, 6 and 7 will analyse and discuss in detail the appraisal of the six core EfW pathways, which were assessed by all participants. Given that the additional pathways were not assessed by all participants, these will not be analysed and discussed in the following chapters.

As particularity of the MCM process implementation, I noticed that the analysis of the pathways under the different criteria (Stage 3 of the MCM) demands a constant "mind-set shift" on the part of interview participants, and this shift turned out to be more difficult for some participants than for others. On several occasions, despite having turned to the assessment of pathways under the next criterion, the interviewee's mind was still focused on or suddenly shifted back to the previous criterion. In some cases, this happened at the beginning of the pathway's assessment under a new criterion, where the interviewee kept talking about the previous one. In other cases, the interviewee's attention had successfully shifted to focus on the new criterion but, as soon as a series of concerns associated to the new criterion were identified, these were easily linked or interrelated to previous criteria, and the focus of analysis in the specific criterion was lost for a few moments. It was part of the interviewer's job to redirect the interview to the criterion in question.

3.4 Results: Analysis and Discussion

With prior permissions of the participants all interviews were audio-recorded and transcribed. The analysis of the quantitative data was done with the MCM Analysis tool, which forms part of the MCM software for analysing data. The qualitative data were explored using NVIVO, a qualitative research software tool. The NVIVO software allows to import interview transcripts, and other file formats, into one database, to then organize, analyse, visualise and code the qualitative data into a desired thematic (node) structure. As part of this process, criteria were coded into different groups. Further detail regarding the analysis and grouping of data, which resulted in different charts, are provided in Chapters 4, 5, 6 and 7.

The MCM database structure allows the display of the interview data in various forms, charts and tables. The MCM Analysis tool software allows data to be grouped in different ways: participants in perspectives, pathways in clusters and criteria in issues (Coburn and Stirling, 2016). Depending on the different ways of grouping participants, pathways and criteria, the patterns of the charts displaying the quantitative data can change. Such changes can be studied and interpreted in conjunction with the corresponding qualitative data, allowing the analyst to compare results obtained for different participants, perspectives, clusters and/or issues. The database is also linked to a set of Microsoft Excel spreadsheets. This enables the generation of performance rankings and other analytical charts for heuristic analysis.

The combination of qualitative data in the transcribed interviews coded in NVIVO and quantitative data represented in charts and spreadsheets enables a comparison between the elicited discursive and textual reasons expressed in the appraisal and the quantitative indicators.

For the analysis of results, participants were grouped in perspectives and criteria were categorised initially into dimensions. Within each dimension criteria were further divided into smaller analytical groupings called issues through which it was possible to further identified cross-cutting “themes”. The empirical findings of this research will be presented in the following Chapters 4, 5, 6 and 7. Figure 3.9 below, illustrates the process undertaken in the grouping of criteria under the different dimension, issues and themes, and shows the chapters where the different analysis and discussion of the groups of criteria will be taking place.

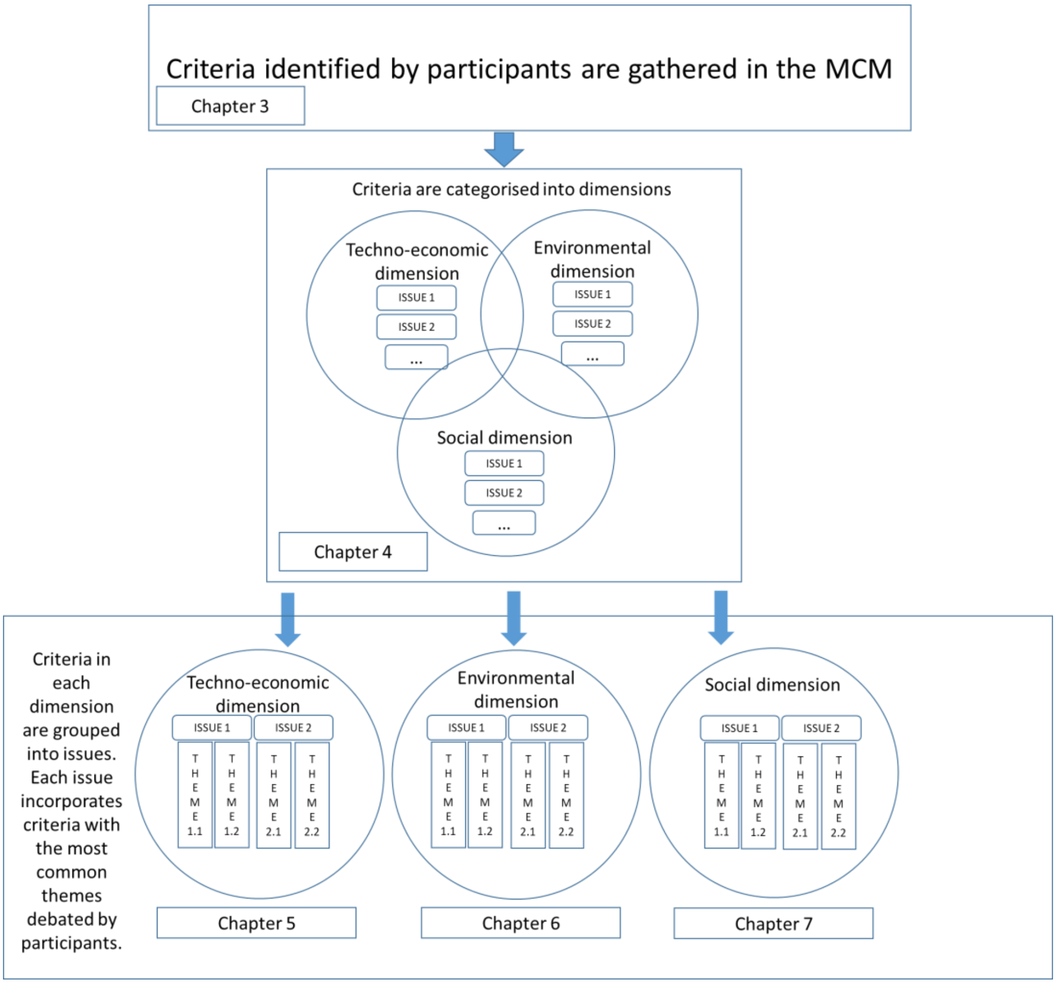

Figure 3.9. Criteria grouping process for analysis and discussion of results

Chapter 4. Criteria Identification and Overall Performance of Pathways

This chapter is the first of the four chapters dedicated to the analysis of results of the Multicriteria Mapping (MCM) process. The chapter aims to present the data captured through the MCM interviews with the 15 participants. This first chapter of results intends to locate the reader at the starting point of the data analysis approach, for the subsequent analysis and discussion of results in the following Chapters 5, 6 and 7. Chapter 4 is divided into two sections. The first section aims to report the criteria that the different participants have identified. A first analysis of the criteria is made, by which criteria are categorised into the three dimensions of sustainability: techno-economic, environmental and social. Within this section, criteria of each dimension are further sub-divided into smaller analytical groupings called issues. This first section finishes by providing an overview of the overall weightings of criteria within each dimension for each group of participants´ perspectives. The second section of this chapter provides an analysis of the final overall performance of the different pathways subjected to the different participants´ perspectives at an aggregated level. The aggregated overall sustainable performance of each pathway is analysed, in relation to the final participant performance of pathways and the criteria scores.

4.1 Criteria identification

To appraise the sustainability of each pathway participants were invited to identify and define a set of criteria, which had to be common for all pathways. To facilitate understanding of what a criterion could be, it was explained to the participants that the criteria should capture the factors that come to mind when assessing the opportunities and barriers for the pathways. The 15 stakeholders interviewed identified a total of 80 criteria, many of which were very shared. For example, the criteria of “waste availability”, “capex”, “carbon emissions”, “public acceptance” and “air quality” were repeatedly identified by different participants. The MCM approach does not impose a limit on the number of criteria that each participant can identify. This allows participants to express their opinions in a more liberal and flexible way. Participants engaged in the MCM interviews each identified at least four criteria; with three participants identifying four, six participants identifying five, four participants identifying six and two participants identifying seven criteria. The MCM identifies groups of participants as representing different types of perspectives. The 15 stakeholders interviewed have been grouped under four different perspectives: Government, Industry, Academia and Civil Society. Tables 4.1 to 4.4 below list the criteria identified by both individual participants and group perspectives.

Table 4.1. Criteria identified by participants within the perspective of Government.

Perspective	Code	Pseudonym	Criteria
Government	G1	BEIS Energy Engineer Expert	Public investment
			Contribution to GHG emissions targets
			Air quality impacts
			UK economy impact
			Contribution to bioenergy development
			Dependence of governmental policies
			Citizens´ engagement and behaviour change
	G2	DfT Advanced Biofuels Policymaker	Waste availability
			Cost of infrastructure
			Size of plants
			Planning permission
			Technology readiness
			GHG emissions
	G3	DEFRA Economic Advisor	Environmental impact of pathways delivered
			Net cost of pathways
			Wider economic impact
			Social acceptability
			Resource security

Table 4.1. Criteria identified by participants within the perspective of Government.

	G4	Waste & Resources Specialist Consultant	Efficiency
			Feedstocks
			CAPEX
			OPEX
			Public acceptance
	G5	Local Authority Waste Management Officer	Cost effective
			Ease of use
			Carbon impact
			Waste availability and volumes
	G6	EA Waste Management Planning and Strategy Regulator Advisor	Calorific value of material
			Net process efficiency
			Transport and handling efficiency
			Ratio biogenic material vs non-biogenic material
			Net GHG emissions
			Environmental net gain
Acronyms: Department for Business, Energy & Industrial Strategy (BEIS), Department for Transport (DfT) Department for Environment, Food & Rural Affairs (DEFRA), Environment Agency (EA)			

Table 4.2. Criteria identified by participants within the perspective of Industry.

Perspective	Code	Pseudonym	Criteria
Industry	I1	Energy from Waste Industry Sales Manager	Bankability/track record
			CAPEX
			OPEX
			Environmental performance
			Performance of outputs
	I2	ESA Executive Director	System costs
			CO_2 emissions
			Air quality
			Technology readiness
			Compatibility with collections
			Output risks
	I3	Energy from Waste Industry Managing Director	GHG emissions
			Chemical efficiency of conversion
			Economic viability
			Landfill reduction
Acronyms: Environmental Services Association (ESA)			

Table 4.3. Criteria identified by participants within the perspective of Academia.

Perspective	Code	Pseudonym	Criteria
Academia	A1	Sustainable Bioenergy Expert	Resource efficiency
			Flexibility
			Reduction in GHG emissions
			Air quality impacts
			Appearance
	A2	Waste Management Process Engineer Scientist	Environmental performance
			CAPEX in pounds per MW
			Efficiency
			Reliability (availability)
			Contribution to circular economy
			Scale
	A3	Public Perceptions of Energy and Sustainability Scientist	Ease of development
			Life cycle environmental
			Scarcity of alternatives
			Public acceptance
	A4	Waste Management Policy Advisor	Waste availability and quality
			Gate fees
			Price of the energy output
			Government incentives
			Planning permission

Table 4.4. Criteria identified by participants within the perspective of Civil Society.

Perspective	Code	Pseudonym	Criteria
Civil Society	CS1	UKWIN Environmental Campaigner	Achievability (realistic)
			Externalities
			Opportunity cost avoided
			Community benefits
			Environmental justice and democracy
			Decarbonisation
			Contribution to circular economy
	CS2	Sustainable and Strategy Developer	Air, land, water pollution
			GHG emissions reduction
			Human health
			Net financial cost
			Fuel poverty
Acronyms: United Kingdom Without Incineration Network (UKWIN)			

4.1.1 Criteria Dimensions and Issues

Sustainable development implies the balancing of economic and social development with environmental protection (Purvis *et al.*, 2019). As the research assesses the relative sustainability of six Energy and Fuels from Waste (EfW) pathways, it was decided to group the criteria in terms of the three dimensions or pillars with which sustainable development is often discussed: Economic, Environmental and Social. Grouping the criteria this way made the qualitative data analysis more manageable for future analysis and discussion by, for example, highlighting that many of the criteria identified by participants had a strong burden associated with technological factors. This observation is perhaps not surprising given the key role of technologies in this research. For instance, while at first I considered including a fourth "technological" dimension for assessing the sustainability development, as the process of qualitative analysis progressed it became clear that the criteria for addressing aspects of economics and technology bore very close similarities, which in many cases were difficult to disentangle. Accordingly, instead of having four pillars to assess the sustainable development of the pathways, the dimension of Economic was extended to Techno-Economic. The Venn diagram below (Figure 4.1) shows the three dimensions of techno-economic, environmental and social and their interconnectedness, and provides a first glimpse of the wide variety of criteria identified by the participants.

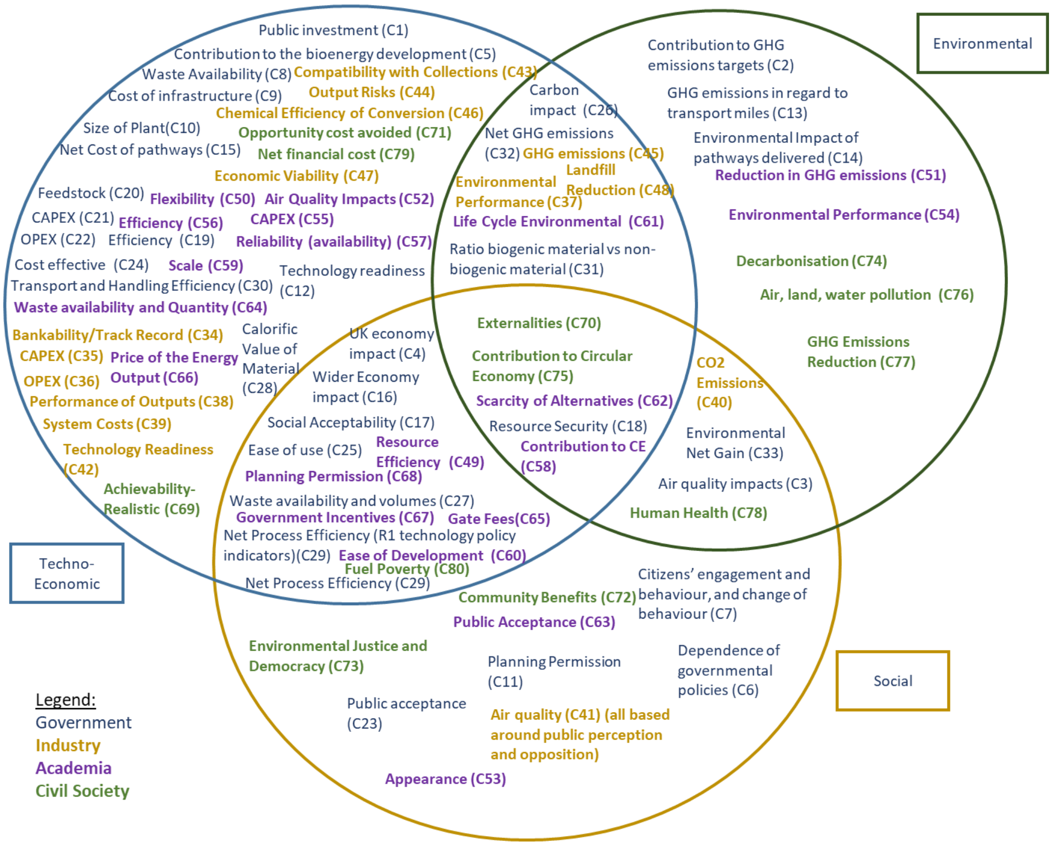

Figure 4.1. Venn diagram with sustainability criteria identified by the 15 participants.

The different coloured text represents the perspective group to which the participant who identified that criterion belongs: blue represents Government, yellow represents Industry, purple represents Academia, and green represents Civil Society perspective.

The process of grouping criteria under the different dimensions was not established before the interviews, but was developed through an inductive process as part of the analysis of the qualitative data produced during developing the range of criteria, including: 1) the definitions for the criteria given by participants, 2) the related discussion around the criteria definitions, and 3) any additional comments or details given by the participants throughout the pathways appraisal process. The classification of criteria through these three different methods of analysis was not straightforward, and rather than facilitating ease of analysis, in some cases it hampered the process due to the interrelationship between the criteria.

The three dimensions include a wide range of criteria associated not only with the thermal conversion of materials into energy processes, to which the pathways developed predominantly refer to, but also to the front-end processes of waste management, collection, segregation and sorting of the waste stream; and back-end processes of energy output production. For example, criteria of “waste availability”, “feedstock”, “compatibility with collections” and “transport and handling efficiency” relate to front-end processes while the criteria of “performance of outputs”, “output risks” and “price of the energy output” relate to back-end processes of the pathways’ supply chain.

At a first glance the criteria may appear distinct from each other, but thematic analysis of the participants’ discussions and arguments indicated the criteria can be grouped into broadly similar categories, referred to as issues. The disaggregation of criteria, according to the different sustainable development dimensions further highlighted that the criteria developed by participants addressed a diversity of issues including feasibility and efficiency, economics and the environment, and society and politics. The following sections elaborate in each of the dimensions and related issues with a twofold objective: to justify the classification of the criteria in the different dimensions, and to examine in greater detail the different issues.

Tables 4.5, 4.7 and 4.9 below show both the list of criteria for each of the dimensions, and the participants who identified the different criteria. Tables 4.6, 4.8 and 4.10 groups the criteria under different issues linked to each of the sustainability dimensions. The text in parenthesis beside each criterion indicates the stakeholder/s who identified the criterion. In cases where a criterion overlapped with more than one dimension, the aspect most emphasised during the interview was used to categorise the criterion for inclusion in the tables.

It is worth emphasising that these issues will be discussed repeatedly throughout the thesis as they help to both: 1) understand the perspectives and value-judgments of the different stakeholders, bringing to light the technological uncertainties, divergent values and social priorities that shape the competing expectations of the EfW sector and lead to differing conclusions about the sustainability, opportunities and barriers of the different pathways; and 2) justify the scoring of the pathways using different criteria to better understand their overall performance along different perspectives and sustainability dimensions.

4.1.1.1 Techno-economic Dimension

The techno-economic dimension contained the highest number of criteria identified by the participants. Of the 80 criteria identified in total, 44 were grouped under this dimension (see Table 4.5), of which 19 criteria were identified from the government perspective, 10 from the industry perspective, 11 from the academia perspective and four from the civil society perspective. All participants identified at least one techno-economic criterion in their appraisal.

Ten participants identified some sort of costs or prices evaluation criteria. However, their focus varied from bankability or the capacity to attract investors, the pathways' s capital cost or individual operational and maintenance costs, to the overall cost of the pathway. Some participants focused on the costs of infrastructure and public investment and others on prices of resources and services to make the pathway economically viable. In general, pathways involving gasification technologies and/or decentralisation tended to perform less well under these criteria.

The techno-economic criteria addressed issues of economics, feasibility, and efficiency. In cases where criteria addressed both issues of feasibility and efficiency, these have been addressed in conjunction. Criteria associated with economic issues included costs and prices evaluation, economic viability, economic sustainability, markets development and growth, economic support and strategic deployment. While criteria associated with feasibility and efficiency issues included waste availability, infrastructure availability, technology availability, technology feasibility, technology efficiency, technology readiness level (TRL) and state of knowledge, business case feasibility, development time, and technological and process efficiency of intended effects. Chapter 5 will analyse and discuss in further detail these techno-economic issues.

Table 4.5. Techno-economic criteria

Perspective	Code	Participant	Criteria
Government	G1	BEIS Energy Engineer Expert	Public investment
			UK economy impact *
			Contribution to bioenergy development
	G2	DfT Advanced Biofuels Policymaker	Waste availability
			Cost of infrastructure
			Size of plants
			Technology readiness
	G3	DEFRA Economic Advisor	Net cost of pathways
			Wider economic impact *
	G4	Waste & Resources Specialist Consultant	Efficiency
			Feedstock
			CAPEX
			OPEX
	G5	Local Authority Waste Management Officer	Cost effective
			Ease of use *
			Waste availability and volumes *
	G6	EA Waste Management Planning and Strategy Regulator Advisor	Calorific value of material
			Transport and handling efficiency
			Ratio biogenic material vs non-biogenic material
Industry	I1	Energy from Waste Industry Sales Manager	Bankability/track record
			CAPEX

Table 4.5. Techno-economic criteria

			OPEX
			Performance of outputs
	I2	ESA Executive Director	System costs
			Technology readiness
			Compatibility with collections
			Output risks
	I3	Energy from Waste Industry Managing Director	Chemical efficiency of conversion
			Economic viability
Academia	A1	Sustainable Bioenergy Expert	Resource efficiency *
			Flexibility
			Air quality impacts
	A2	Waste Management Process Engineer Scientist	CAPEX in pounds per MW
			Efficiency
			Reliability (availability)
			Scale
	A3	Public Perceptions of Energy and Sustainability Scientist	Scarcity of alternatives *++
	A4	Waste Management Policy Advisor	Waste availability and quantity
			Gate fees *
			Price of the energy output
Civil Society	CS1	UKWIN Environmental Campaigner	Achievability (realistic)
			Externalities * ++
			Opportunity cost avoided

Table 4.5. Techno-economic criteria

	CS2	Sustainable and Strategy Developer	Net financial cost
* indicates corresponding criterion also addressed some social aspects ++ indicates corresponding criterion also addressed some environmental aspects Acronyms: Department for Business, Energy & Industrial Strategy (BEIS), Department for Transport (DfT) Department for Environment, Food & Rural Affairs (DEFRA), Environment Agency (EA), Environmental Services Association (ESA), United Kingdom Without Incineration Network (UKWIN)			

Table 4.6. Grouping criteria into techno-economic dimension issues

Techno-economic dimension	**Criteria**
Economic issues	Public investment (G1), UK economy impact * (G1), contribution to bioenergy development (G1), cost of infrastructure (G2), technology readiness (G2, I2), net cost of pathways (G3), wider economy impact * (G3), CAPEZ (G4, I1, A2) , OPEX (G4, I1), cost effective (G5), bankability and track record (I1), system cost (I2), economic viability (I3), gate fees (A4), price of the energy output (A4), externalities * (CS1), opportunity cost avoided * (CS1), net financial cost (CS2)
Feasibility issues	Size of plant/scale (G2, A2), feedstock (G4), waste availability/ and volumes/and quality (G2, G5, A4), compatibility with collections (I2), achievability/realistic (CS1), technology readiness (G2, I2), ease of use (G5), bankability/track record (I1), reliability (availability) (A2)

Table 4.6. Grouping criteria into techno-economic dimension issues

<u>Efficiency issues</u>	Waste availability/and volumes (G2, G5), efficiency (G4, A2), feedstock (G4), ease of use (G5), calorific value of materials (G6), transport and handling efficiency (G6), ratio biogenic vs non-biogenic material (G6), performance of outputs (I1), compatibility with collections (I2), output risks (I2), chemical efficiency of conversion (I3), resource efficiency (A1), flexibility (A1), air quality impacts (A1), scarcity of alternatives (A3)

4.1.1.2 Environmental Dimension

Of the 80 criteria identified, 18 were grouped under the environmental dimension (see Table 4.7). Six criteria were identified from the government perspective, four from the industry perspective, and four each from academia and civil society perspectives. Participants G4 and A4 did not score any form of environmental criterion.

The environmental dimension was dominated by the criteria, “GHG/CO_2 emissions” and “carbon impact”, identified by five participants. Depending on the participant´s perspective, these criteria focused on the emissions of different parts of the pathways, including emissions from transport, collections and prepossessing of waste streams and infrastructure development and/or from the conversion process itself. For example, while the “GHG emissions” criterion from participants G2 and G6 focused on emissions from transport miles, participant I2 focused on the overall carbon impact, including the emissions from collection, pre-processing and extra pre-processing of waste streams, depending on the pathway. For participant G5, it included both transport miles’ emissions, extra processing emissions plus the construction of infrastructure required, such as heat networks. The “GHG emissions” criterion from participant I3 is predominantly focused on the emissions from the conversion process itself, considering the technologies and infrastructure in place under different assumptions. These assumptions will be revealed and investigated in Chapter 6. Discussion of other environmental criteria, such as “environmental impact of pathways delivered”, “air, land water pollution” and “environmental performance”, focused on environmental stressors to assess the environmental performance of pathways.

Participants identified criteria focused on a wider range of environmental efficiency issues, including the capacity of the pathways to reduce greenhouse gas emissions, the degree to which the pathways can help to minimize adverse effects such as landfill, and the degree to which pathways can contribute, boost, strength and maintain a circular economy.

Table 4.7. Environmental criteria

Perspective	Code	Participant	Criteria
Government	G1	BEIS Energy Engineer Expert	Contribution to GHG emissions targets
	G2	DfT Advanced Biofuels Policymaker	GHG emissions
	G3	DEFRA Economic Advisor	Environmental impact of pathways delivered
	G5	Local Authority Waste Management Officer	Carbon impact (-)
	G6	EA Waste Management Planning and Strategy Regulator Advisor	Net GHG emissions (-)
			Environmental net gain *
Industry	I1	Energy from Waste Industry Sales Manager	Environmental performance (-)
	I2	ESA Executive Director	CO_2 emissions
	I3	Energy from Waste Industry Managing Director	GHG emissions (-)
			Landfill reduction (-)
Academia	A1	Sustainable Bioenergy Expert	Reduction in GHG emissions
	A2	Waste Management Process Engineer Scientist	Environmental performance
			Contribution to circular economy * (-)
	A3	Public Perceptions of Energy and Sustainability Scientist	Life cycle environmental (-)
Civil Society	CS1	UKWIN Environmental Campaigner	Decarbonisation
			Contribution to circular economy * (-)

Table 4.7. Environmental criteria

	CS2	Sustainable and Strategy Developer	Air, land, water pollution
			GHG emissions reduction
* indicates corresponding criterion also addressed some social aspects (-) indicates corresponding criterion also addressed some techno-economic aspects Acronyms: Department for Business, Energy & Industrial Strategy (BEIS), Department for Transport (DfT) Department for Environment, Food & Rural Affairs (DEFRA), Environment Agency (EA), Environmental Services Association (ESA), United Kingdom Without Incineration Network (UKWIN)			

Table 4.8. Grouping criteria into environmental dimension issues

Environmental dimension	**Criteria**
Environmental efficiency issues	GHG emissions (G2, G6, I2, I3), environmental impacts of pathways delivered (G3), carbon impact (G5), environmental net gain (G6), environmental performance (I1, A2), decarbonisation (CS1), air, land and water pollution (CS2), GHG emissions reduction (G1, A1, CS2), life cycle environmental (A3), landfill reduction (I3), contribution to circular economy (A2, CS1)

Environmental criteria addressed issues of environmental efficiency in production processes. The discussion was around environmental impacts, greenhouse gas reduction and efficiency of intended environmental effects. Chapter 6 will analyse and discuss in further detail these environmental issues.

4.1.1.3 Social Dimension

Of the 80 criteria identified, 18 were grouped under the social dimension (see Table 4.9). Of these, eight were identified from government perspective, only one from the industry perspective, five criteria from the academia perspective, and the remaining four criteria from the civil society perspective. Participants G5, I1, I3 and A2 did not score any form of social criterion.

Seven participants identified a “social acceptability” criterion, and one participant identified a “public engagement and behaviour” criterion. The way in which they were discussed and scored suggested that acceptability and engagement were barriers to pathways development and uptake. Two participants identified an “air quality” criterion, distinguishing it from the previous “air quality” criterion in the techno-economic dimension by a focus on human health. Some participants identified criteria which focused on a wider range of political issues, for example, the degree of government support required for developing the pathways, the degree to which pathways would improve the development, planning and benefits of communities to promote sustainable living, or the degree to which the pathways enabled more energy security and reduced dependency on other countries for energy.

The “net process efficiency” criterion was hard to categorise under a specific dimension. This was because the name is suggestive of a technological criterion. However, the nuanced discussion by participants G6 referred to the need to develop new directives that include new conversion efficiency indexes and formulas specific to advanced conversion technologies (ACT) to produce more valuable products, such as liquid biofuels. The EU Waste Framework Directive (WFD) has the energy recovery efficiency formula, which index is known as R1. This is used to differentiate waste processing plants with energy recovery from plants without energy recovery. Participant G6 argued that considering the recovery and energy efficiency of a process producing heat and power and another producing liquid biofuel would not be the same, there should be a differentiation in terms of types of energy recovery efficiency indexes. Therefore, the criterion addressed political considerations, which make it a social dimension criterion.

Table 4.9. Social criteria

Perspective	Code	Participant	Criteria
Government	G1	BEIS Energy Engineer Expert	Air quality impacts ++
			Dependence of governmental policies
			Citizens´ engagement and behaviour change
	G2	DfT Advanced Biofuels Policymaker	Planning permitting
	G3	DEFRA Economic Advisor	Social acceptability (-)

Table 4.9. Social criteria

			Resource security ++ (-)
	G4	Waste & Resources Specialist Consultant	Public acceptance
	G6	EA Waste Management Planning and Strategy Regulator Advisor	Net process efficiency (-)
Industry	I2	ESA Executive Director	Air quality
Academia	A1	Sustainable Bioenergy Expert	Appearance
	A3	Public Perceptions of Energy and Sustainability Scientist	Ease of development (-)
			Public acceptance
	A4	Waste Management Policy Advisor	Government incentives (-)
			Planning permission (-)
Civil society	CS1	UKWIN Environmental Campaigner	Community benefits
			Environmental justice and democracy
	CS2	Sustainable and Strategy Developer	Human Health ++
			Fuel Poverty (-)
++ indicates corresponding criterion also addressed some environmental aspects (-) indicates corresponding criterion also addressed some techno-economic aspects Acronyms: Department for Business, Energy & Industrial Strategy (BEIS), Department for Transport (DfT) Department for Environment, Food & Rural Affairs (DEFRA), Environment Agency (EA), Environmental Services Association (ESA), United Kingdom Without Incineration Network (UKWIN)			

Criteria embedded within the social dimension addressed issues of society and politics (see Table 4.10). The discussion raised questions around public acceptability and engagement, human impacts, community benefits, and government support. Chapter 7 will analyse and discuss in further detail these social and political issues.

Table 4.10. Grouping of criteria into social dimension issues

Social dimension	Criteria
Social issues	Air quality (G1, I2), citizens engagement and behaviour and change of behaviour (G1), social acceptability (G3, G4, A3), resource security (G3), appearance (A1), community benefits (CS1), environmental justice and democracy (CS1), human health (CS2), fuel poverty (CS2)
Political issues	Dependence of governmental policies (G1), planning permission (G2, A4), net process efficiency (G6), ease of development (A3), government incentives (A4)

4.1.2 Weighting of Criteria

With the intention of eliciting information on the relative importance of criteria, as part of the MCM approach, participants were also asked to weight each of the criteria identified. As mentioned in Section 3.1.4.4, the weightings are essentially subjective judgements that help to acknowledge and better understand the participants' priorities and values. This data can be graphically displayed using the MCM software. Figure 4.2 below provides an overview of the weightings within each dimension for all participants. The figure brings to light which dimensions overall were judged to be the most important. The vertical axis displays the sustainability dimensions used to organise and structure the analysis to capture all the criteria identified by the participants. The horizontal axis uses a scale from 0 to 100 to express (in percentage terms) the overall value of the weights attached to each dimension. The blue horizontal lines show the ranges between the lowest and highest weights attached to criteria within each of the dimensions.

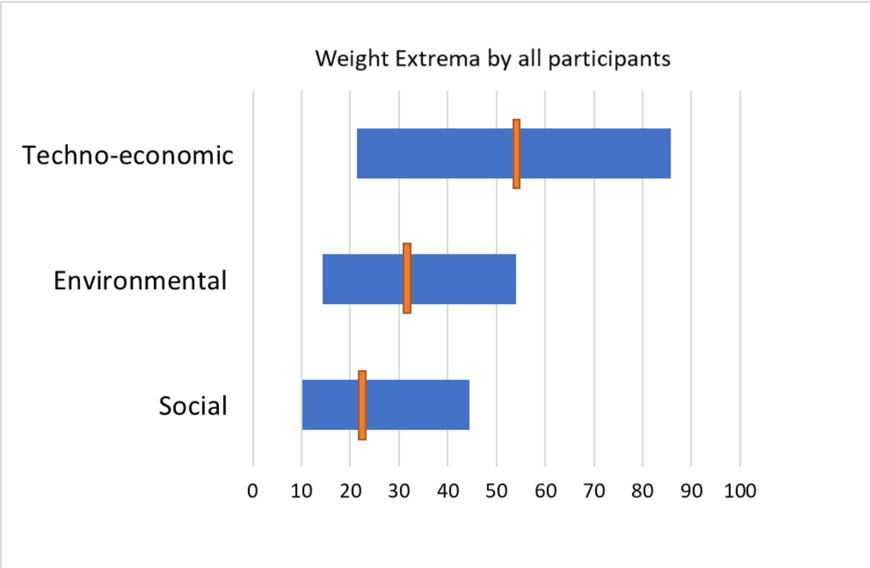

Figure 4.2. Weight chart of criteria dimension for all participants

Figure 4.2 shows that there is a substantial spread of views around the importance of the techno-economic criteria, illustrated by the wide blue band of the diagram. Overall, techno-economic criteria received higher average weightings than environmental criteria, with social criteria receiving the lowest overall weightings.

To have a better understanding of the importance given to the criteria dimension by each of the perspectives, Figures 4.3 to 4.6 below illustrate the range of weightings given by participants in each perspective, with the criteria grouped into dimensions.

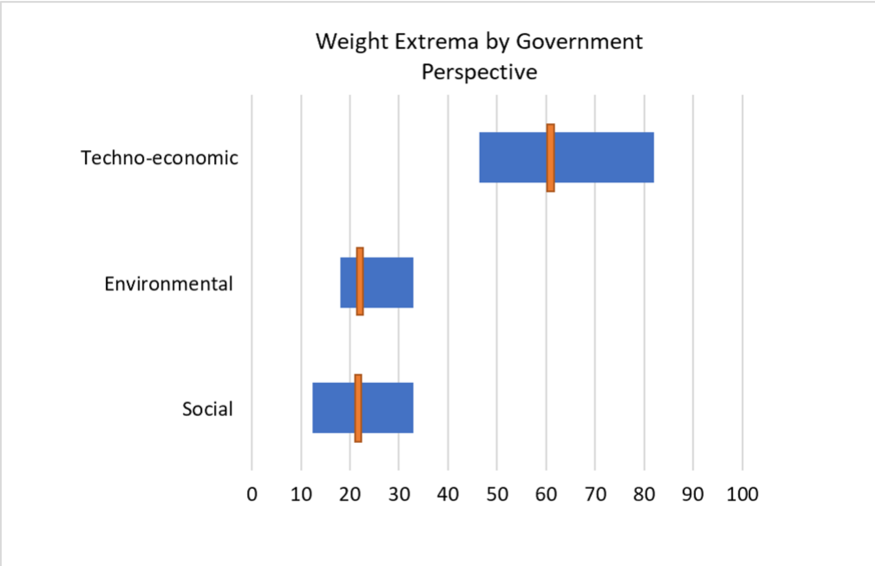

Figure 4.3. Weight chart of criteria dimensions for Government perspective

The Government perspective (see Figure 4.3) comprises the highest number of participants and correspondingly, each dimension comprises the highest number of criteria. There is a clear divergence between the relative weighted importance given to techno-economic criteria in comparison to environmental and social criteria. Environmental and social dimensions' criteria received similar average weightings.

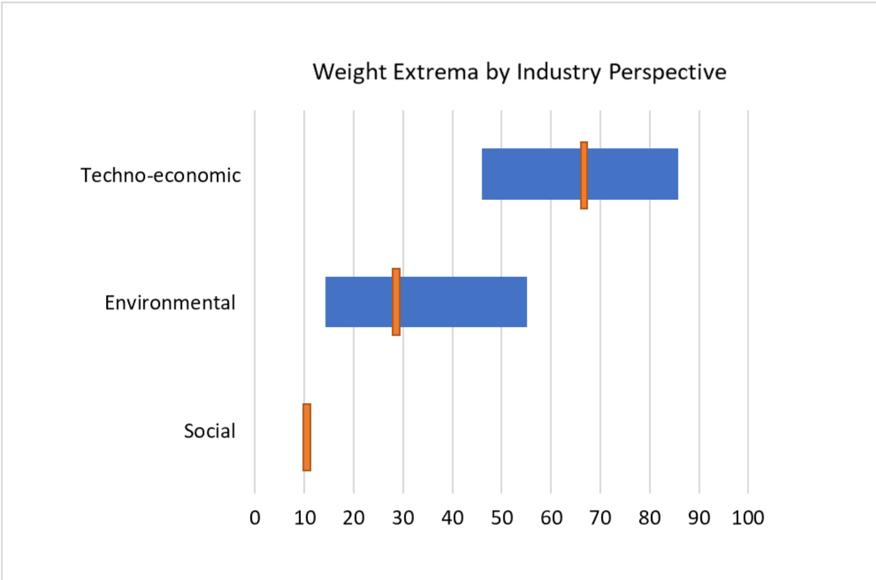

Figure 4.4. Weight chart of criteria dimensions for Industry perspective

The Industry perspective saw the techno-economic criteria as being of greater importance than environmental and social criteria (see Figure 4.4). Nonetheless, the wide range of the blue band in both the techno-economic and environmental dimensions suggests disagreements on the importance of these dimension criteria among the different stakeholders.

Only one social criterion was identified from this perspective, which explains the absence of a blue band for the social dimension and the presence of just the orange line of average weighting.

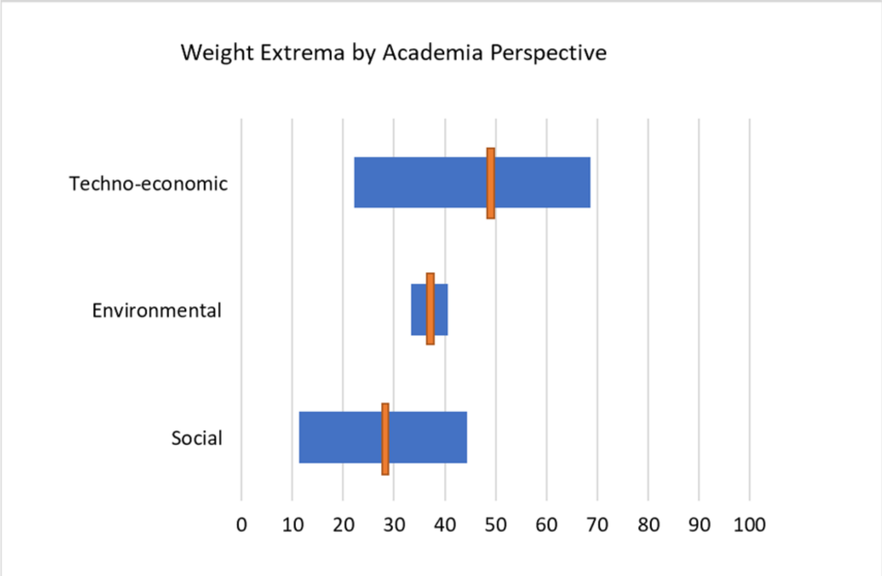

Figure 4.5. Weight chart of criteria dimensions for Academia perspective

The Academia perspective gave a wide range of weights to techno-economic and social criteria, while environmental criteria received a lower range of weightings (see Figure 4.5). This suggests a stronger disagreement (wider bar) on the relative importance of criteria within the techno-economic and social dimensions compared to the environmental criteria. Overall, techno-economic criteria received higher average weightings, followed by environmental criteria and social criteria.

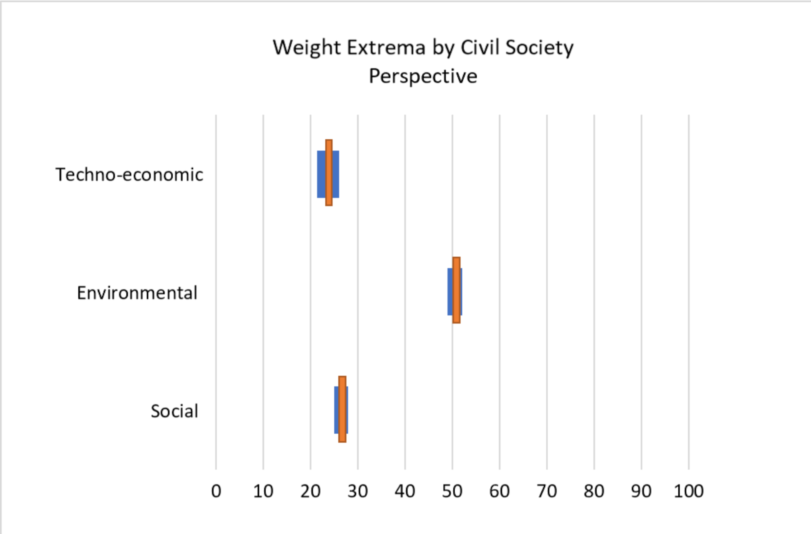

Figure 4.6. Weight chart of criteria dimensions for Civil Society perspective

There were only two participants from the Civil Society perspective. Both participants identified techno-economic, environmental and social dimensions; therefore, the narrow blue band suggests there was strong agreement in how much importance to give to each of the criteria dimensions. The graphic display (Figure 4.6) illustrates that participants gave more emphasis to environmental criteria, than to social and techno-economic criteria. Techno-economic and social criteria weights are very close to each other, nonetheless techno-economic criteria received the lowest range of weighting. It is the only perspective where techno-economic criteria were judged to be the least important.

Overall, techno-economic criteria were judged to be more important than environmental and social criteria. And social criteria were judged to be the least important. Only in the case of the Civil Society perspective, were the techno-economic criteria considered the least important and the environmental criteria considered the priority.

This section has analysed the criteria identified by the stakeholders. The following section will assess the overall performance of the different pathways at an aggregated level.

4.2. Overall Performance of Pathways

This section assesses the overall sustainability performance of the six different EfW pathways. The analysis was done by observing the relative performance of pathways at an aggregate level, by grouping the appraisal of each of the stakeholder participants into the same chart (Figure 4.7), and by assessing the perspective of each participant on the overall performance of the pathways (see *Appendix 2.2* for the final overview of pathways performance per each stakeholder participant (Figures 2.2.1 to 2.2.15)).

Figure 4.7 below displays the aggregated overall performance of the six core EfW pathways. On the vertical axis, the chart displays all the "core" pathways under appraisal by all 15 participants during the MCM process. In order of appearance in the vertical axis of the charts below, the core pathways are: Business as Usual, Centralised Gasification, "Decent AD HN" refers to Decentralised Anaerobic Digestion for the decarbonisation of the heat sector, "Decent AD TF" refers to Decentralised Anaerobic Digestion for the decarbonisation of the transport sector, "Decent Gasification HN" refers to Decentralised Gasification for the decarbonisation of the heat sector, "Decent Gasification TF" refers to Decentralised Gasification for the decarbonisation of the transport sector.

On the horizontal axis, the chart displays an arbitrary scale from 0 to 100 expressing the ranks assessed for each pathway by the different participants. Higher values indicate higher performance.

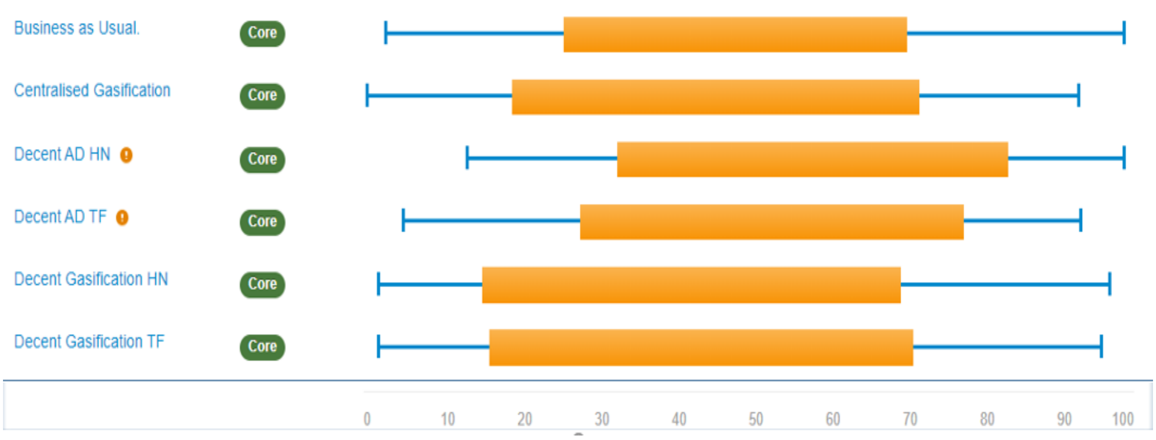

Figure 4.7. Aggregated overall performance of the six EfW pathways.

The blue lines of the pathways, called rank extrema data, give a full picture of the variability in the performance of the pathways assigned by the different participants. The left side end of the blue lines indicates the lowest rank assigned to each pathway by any of the 15 participants that appraised the pathways. The right side end of the blue lines indicates the highest rank assigned to each pathway by any of the 15 participants that appraised the pathways.

The orange bar, called rank means data, gives an indication of the distribution of participants' ranks within the ranges defined by the extrema. The left side end of the orange bars indicates the means of the pessimistic (low) ranks assigned by each of the 15 participants that appraised the pathways. The right ends of the orange bars indicate the means of the optimistic (high) ranks assigned by each of the 15 participants that appraised the pathways.

The MCM interview transcripts provide a wealth of detailed qualitative reasoning behind the participants´ quantitative scoring of the pathways´ performance. The results of the qualitative assessment of pathways performance are discusses in Chapters 5, 6 and 7. Aggregation of the optimistic and pessimistic scores of pathways performance, and of criteria weightings, given by participants reveals their assumptions about the relative performance rank of the different EfW pathways.

4.2.1 Business as Usual

Business as Usual (BAU) was the pathway with the narrowest distribution of rankings. Ten of the 15 participants (G1, G2, G3, G4, I1, I2, I3, A1, A2, CS1) showed the least uncertainty in their appraisal of this pathway. Most participants recognised this pathway as playing a well-established role in the EfW sector. The reasons expressed by two thirds of participants were largely based on their knowledge and understanding of the technology in the context of the existing energy system in terms of its techno-economic and environmental performances. Incineration was perceived as a proven, well understood, and deployed technology.

In the view of four participants (G5, I1, I2, A4), BAU performed higher than any other pathway. This was because of the strong performance of the techno-economic criteria. Of these four participants, participants G5 and I1 viewed BAU as the best performing under both, optimistic and pessimistic assumptions. Participants G5, I1 and I2 argued that 'BAU performs well because of the ease of use of the system [pathway]´ (G5) and ´its compatibility with collections' (I2). The robustness, readiness and flexibility of the technology with ability to treat all types of wastes; and its bankability/capacity for attracting investment, associated with the number of references and track records of successful projects were additional aspects for its optimistic performance. The three of them explained that the incineration technology is available, proven and already in place with robust and numerous references where investment is happening. The number of successful conventional incineration projects has de-risked the technology by providing an attractive price that the market can sustain. Participants G5 and I2 repeatedly referred to how the pathway of conventional incineration is set around what is needed, generating the least disruption to collection systems. The incineration technology 'allows to throw anything that anyone would put into a bin' (G5, I2). Considering how waste composition changes over time, a big advantage in terms of compatibility with collection for BAU is the flexibility of the technology which allows to be flexible in terms of inputs that do not need much processing. Likewise, they argued that the lower the sorting and processing of waste at the front-end of the pathway is, the lower the costs will be. Participant A4 ranked this pathway as the best performing in relation to the electricity market prices fluctuations and the need to be nationally energy secured, arguing that 'as we leave Europe, we are going to need as much energy from our own resources as we can possibly have. Because at the moment we import quite a lot of electricity from France, and … they might turn off the interconnector and we won't have much electricity. So the driver is for more electricity made at home…. BAU would perform better because we need it...if the driver is for more energy made at home, prices of the energy output will be higher.' (A4)

In contrast, participants A3 and CS2 ranked this pathway as the worst performing. The latter because of the potential impacts on human health. Nonetheless, participant CS2 also gave this pathway a high degree of uncertainty, which resulted in a wide rank for BAU. Participant CS2 raised concerns around the location of the plants, their potential proximity to areas of dense population and vulnerable communities such hospitals or schools, as well as concerns around transport miles and associated emissions. Only from the perspective of participant A3 the pathway performed worse than any other pathway even under the most optimistic assumptions, because of techno-economic, environmental and social criteria. Participant A3 considered BAU to be an inefficient pathway in terms of environmental performance, energy efficiency and the production of added-value products. The pathway was perceive as contributing little to issues of energy scarcity. Participants A3 also spoke of the high degree of public opposition towards incineration technology and centralised pathways.

This pathway was ranked worst under most optimistic assumptions by six participants, including two from the government perspective (G1, G3), one from the industry perspective (I3), two from the academia perspective (A1, A3) and one from the civil society perspective

(CS1). This was due to environmental and social criteria, such as: “contribution to GHG emissions reduction”, “social acceptability”, “resource security”, “air quality impacts”, and “appearance”**.** In contrast, it was ranked best under most pessimistic assumptions by three participants, including two from the government perspective (G2, G5) and one from the industry perspective (I1). This was due to techno-economic criteria, such as “waste availability” and “capital costs” (CAPEX).

4.2.2 Centralised Gasification

Centralised Gasification, together with Decentralised Gasification for the decarbonisation of the transport sector, was the pathway with the widest range of rankings; meaning the highest uncertainty. Four participants (G4, G5, I2, A4) showed the highest uncertainty for this pathway. They expressed concerns around feasibility, carbon impact, costs, public acceptance, as well as scepticism about the technology readiness, and the availability of sufficient waste at the required quality to make the gasification for added-value products scalable to accommodate the national energy demand needs. Centralised Gasification for liquid biofuels and chemicals was seen as viable only in the long term.

Participants G4, G5, I2 and A4 analysed the pathway in terms of its feasibility, highlighting the need for heavily processed high-quality feedstock in order to make the usual collected feedstock suitable for the technology. They all stressed the need for extra-processing activities at the front-end of the pathway, and participant G4 stated that ‘The UK needs more sorting plants, more and better systems in terms of collection and handling… Keeping processes as they are currently, there is no foreseen future of gasification.’ In light of the extra layers of feedstock processing at the front-end of the pathway, concerns around “carbon impact” and “CAPEX” were also identified. Participants I2 and G5 follow the same line of thinking with regard to the overall carbon impact of the pathway, but each of them focus on different matters. In the view of participant I2, the extra-processing to get the feedstock suited to the technology comes with extra emissions. With the current front-end activities on waste management which do not enable to make suitable feedstock for the technology, and the low TRL of gasification, the carbon impact cannot be offset. However, if the technology improves and the conversion process reaches high efficiency levels, the emissions at the front-end of the pathway could potentially be offset. In the view of participant G5, the main barrier related to the emissions associated with the transportation of the waste. As centralised pathway with a large-scale plant, larger amounts of waste would need to be collected from different places, and would need to be transported to the processing plant. This would entail additional transport miles. This raised the question of whether the gasification pathway is efficient enough to offset the carbon impact and take care of the additional transport emissions involved.

Participants G5 and A4 raised concerns around the additional costs coming from both the pre-processing of the feedstock and the transportation embedded in the Centralised Gasification pathway. They both agreed that unless gasification technology improves and the pathway works efficiently, additional costs would never be offset. Moreover, participant A4 chose nil performance under pessimistic assumptions, meaning there is no existing future for the gasification pathway unless there are improvements in the TRL of gasification. Nonetheless, both participants (G5, A4) also gave this pathway a high degree of uncertainty. Their uncertainties were related, on the one hand, to gate fees fluctuations, and on the other, to the potential future of gasification technology in terms of efficiencies and energy outputs production. Participant G5 stated that:

> ‘if gasification did work it can compete with mass burning incineration… If you produce more energy, you can almost offset your costs. It is always the balance here. So the more energy you produce, actually the more efficient your plant is, therefore cheaper your gate fees are, and the cheaper cost.’

Conversely, participant A4 argued that:

> ‘the pathway would perform well if the gate fee stays high. The same reasoning as in Business as Usual. There is more sorting needed; but if the gate fee is continuing to increase [because the landfill tax continuous to increase] then there is the budget to do the sorting. It is better than BAU, because the pathway adds a new market product.’

Participant A1 ranked this pathway as the best performing, under both optimistic and pessimistic assumptions, arguing that Centralised Gasification has, of all the pathways, the potential for both the highest “resource efficiency” and the reduction of “air quality impacts”. A feature about participant A1 perspective was the debate about the “resource efficiency” of the pathway in relation to job satisfaction, skills level and technology reliability:

> ‘…. anyone that is really good at their job would prefer to be in a big chemical plant, rather than in a tiny plant locally… This is related to the technology; it is about the technology; it is about whether an individual who would operate that plant, would

be attracted to that technology… If I have a big shiny plant, that is the biggest one in time, then everyone wants to work there, and then you get the best people, and you can maintain a really high level of reliability of the plant because you have top quality operators, who have proper engineering degrees, who have good experience, and they work in there because it is an exciting, challenging environment.'

This pathway was seen as the worst performing by five participants. Two from the government perspective (G5, G6), one from the industry perspective (I3), one from the academia perspective (A4) and one from the civil society perspective (CS1). This was mainly due to techno-economic and environmental criteria, particularly associated with the costs of the pathway, the thermochemical process and management of waste. Moreover, as participants A4, participant G6 also showed nil performance under pessimistic assumptions. In the view of participant G6, Centralised Gasification performed worse than any other pathway under both pessimistic and optimistic assumptions. This was because of poor performance of techno-economic, environmental and social criteria. For participant G6 'the energy balance between recovering, recycling and reuse, are very big steps' and believed that there are many other more sustainable things to do with waste, before sending it for recovery. In the view of participant G6, EfW can have a place, but only if questions such as: 'What is the transitional step required to being fully renewable? Can the EfW have a role in it?' are resolved.

4.2.3 Decentralised Gasification for the decarbonisation of the heat sector

In the case of eight participants: four from the government perspective (G1, G2, G3, G6), one from the industry perspective (I3), two from the academia perspective (A3, A4), and one from the civil society perspective (CS2) Decentralised Gasification for the decarbonisation of the heat sector performed relative well (over 70% optimistic performance) under optimistic assumptions. In no case was Decentralised Gasification for the decarbonisation of the heat sector seen as the best performing pathway.

In contrast, participants G3, G4, I2 and A2 ranked this pathway as the worst performing. This was because of poor performance on techno-economic and environmental criteria. These participants agreed with the statement that economies of scale would influence negatively the decentralised pathway in terms of net cost. The pathway would not have the economies of scale savings of having invested in just one large-scale plant. To treat the same quantity of waste that is treated in a large-scale plant, it would be required to invest in several different plants, probably incurring more cost. Considering the TRL of gasification, it could happen that it does not work or it could have overall higher cost for lower benefits. Participant G4 argued that these types of pathways are very expensive ways of managing waste, and stated that 'it is even more expensive than landfill but there is a lot of effort put on combusting varied waste… Someone will drill the sea for this oil, they will refine it, and they will make it into some plastic cup. And then, are you throwing it away?' (G4). Participant G4 emphasised the need to manage the waste higher up in the waste hierarchy.

In general, the debate over the relative sustainability of the Decentralised Gasification pathway for the decarbonisation of the heat sector was based around concerns of environmental performance, techno-economic and social. Participants expressed concerns around the gasification TRL, its sensitivity to feedstock, and the need of extra-processing activities at the front end of the pathway for making feedstock suitable for the technology. Others, highlighted concerns around the availability, reliability and flexibility of the heat networks. In relation to the reliability and flexibility of the heat networks, two discrete and conflicting reasons emerged. On the one hand, some participants highlighted the fact that building a heat network and connecting it to the plant means building reliance on that plant working for a very long time to make the payback to work. On the other hand, the pathway was seen as a way to deliver an optimal contribution to renewable heat, if energy was largely coming from biomass. The overall cost of the pathway, including the cost associated with building a heat network, if not available, and the potential transport emissions which some participants considered as higher in decentralised pathways, together with the location of the plant, and issues of social acceptability, were additional concerns undermining the performance of the pathway.

Participants G5, I2 and CS2 ranked it worst under most optimistic assumptions. This was due to concerns around waste availability and disadvantages of economies of scale.

4.2.4 Decentralised Gasification for the decarbonisation of the transport sector

As with the case of Centralised Gasification, this pathway was also new to many of the participants. Several participants were sceptical of its likely feasibility and costs due to economies of scale. However, the future of this pathway was also recognised as playing a potential key role in the transport sector and hydrogen economy.

It was the pathway with the widest range of rankings, together with the Centralised Gasification. Participants G3, I1 and A1 saw this pathway performing the best under optimistic assumptions and the worst under pessimistic assumptions. This was due to techno-economic, environmental and social criteria. Participants saw scope for this being the pathway with the highest degree of uncertainty in terms of the overall cost/economic viability of the pathway, the environmental performance of the pathway taking into account the GHG emissions reduction effectiveness, the technology readiness and deployment, the air quality impacts, and the type of waste used (biogenic, non-biogenic, or mixture). Other participants addressed this uncertainty in terms of the performance of outputs, social acceptability and economic growth benefits.

For participants G1 and I3, Decentralised Gasification for the decarbonisation of the transport sector was seen as the best performing pathway under both optimistic and pessimistic assumptions. This was on the basis of techno-economic and environmental criteria. Concerns associated with public investment, GHG emissions reduction effectiveness, air quality impacts, chemical efficiency of conversion, economic growth and UK bioenergy development recurred throughout the pathway dataset. Both participants saw this pathway as the most sensible and desirable pathway because of its potential contribution to GHG emissions reduction in the transport sector which, in words of participant G1: 'is a sector which nowadays, and in the medium and long term for maritime, aviation and heavy good vehicles (HGV), the only option that we have is biomass'. Moreover, in the view of participant G1 the decarbonisation of the transport sector is an issue of international interest. If the UK managed to produce liquid biofuels via gasification, it could strongly benefit in terms of market opportunity and deployment of the gasification technology, and the creation of national and international market for biomass and waste. These would strongly contribute to the UK economy growth and the UK EfW development.

An interesting result and common view amongst these two interviewees is their emphasis on the need for carbon capture and storage (CCS) deployment for delivering negative emissions. The optimistic assumption involved the deployment of CCS. Interestingly, even under least optimistic circumstances, in which CCS failed, the pathway was still seen by participants G1 and I3 as the pathway with the highest performance. This view surfaced mainly in relation to the techno-economic issue of chemical efficiency of conversion, identified by participant I3 as a criterion, and echoed by participant G1: 'If CCS fails, gasification technology for the production of liquid biofuels from waste can still deliver carbon savings… If there were no CCS in place, in the medium to long term, gasification for the production of transportation fuels would still be a better option [pathway] than gasification for the production of power and heat.'

Decentralised Gasification for the production of liquid biofuels and chemicals was seen as viable only in the long term. Participant G1 stated that Decentralised Gasification for the decarbonisation of the transport sector will require CCS, however at a later stage. By then, gasification and CCS technology and infrastructure would be much more developed. Uncertainty on the cost on how to do it would probably have diminished and its financial cost and required public investment reduced. In terms of air quality impact, it would depend on the final end use of those transport fuels and their distance to people. If dedicated to HGV, these vehicles tend to go around cities, in between cities, rather than within the cities, so air quality impacts would be far from population. If liquid biofuels were dedicated to jet fuels the emissions and air quality impacts would be farther from people, as airport tend to be at the edges of cities. Hence, liquid biofuels for HGV were viewed as having a higher air quality impact than liquid biofuels used in jet fuels.

Finally, it is worth noting that both participants, I3 and G1, recognised the importance of hydrogen as a future element of this pathway, by arguing 'if CCS is available, synthetic natural gas, and in the future, transforming that synthetic natural gas into hydrogen…, through this process is probably the best alternative that we can get in the medium to long term.' (G1) and 'If you use biogenic and you make hydrogen and CCS at the plant. It means that carbon emissions can be captured, vehicles have zero emissions using hydrogen and I think that is almost as good as you can get.' (I3)

This pathway was also seen as performing the worst according to five participants (G3, G4, I1, I2, A1). Under these participants' views, Decentralised Gasification for the decarbonisation of the transport sector performed poorly because of techno-economic and environmental criteria. This was because of concerns about GHG emissions and air quality impacts, costs and bankability, feedstock quality and its suitability for the gasification technology, performance of outputs and the additional complexity of the back-end treatments, the technology readiness and planning permission, and the scepticism around the efficiency of the pathway to make a relevant contribution to the decarbonisation of the transport sector. Only in the views of participants G4 and I2 Decentralised Gasification for the decarbonisation of the transport sector remained performing worse than any other pathway even under most optimistic assumptions. Both participants felt this pathway performed badly because of the high CAPEX. Participant I2 also addressed poor performance to the pathway arguing that obtaining planning permission would be difficult because of public concerns towards transport emissions and air quality impacts, which were perceived as higher in a decentralised pathway. Participant G4 felt it to be implausible because of the efficiency of the pathway, the current TRL of gasification, and the reduced number of waste sorting plants in the UK, and argued that '…the issue with transport is that the system [pathway] would not make a big enough impact. …. 20% contribution of UK demand for HGV would not be enough to put massive investment into the system [pathway]. It is needed something that would solve the problem complementary, like 80%, not 20%.' Participant G4 stated that a potential energy mixed for the decarbonisation of the transport sector could be formed by hydrogen for HGV, electricity for small vehicles, and liquid biofuels for aviation; and added that 'The UK needs to do better in order to make the gasification system [pathway] to work. Keeping sorting processes as they are currently, there is no foreseen future of gasification.'

In the appraisals of participant A4, Decentralised Gasification for the decarbonisation of the transport sector was ranked as the most certain pathway. In this participant view there is no purpose in doing liquid biofuels at small scale, as it would not be marketable.

4.2.5 Decentralised Anaerobic Digestion for the decarbonisation of the heat sector

The Decentralised Anaerobic Digestion (AD) for the decarbonisation of the heat sector pathway was ruled out for appraisal by participants I3 and A4 because they both felt they did not have the necessary expertise and knowledge to assess the pathway.

In the views of participants G6, A3 and CS1 this pathway was ranked with the highest degree of uncertainty. However, while for participants G6 and A3 the degree of uncertainty was reflected as higher than 70%, for participant CS1, the degree of uncertainty was around 25%. In other words, the degree of uncertainty for participant CS1 for the remaining pathways is even lower than 25%. In contrast, in the view of participant I2, AD for the decarbonisation of the heat sector was the least uncertain pathway.

Participant G2 saw it as potentially the best performing pathway under optimistic assumptions. Five participants (G4, G6, A2, A3, CS1) ranked AD for the decarbonisation of the heat sector best performing under both optimistic and pessimistic assumptions. This was in a lesser extent on the bases of techno-economic criteria looking at concerns around cost and efficiencies of conversion, transport, and handling; and in a larger extent to both environmental and social criteria. The most striking result to emerge from the data is that the best performance of this AD pathway was reflected predominantly through criteria examining the impacts on society and the environment. These criteria are: “environmental performance”, “externalities”, “public acceptance”, “planning permitting”, “environmental justice and democracy”, “opportunity cost avoided”, “community benefits”, “decarbonisation”, “ratio of biogenic vs non-biogenic material”, “contribution to the circular economy” and “scarcity of alternatives”.

Participants G2 and G4 both argued that the planning permission can be easier to get because of their small size and their visual look, they can be blended within the landscape a bit better than other technologies. Participant G4 identified issues of odours and transport that might hamper the planning permissions due to public opposition. In the view of participant A3, decentralised pathway with its dendritic infrastructure and plants located closer to people could have a negative impact on the public. However, participant A3 also argued that it would all depend on the structure of ownership and management of the pathway that people might perceive it in one or another way. In the view of this participant the pathway could offer potential for educational connections and use of the plants. For example, the positive public engagement could be boosted by providing the digestate for composting for free to people. Similar concerns of odour, traffic, and potential benefits that could out-weight the dis-benefits of the plant development were highlighted by participant CS1 when assessing the pathway in relation to the criteria of “environmental justice and democracy” and “community benefits”.

In the views of participants G4 and A2 the performance of the AD for the decarbonisation of the heat sector would increase if the heat efficiency works well. Participants considered that one of the advantages of the AD was the displacement of other fuels by using organic waste that cannot be recycled. However, they both highlighted the dependency of the AD technology to the need of a consistent quality and suitable feedstock to obtain the desired methane content; otherwise, if the consistent feedstock changes, the plant might not work as designed.

Participant G6 brought to light concerns with regard to the handling and transport of materials, and assessed the efficiency of the pathway in these matters. In the view of participant G6, AD was the most efficient pathway (relatively to the other pathways) and argued that changes in collection systems, such as the compulsory segregation of food waste, would drive AD. Moreover, the front-end processes required for the gasification technology, could potentially boost AD as well. Participant G6 raised concerns around scale of the plant, capacity, food waste availability, and digestate use, which could negatively affect the performance of the pathway. The problem would be, for example, if there is not enough AD capacity, the segregated food waste would end up going into thermochemical conversion processes where it has a fairly low calorific value because of its moisture content. It could also happen that the plant might require food waste from other places and that would increase the transport miles. Another issue in handling and transport efficiency could be at the back-end of the process with the digestate; it would be important to ensure digestate is used locally, otherwise, it would have to be transported and that would reduce efficiencies.

The quality of the digestate appeared as a major concern for debate when assessing the pathway in relation to criteria of: "environmental performance", "opportunity cost avoided", "community benefits", "contribution to the circular economy" and "scarcity of alternatives". In the view of participants G6, A2, A3 and CS1 the important aspect of this pathway is not the process, but the capacity to generate bio-fertiliser to improve soil conditioning and biodiversity. Food waste would have to be managed carefully and ensure very well segregation of it to control appropriately the digestate quality, avoid contamination from other waste streams, and meet the digestate quality standards to be fully recycle to land. Otherwise, the digestate could not be used as fertiliser in the soil because it might be full of contaminants from other waste streams such as plastics and glass. Nonetheless, even under circumstances where the digestate quality could not be met, the pathway was still seen as making a good contribution to the production of renewable heat.

In contrast, the pathway was seen as the worst performing by participant G1. This was due to techno-economic and social criteria. Nonetheless, this participant also gave this pathway a high degree of uncertainty. Participant G1 saw scope for this being the worst performing pathway in terms of "public investment", "contribution to the bioenergy development" and "citizens´ engagement and behaviour change". Three discrete reasons emerged from this. First, heat network would require CCS in the long term (it seems worth to remind than participant G1 addressed large part of the interview to the need and relevant role of CCS technology for the deployment of these EfW technologies). However, the construction of its dendritic grid structure embedded within the cities reaching multiple places will require higher public investment to put the infrastructure in place; and in some areas distribution networks might need to be built, and would entail more number of capturing points for the CO_2, which would increase the cost. Second, the impact of AD in the bioenergy economy at the moment is limited as the technology can only treat certain types of wastes such as wastewater, sewage, food waste, certain agriculture, and farm wastes. This provides limited potential to stimulate the international biomass market. Third, the segregation of food waste at home level would involve strong change of behaviour.

The pathway was best ranked under least optimistic assumptions by seven participants (G4, G6, I2, A2, A3, CS1, CS2). This was due to criteria of “efficiency”, “ratio of biogenic material vs non biogenic material”, “public acceptance”, “contribution to the circular economy”, “community benefits” and “GHG emissions”.

4.2.6 Decentralised Anaerobic Digestion for the decarbonisation of the transport sector

As in the case of Anaerobic Digestion for the decarbonisation of the heat sector, Anaerobic Digestion (AD) for the decarbonisation of the transport sector was also ruled out for appraisal by participants I3 and A4 because they both felt they did not have the necessary expertise and knowledge to assess the pathway.

In the views of participants G1 and G2, this pathway was ranked with the highest degree of uncertainty. While in the appraisals of participants G6 and A1, AD for the decarbonisation of the transport sector was ranked as the most certain pathway.

Participants G4 and CS2 saw AD for the decarbonisation of the transport sector as the best performing pathway under optimistic assumptions. Only in the case of participant G4 the pathway remained best performing even under most pessimistic assumptions. These participants felt this pathway to perform well because of features of cost associated with TRL; efficiency, air quality impacts, and human health impacts associated with transport miles; the production and flexibility of the end products, GHG emissions reduction, and public acceptance.

In the view of both participants, the level of readiness of AD technology made the pathway economically feasible leading it to perform well under techno-economic criteria. The decentralisation of the pathway was seen by participant G4 as a key element for better public acceptance and by participant CS2 as an advantage in terms of air quality impacts on human health. In the view of participant G4, public acceptance for AD pathways would be easier to achieve because of their small size and their visual appearance, which facilitates planning permitting processes. In the view of participant CS2, the decentralised pathway would have shorter transport miles for the feedstock delivery which would have a direct positive impact not just in the air quality of the area but also on human health by reducing exposure of process pollutants to receiving populations. In addition, in terms of GHG emissions, the pathway would deal with the methane which has got a higher GHG impact than carbon dioxide, so it would be controlled through the AD, and would produce a cleaner alternative to liquid fossil fuels. The back-end process of producing transport biofuels was seen, by both participants, more as an environmental and social advantage rather than as a technological challenge. Participants G4 and CS2 repeatedly referred to the practicality of the pathway because of the flexibility of biofuels. The produced transport biofuels could be used for multiple purposes, which would help in the decarbonisation of the transport sector. Transport biofuels could be used at a local level where the plant is located, or at a national or international level; although this would entail further transportation of the products, and that might generate higher emission. Another alternative could be the use of transport biofuels for the support of companies own transportation fleets, such as, for example, the waste management companies own truck fleet….

The pathway was seen as the worst performing under pessimistic assumptions by participant G2. This was due to poor performance of techno-economic criteria. Participant G2 felt that the pathway was not plausible given the complexity to decarbonise the transport sector and the required amount of waste that would be needed for it. Considering that the eventual plan is to move from liquid fuels to electric for the regular lighter transport sector, the waste could be used for the aviation and HGV transport sectors. Nonetheless, in the view of participant G2, food waste is not the answer to decarbonising all of the heavy transport because food waste availability for the required production of transport biofuels for HGV and especially for aviation would be very low. Moreover, participant G2 expressed scepticism towards the future deployment of the EfW sector in the UK, by addressing concerns of overcapacity deployment, minimisation of waste streams and changes in legislation. It seems worth quoting at length:

> ‘if we build the EfW sector based on current waste availability, there could be in the future a situation of overcapacity. As the reduction of waste keeps been encouraged and new waste policies are coming to light where different material products start to be banned for production, and therefore as waste; there might be less available waste. This means, that maybe in the short or medium term the deployment of energy from waste facilities along the country is a good idea, but maybe in the longer

> term this might not be the answer, because waste is going to be so minimal that we can't run plants'

The feeling overall seemed to be that while AD and transport biofuels individually were likely to play important roles in the transition to a low carbon economy and the decarbonisation of the transport sector, in some circumstances, the sole production of transport biofuels from AD was unlikely, considering the large amount of food waste that would be required to meet demand.

Participant I1 saw this pathway as the least favourable under optimistic assumptions, this was due to economic criteria; while participants G3, A3 and CS1 considered this pathway as performing the best under pessimistic assumptions, this was due to criteria of "public acceptance", "community benefits" and "wider economic impacts".

It seems important to notice that the overall performance of both AD pathways ranked similarly under both, pessimistic and optimistic assumptions. This was because in many cases when assessing the pathways under the different criteria, same scores were given to both pathways under pessimistic and optimistic assumptions.

Conclusions

The first section of this chapter analysed the criteria obtained from the MCM. The analysis has enabled the categorisation of the 80 criteria identified by the 15 stakeholders' participants into the three different sustainability dimensions: techno-economic, environmental and social. Of the 80 criteria identified in total, 44 have been categorised into the techno-economic dimension, 18 into the environmental dimension and the remaining 18 into the social dimension. Likewise, criteria within each dimension have been further divided into subgroups called issues. The criteria within the techno-economic dimension predominantly relate to issues of economics, feasibility, and efficiency. These will be further analysed and discussed in Chapter 5. The environmental criteria relate to issues of environmental efficiency, and these will be further analysed and discussed in Chapter 6. The social criteria relate to social and political issues, which will be further analysed and discussed in Chapter 7.

Overall, techno-economic criteria were judged to be more important than environmental and social criteria; and social criteria were judged to be the least important. Only in the case of the Civil Society perspective were the techno-economic criteria considered the least important, and the environmental criteria considered the priority.

The second section of this chapter provided a first overview analysis of the overall sustainability performance of the six EfW pathways at an aggregated level. In other words, the chart shows the final performance of the pathways when the appraisals of each of the stakeholder participants are grouped.

Drawing on the final overall performance of the six EfW pathways per participant perspective (see *Appendix 2.2* for the final overview of pathways performance for each stakeholder participant), this section has brought to light the most striking factors as to why participants appraised and scored optimistically or pessimistically each of the different EfW pathways, which ultimately lead to what is reflected at the aggregated level. The analysis provides a useful overview of the rankings across all participants, and across the various criteria identified.

Overall, there is wide overlap between all pathways, which confirms the contested nature of the debate. BAU was the least uncertain pathway. This was because the technology is available, proven and widely deployed worldwide. The overall optimistic performance of BAU was strongly related to techno-economic criteria, such as “ease of use”, “technology readiness”, “compatibility with collections”, “CAPEX” and “waste availability”. Two participants viewed BAU as the best performing under both, optimistic and pessimistic assumptions. In contrast, its overall pessimistic performance was more largely related to environmental and social criteria, such as: “contribution to GHG emissions reduction”, “social acceptability”, “resource security”, “air quality impacts”, “appearance”.

Pathways dedicated to the decarbonisation of the transport sector were scored the most uncertain. In particular, the Centralised Gasification pathway stands out for its wide uncertainty around techno-economic and environmental criteria. The most pessimistic performances were associated with the TRL, which could make the pathway unfeasible. Only one participant perceived it as the best performing pathway, in part due to the techno-economic and environmental criteria.

Decentralised Gasification for heat network obtained relatively intermediate scores. The main concerns around this pathway were related to the TRL of gasification, the lack of heat networks in the UK, and the disadvantages of economies of scale.

Wide ranges of uncertainty were also predominant in Decentralised Gasification pathway for the decarbonisation of the transport sector. Whilst with Centralised Gasification, the uncertainty related mainly to techno-economic and environmental criteria, in the case of Decentralised Gasification, it had wider uncertainty in relation to social criteria, largely due to its potential proximity to populated areas which may influence the degree of social acceptability. In comparison to Centralised Gasification, the final overall performance of this pathway was more contested between participants.

The optimistic performance of the two AD pathways was reflected predominantly through criteria examining the impacts on society and the environment. However, they were undermined by pessimistic techno-economic criteria. In the case of Decentralised AD for the decarbonisation of the heat sector, there were feasibility and economic issues related to the deployment of heat. In the case of Decentralised AD for the decarbonisation of the liquid biofuels, it was hampered by issues of feasibility associated with concerns of waste availability.

By looking at the performance of the pathways under the different sustainability dimensions and issues, it is possible to learn about and understand more in depth the reasons why the different participants selected those criteria, as well as the reasons why they scored the pathways in this way.

As explained previously, in the interviews the participants identified different criteria with which they evaluated the sustainability of the different pathways. The criteria were divided into groups and sub-groups spanning three increasingly analytical stages. First, the 80 criteria were grouped into different sustainability 'dimensions': techno-economics, environment and social. Second, the criteria related to each of the dimensions were further sub-divided into substantive 'issues' under which were identified more specific 'themes' to complete the third stage of the analysis. Therefore, the following Chapters 5, 6 and 7 explore what the Multicriteria Mapping (MCM) process tells us about the sustainability of the competing EfW pathways by examining the most debated themes in participants' perspectives around the various issues of the techno-economic, environmental, and social dimensions.

Chapter 5. Techno-economic Dimension – Results and Discussion

This chapter analyses and discusses the techno-economic issues identified by participants in response to their appraisal of the sustainability of the Energy and Fuels from Waste (EfW) pathways. Section 4.1.1.1 provided an overview of the criteria identified by participants which were related to the techno-economic dimension. Of the 80 criteria identified in total across all dimensions, 44 were grouped under this dimension (see Table 5.1). All participants identified at least one techno-economic criterion as part of their appraisal. The techno-economic criteria addressed issues of feasibility, efficiency and economics.

The debate around efficiency issues focused on three main themes: 1) handling efficiency (G4, G5, G6, I2), 2) feedstock efficiency (G4, G5, G6, A1, A2), and 3) impact and contribution of the pathways to decarbonisation of the heat and transport sectors (G2, G4, G5, I2). The themes intersect feasibility, economic, and environmental issues.

The debate around economic issues focused on two main themes: 1) net financial cost of pathways (G2, G3, G4, G5, I1, I2, I3, A2, A4, CS1, CS2) and 2) UK economic impacts (G1, G3, I2). The themes intersect feasibility, efficacy, and environmental issues.

The themes associated with each of these issues are explored in detail below.

Table 5.1 Techno-economic Criteria

Perspective	**Code**	**Participant**	**Criteria**
Government	G1	BEIS Energy Engineer Expert	Public investment
			UK economy impact *
			Contribution to bioenergy development
	G2	DfT Advanced Biofuels Policymaker	Waste availability
			Cost of infrastructure
			Size of plants
			Technology readiness
	G3	DEFRA Economic Advisor	Net cost of pathways

Table 5.1 Techno-economic Criteria

			Wider economic impact *
	G4	Waste & Resources Specialist Consultant	Efficiency
			Feedstock
			CAPEX
			OPEX
	G5	Local Authority Waste Management Officer	Cost effective
			Ease of use *
			Waste availability and volumes *
	G6	EA Waste Management Planning and Strategy Regulator Advisor	Calorific value of material
			Transport and handling efficiency
			Ratio biogenic material vs non-biogenic material
Industry	I1	Energy from Waste Industry Sales Manager	Bankability/track record
			CAPEX
			OPEX
			Performance of outputs
	I2	ESA Executive Director	System costs
			Technology readiness
			Compatibility with collections
			Output risks
	I3	Energy from Waste Industry Managing Director	Chemical efficiency of conversion
			Economic viability
Academia	A1	Sustainable Bioenergy Expert	Resource efficiency *

Table 5.1 Techno-economic Criteria

			Flexibility
			Air quality impacts
	A2	Waste Management Process Engineer Scientist	CAPEX in pounds per MW
			Efficiency
			Reliability (availability)
			Scale
	A3	Public Perceptions of Energy and Sustainability Scientist	Scarcity of alternatives *++
	A4	Waste Management Policy Advisor	Waste availability and quantity
			Gate fees *
			Price of the energy output
Civil Society	CS1	UKWIN Environmental Campaigner	Achievability (realistic)
			Externalities * ++
			Opportunity cost avoided
	CS2	Sustainable and Strategy Developer	Net financial cost

* indicates corresponding criterion also addressed some social aspects

++ indicates corresponding criterion also addressed some environmental aspects

Acronyms: Department for Business, Energy & Industrial Strategy (BEIS), Department for Transport (DfT) Department for Environment, Food & Rural Affairs (DEFRA), Environment Agency (EA), Environmental Services Association (ESA), United Kingdom Without Incineration Network (UKWIN)

5.1 Feasibility Issues

Participants´ debate around feasibility issues focused on two main themes: 1) waste availability (G2, G4, G5, I2, A4, CS1) and 2) technology readiness and bankability (G2, I1, I2, A2, G5). These themes intersect efficiency and economic issues.

5.1.1 Waste Availability at the Required Quality and Quantity

Waste availability relates to the availability of appropriate waste feedstock in terms of quality and quantity. Participants regularly commented that waste must be available over time at the required quality for the specific technology and in the required quantity for the scale of the pathway. Participants felt that achieving the required quality and quantity of feedstock for the different pathways over time was influenced by aspects of waste management systems and conversion technology selectiveness, the availability of sorting/processing infrastructure, legislation changes on waste management, behavioural changes and the scale of operations/pathways' models of distribution, whether centralised, or decentralised. Moreover, participants raised concerns around the constant changes in waste composition and quantity over time. The constant changes in waste overtime were an inherent challenge to the waste availability theme, identified as the major source of uncertainty when appraising the performance of the pathways.

For some participants (G2, G4, G5 and I2) concern about waste availability was to do with the degree of compatibility of the waste management processes that go before the waste arrives to the EfW plant, and to the selectiveness of the conversion technology. For these participants, concerns were related to what types of wastes are available with current waste management and collection systems, whether the technology used in the pathway is flexible for the type of waste available and what changes in waste management and collection systems would be required to make the appropriate waste available for the technology of the pathway.

Waste availability, its composition and quality variability (providing flexibility) was not a concern for incineration but was for gasification and anaerobic digestion (AD) as these processes have specific waste composition requirements. As one participant expressed: 'As long as it is not bulky' the incineration technology 'allows [us] to throw [in] anything that anyone would put into a bin' (G5). Whilst the flexibility of incineration technology allowing it to take all types of feedstock was cited as a strength, the sensitivity of the gasification and AD technologies to heterogeneous feedstock was cited as a weakness. Gasification and AD pathways would need extra-processing activities to achieve the appropriate consistency and quality of feedstock and meet the selectiveness of the conversion technology. This is in good agreement with Arena (2012), Evans (2017), Waldheim (2018), Foster *et al.* (2021) and Ng *et al.* (2021) with regard to gasification, and with DEFRA (2011), Ng *et al.* (2019) and Slorach *et al.* (2020) with regard to AD. To make the feedstock consistent and reliable for the selected technology would require changes to the waste management systems and collection. Participants felt that this could be a challenging outcome in the long-term considering the constant changes in waste quality and volumes over the years (DEFRA, 2014; Evans, 2017; Waldheim, 2018). As similar arguments were made by several participants, it seems worth quoting the view articulated by participant G5:

> 'You go back 20 years, we still had a lot content of limes, which included ash. That is not existing nowadays. We had a high content of fibre paper that is way down the list now. What we see a lot more now is lightweight materials, plastics, and lightweight metals, and glass, etc. So the mixture in waste changes.' (G5)

Segregated collection of waste streams and sorting and processing infrastructure would make waste more usable in gasification and AD, but it would require infrastructure investment, policy intervention, legislation changes, and behavioural changes. The lack of infrastructure available for sorting and processing waste in the UK was cited as a weakness and a significant limitation to the feasibility of gasification and AD pathways. This is in good agreement with findings from ESA (2017) and Rhodes and Thair (2017). As one participant argued, 'The UK needs to do better in order to make the gasification system [pathway] work. Keeping sorting processes as they are currently, there is no foreseen future of gasification.' (G4) Participants converged on the idea of a need for more sorting and processing infrastructure in the UK, as well as better collection and handling systems, to increase waste availability of the required quality, for gasification, and AD pathways. This would entail investments in terms of both infrastructure and waste management systems. The segregation of food waste at household level was seen of great relevance for achieving the compatibility of waste management and collections systems to AD technology selectiveness.

As one participant argued: 'The main issue would be how to get the selective waste…There would have to be a lever to make that happen. Something that makes the waste available.' (G5) This was a common view among participants. Although Business as Usual (BAU) could be adversely affected by legislation changes (which will be discussed further below), most participants felt that the only way to make waste available and achieve the appropriate feedstock for both gasification and AD pathways was by applying legislation changes for waste management. Legislation changes were seen by participants as particularly relevant for ensuring the segregation of food waste and waste availability for AD pathways. As participant G5 said: 'There needs to be a political driver for segregating waste for use in AD. Otherwise, it would never happen.' Participants G5, G4 and I2 pointed out that the legislation changes should go hand in hand with public behavioural changes and public understanding. Otherwise, there would be undesirable consequences in terms of waste availability, but also efficiency. See Section 5.2 for further discussion on this topic.

Legislation changes were cited both as a strength and as a weakness for the performance of the pathways in terms of waste availability. Whilst legislation changes were seen as drivers to achieving the required quality and consistency of feedstock for the specific technology; participants felt that as legislation became stricter, more feedstock would become available for gasification and AD. The same legislation drivers were also seen by participants as handicaps in terms of securing waste availability over time. In this regard, the legislation changes could have a negative impact on the quantity of waste available to fulfil scale capacity of the EfW plants, reducing the feasibility of large scale centralised pathways, while boosting the feasibility of decentralised pathways. If conditions were met, it would be easier to secure consistent feedstock at the required quality for decentralised pathways. Reduced feedstock availability could lead to impacts in the operational scale of the pathways, which in turn, could impact on the efficiency and economics of the pathways. This will be discussed further in Sections 5.2 and 5.3. This is consistent with observations reported in the Waldheim (2018) review, where it is argued that the barrier to having enough consistent feedstock for a gasification technology plant, when legislation changes come into place and further recycling will be done, will be of greater relevance in those regions where there is already an incineration plant with excess capacity.

Segregated collection, sorting, and processing of waste could adversely affect BAU performance by reducing waste quantity and composition available for incineration. In this regard, some participants (G5, I2) showed resistance to making changes in terms of segregation of food waste, because it could have adverse consequences on the BAU performance. The segregation of food waste from residual waste stream could have a negative effect on achieving the desired calorific values for incineration technology. Concerns associated with this were more to do with efficiency, economic, and political elements, rather than waste availability. These concerns will be discussed further below in Sections 5.2, 5.3 and Chapter 6. Nonetheless, if it was just a matter of increasing recycling rates, participants G2, G5, I2 were broadly convinced that there would still be enough waste availability to run centralised incineration pathways. The reasons behind these participants' statements were not discussed in detail, but a possible explanation for this outcome may be related to the waste exports situation in the UK. Large amounts of waste produced in the UK are exported however, as documented in the literature, this situation might experience challenges to remain at current state in the future. Moving by political and market pressures, both internationally and nationally, the waste will potentially remain in the UK and will need to be managed nationally.

The scale of operation associated with waste availability was another matter of debate. For some participants (G2, G4, G5, I2, A4) the performance of pathways in regard to waste availability was related to the scale of operation and distribution of the pathways, the proximity of the required quantity of waste to the plant and the number of points of supply of the waste. The questions these participants were interested had to do with: Where is the waste coming from? Is there enough waste locally to fulfil capacity? They were concerned about transport miles, which could impact on carbon emissions. This will be further discussed in Chapter 6. Participants felt that centralised pathways were favourable in terms of securing waste availability for the capacity built over time. This was because of the multiple points of supply network which they usually have. Participants G4, G5 and A4 cited the Private Finance Initiative (PFI) contracts between large waste management companies and Local Authorities as strength for waste availability in centralised pathways (Ng *et al.*, 2019). In contrast, decentralised pathways were seen to be more dependent on the availability of supply in the area to fulfil/accommodate capacity. Participants felt that for decentralised pathways to perform relatively well in terms of waste availability to fulfil capacity, the waste should be made available locally. Otherwise, with a lack of sufficient waste, the pathway would be dependent on other places for available waste to fulfil the capacity of the plant. This could ultimately generate constraints in reliability and efficiency, as well as an increase in transport miles. Moreover, while PFI contracts were seen as advantageous for securing waste for centralised pathways, they were highlighted as handicaps for decentralised pathways. In other words, securing waste availability over time for decentralised pathways could be difficult due to competitive pressures and market forces. This fits well with arguments from Hall (2014), who claims that the long-term PFI contracts have located Local Authorities in a lock-in situation with the private sector and large waste management companies, by means of which, while the contract is still in force, other waste management alternatives cannot be undertaken.

Participants also acknowledged that with legislation changes and infrastructure investment in sorting and processing of feedstock there should be improvements in recycling rates and food waste segregation. While these improvements were cited as strengths in terms of feedstock quality and quantity for gasification and AD pathways, participants pointed out that they could also have an adverse impact on feedstock quantity for Centralised

Gasification and BAU pathways. An increase in recycling rates should ultimately lead to a decline in waste availability, which in turn could impact on the scale of plants needed, making decentralised pathways easier to deliver. Such impacts on scale could have an impact on the efficiency of pathways. Likewise, the decentralised pathways could be affected by economies of scale, which will be further discussed in Section 5.3.1.1.

The chart of the overall performance of the six pathways against waste availability theme can be found in *Appendix 2.3. Figure 2.3.1*.

5.1.2 Technology Readiness and Bankability

Technology readiness and bankability theme relates to the demonstrated availability/reliability of the plant (dependable operating hours), which is seen as a pre-requisite for the ability to attract investment (''bankability''). The questions brought up by participants were: How ready is the technology? How close to commercial investable reality is the technology? How many operational hours per year can the plant be running for? Considering the use of different feedstocks, are the technologies ready for the planned different feedstocks? The technology readiness and bankability theme intersects with efficiency and economic issues.

The aspects of availability, reliability, and bankability were considered by participants to be interrelated. The higher number of operational hours, the more reliable and robust a pathway would be. It would be of little use to have a technology, which operates for a reduced number of hours, as its availability would be limited. Being able to operate for sufficient hours increases the number of references and track record about the readiness of the technology, which in turn supports its availability on the market and bankability. Bankability relates to the capacity of the pathway to attract investment to make it a reality. The capacity of investment is related to the track record and references about the technology in question, which is measured/generated by the number of operating plants of a specific technology and the number of operational hours of each of the plants. As one participant stated: 'If there are a significant number of references/track records regarding plant operations, bankability is not an issue' (I1). In other words, a high number of references, provides reliance on the technology and the engineering companies, which de-risks for the project in question, increasing the capacity for investment, or bankability. This also relates to the level of trust that investors have in the technology working well and their willingness to invest.

Owing to the potential changes in waste composition and quantity over time, ensuring consistency of feedstock quality over time to meet the selectiveness of the conversion technologies (see Section 5.1.1) was another concern identified by some participants. This was seen as a determinant factor undermining the technology readiness and bankability, particularly for gasification, AD, liquid biofuels conversion technology, and heat networks. Finally, for some participants another key issue undermining the technology readiness of the pathways dedicated to the decarbonisation of the heat sector was to do with the non-existence of heat networks in the UK.

The interrelation of technology readiness and bankability made by participants was of great relevance, especially in the case of gasification technology, with which it was difficult to treat the two elements separately. Technology readiness and bankability are therefore discussed together in here. The bankability theme is also discussed further with economics issues, in Section 5.3.1.

BAU performed the most highly against technology readiness and bankability theme. Incineration was seen as a proven technology, with wide deployment, and long operating history in the UK and internationally (Yap and Nixon, 2015; Foster *et al.*, 2021). The number of references regarding operational plants and the robustness, and reliability of the pathway were cited as strengths by all participants. There was little uncertainty around the performance of BAU in terms of technology readiness. The adaptability of BAU to changes in waste availability were cited as a potential weakness (see Section 5.1.1); however, this was considered to be of a more determining factor for the efficiency and economic feasibility of the pathway, rather than influencing technology readiness.

Gasification technology was seen as an unproven technology, requiring further demonstration to improve technology readiness and support the investment case. At present, there were very few examples of gasification pathways operating on waste streams, and this was seen by participants as a weakness that would prevent investment. Participants highlighted the need to improve technology readiness of gasification by supporting demonstration scale operations to gain experience and a track record to support investment; this could be achieved at smaller plants, and then roll it out on commercial scales. The progression from small/medium scale plants to large scale plants was seen as a way to increase track record and gain trust in the technology. This would reduce the perceived risk of business failure, which participants considered to be very high by investors, thus potentially increasing the willingness of investors to invest. As one participant argued: ‘Public investors need to come forward to invest in the technology. It is the problem that we are having at the moment, getting people to back it, because it is such an innovation so there is nothing that is known yet; it is difficult to get the money for it' (G2). There have also been some rather outstanding technical failures (e.g., the Teesside project) and financial problems (e.g. the GreenSky London project) with gasification projects in the UK that also deter investment in gasification technology (Letsrecycle, 2014; Bioenergy International, 2015; ENDS Waste & Bioenergy, 2016b). According to Ng et al (2019) more evidence of technology success or failures with for gasification are needed to formulate a supportive incentive scheme for the technology.

Following the process of research and development, the technology readiness of Decentralised Gasification pathways, with small/medium scale plants, could be quicker to achieve in comparison to large scale plants of centralised pathways (G2, A2). However, making small scale decentralised plants bankable and economically attractive to investors was recognised as more difficult relative to large scale plants. Even if technology readiness drawbacks were overcome, decentralised pathways would be adversely affected by economies of scale. This intersects economic issues in which elements of capital cost (CAPEX) and operational cost (OPEX) would be relatively higher than with large scale plants, making the internal rate of return too small to attract investment (I2, I1). This is discussed further in Section 5.3.1.

In relation to the reliability and feasibility of the pathway, participants were concerned about the selectiveness of the conversion technology to specific quality of feedstock. The larger the plant, the more feedstock needs to be sourced; given the reprocessing that is required this could be more challenging for large plants. The changes in waste quality and quantity over time were cited as drawbacks for achieving reliability in gasification pathways. This intersects with efficiency issues and matches well with the Waldheim (2018) review insights. In spite of this, participant I2´s perspective was that any of the gasification pathways under appraisal would be unlikely to be widely delivered at any scale within the next 10-15 years.

The views of participants towards the readiness of the liquid biofuels conversion technology in the gasification pathways were variable. Some participants (G5, I1) considered the process unproven and of high technical complexity, which would require high investments to become ready. Others (G2, I2) did not address its readiness level but pointed out the role of liquid biofuels subsidies as an economic driver to boost the development and establishment of gasification and to attract investors. The reliability of liquid biofuels conversion technologies was also considered dependent on the consistency of the feedstock, as also concluded by Waldheim (2018). This is discussed further in Section 5.2.

AD was considered a proven technology by participants but securing feedstock to ensure reliable operation was viewed as a potential risk to investment. The consistency of feedstock quality over time was cited as the major risk that could limit the reliability of the AD technology. This was related to the availability of segregated food waste and the capacity to secure feedstock over time (G2, A2, I2, I1); thus potential changes in waste composition and quantity over time and the selectiveness of the technology to specific feedstock quality were viewed as hindrances.

Regarding the pathways dedicated to the decarbonisation of the heat sector, participants also raised concerns around the availability and reliability of heat networks. Whilst the technology of heat networks was regarded as proven and already commercialised, the reduced number of heat networks in the UK were cited as weakness, for both centralised and decentralised pathways, in terms of technology readiness. The lack of heat networks in the UK as barrier undermining the decarbonisation of the heat sector is widely reported in the literature (Wright *et al.*, 2014; ETI, 2018; ERA, 2020; Cross *et al.*, 2021). Likewise, the reliability of heat networks technologies was considered to be dependent on the consistency of feedstock (A2). District heating viability was not identified as a function of technology, but as a function of demand (I2, G4). There need to be sufficient customers willing to connect to the heat network, to make the business case attractive (Wright *et al.*, 2014; ETI, 2018). Some participants pointed out the role of heat subsidies (G2), such as renewable heat incentives, as economic drivers to boost the deployment of the technology. These results are consistent with what other stakeholders reported in previous stakeholder perceptions studies (Cross *et al.*, 2021).

The chart of the overall performance of the six pathways against technology readiness and bankability theme can be found in *Appendix 2.3. Figure 2.3.2.*

5.2. Efficiency Issues

The issues of efficiency relate to the overall conversion efficiency of the pathways. Efficiency criteria used by participants were assessments of the overall energy obtained per tonne of waste input into the pathway.

Participants addressed the efficiency issues from different focuses/anchor points. Some participants focused on the discussion of efficiency around the front-end activities of collection/sorting/processing of the waste (G4, G5, G6, I2, I3, A1, A2), others around the waste availability, its energy content and related conversion efficiency within the process (G6, A1, A2), while others focused it around the back end activities of energy outputs production (G2, G4, A2). These varied, multiple understandings of the concept of efficiency amongst participants are partly due to the contextual field of work of each participant, their values, and priorities. While these focuses were sometimes addressed by participants as individual criteria, they were primarily used as offsetting elements of a same criterion. The difference in focus among participants in the appraisal helped identify themes for the efficiency issues. As explained in Chapter 3, appraisal of the six designed pathways include quantitative indicators to give a sense of the scale of the pathways and technological deployment. These indicators reflect quantities of feedstock used and expectations in terms of technology efficiencies and contribution of the different pathways to UK energy demand (see the *Expert Booklet* in *Appendix 1.1* for detailed information). Some of the themes emerging from the participants' arguments were built upon these expectations.

The debate around efficiency issues focused on three main themes: 1) handling efficiency (G4, G5, G6, I2), 2) feedstock efficiency (G4, G5, G6, A1, A2), and 3) centralised vs decentralised: impact and contribution of the pathways to the decarbonisation of the heat and transport sectors (G2, G4, G5, I2). The themes intersect feasibility, economic, and environmental issues.

Moreover, the themes of handling efficiency and feedstock efficiency could be seen as subjacent and interdependent elements which go hand in hand with the theme on waste availability. Waste availability may influence not only the efficiency of the pathway but also the feasibility.

The three themes are explained in further detail in the next sub-sections, by examining the most recurred concerns identified by participants.

5.2.1 Handling Efficiency

The handling efficiency theme relates to the activities of sorting and processing of waste at the front-end of the pathway. The theme intersects with themes of waste availability and feedstock efficiency (Section 5.2.2).

Depending on the sensitivity of the conversion technology to the feedstock properties, there would be needed more or less pre-processing of the waste at the front-end of the pathways. The more consistent the feedstock has to be; then the more levels/layers of pre-processing will be required. The more levels/layers of pre-processing required, then the lower the handling efficiency of the pathway will be. Thus, whilst putting in more effort with pre-processing activities, to get more valuable feedstock- appropriate for the selectiveness of the technology-, would not necessarily mean a less efficient process, but a potential increase in resource efficiency; for some participants (G5, I2), the need for extra levels/layers at the front-end of processing implied a reduction in process efficiency from a whole supply chain perspective. These findings should be interpreted with caution, as this type of handling efficiency interpretation expressed by some participants underestimates the value that clean feedstock may have for increasing resource efficiency, both in terms of recycling and energy recovery. This seems to confirm observations by Ng and To (2020) regarding the lack of appreciation of the concept of resource recovery from waste. Although there is a lack of appreciation of the concept of resource recovery from waste at a domestic level, these findings reveal that it also exists at governmental and industrial levels.

Participants (G5 and I2) repeatedly argued how the pathway of conventional incineration was set around what is needed in terms of waste management, and generating the least disruption to collection systems, while producing some energy. The flexibility of the incineration technology, being designed to take all types of waste, its compatibility to current waste management systems and the availability of a reliable and well understood infrastructure for sorting and processing the waste to required feedstock efficiencies were cited as strengths in terms of handling efficiency. As one participant argued: ‘the incineration system is set around what is needed’ (G5). Unless there were legislation changes, BAU was not perceived to require any changes to collection and processing systems. This was seen by some participants as an equivalent to better handling efficiency performance. However, this last statement seems to be based on past needs, when waste was considered a nuisance. There is a need to look forward and shift towards what is currently needed to transition to a low carbon economy, make more efficient use of materials, and reach net zero emissions by 2050. Similarly, the findings also reveal that depending on the participant´s context and field of work, understanding of the concept of efficiency varied. It is interesting to note that participant G5 represents a local authority of which main goal is to manage waste in the quickest way so that it does not accumulate in households. This could explain participant G5´s perspective and statements, bringing to light how values and priorities shape participant's understanding of the field and their views of sustainable performance; this corroborates previously published work by Thornley and Gilbert (2013).

In contrast, the selectiveness of the gasification and AD technologies were cited as weakness. As mentioned in Section 5.1.1, gasification and AD pathways would need extra-processing to achieve the appropriate consistency and quality of feedstock and meet the selectiveness of the technology. Changes would be required in waste management systems and collections to make the feedstock consistent and reliable for the technology. This would mean extra-processing layers/levels at the front-end, reducing the performance of gasification and AD pathways in terms of handling efficiency. Hence, while the changes in waste management and collection, with increased recycling and segregation of food waste from the residual waste, were cited as strengths in terms of waste availability for the feasibility of gasification and AD pathways, they were also seen as weakness in terms of handling efficiency. These findings, once again, should be interpreted with caution. From a waste management and energy point of view, these extra-processing layers/levels at the front-end of gasification and AD would enable an increase in resource efficiency, by increasing recycling, and reducing waste going into energy recovery, potentially producing added-value products, and progressing towards a more circular economy (CE). This is in line with what the Resources and Waste Strategy (RWS) has committed to achieve.

As a subjacent element to an increase in handling efficiency, the development, and expansion of the sorting and processing infrastructure in the UK would be required. The behavioural change required by the public would depend on where the sorting process took place (kerbside or post-collection), and this would also have an effect on handling efficiency.

'If the sorting happens at the kerbside, the system would be less easy, as more public behavioural, and educational change would be required. There would be also a need for additional vehicles. If the sorting is done post-collection, by a certain party elsewhere, then it [referring to the behavioural change from the public] would still be relatively easy' (G5).

Implementing a scheme for sorting and segregation of food waste would necessitate involving Local Authorities to arrange food waste collection and communication, and education services to inform citizens about the new way of separating waste streams.

With legislation changes and more recycling and segregation, there would be more handling overall and more processing overall. This would reduce the handling efficiency of all the pathways. Participants felt, this could benefit the business cases for gasification and AD.

As already discussed in Section 5.1, however, an increase in handling efficiency could ultimately lead to a decline in the amount of waste available for the pathways. This could lead to impacts on the scale of the plants and/or the feedstock efficiency.

5.2.2 Feedstock Efficiency

Feedstock efficiency theme relates to the amount of energy that can be obtained from the materials to be used as feedstock in the different pathways, and additionally, the ability of homogenisation of the feedstock to achieve the desired consistent quality and its most efficient calorific value for the plant to work at its maximum efficiency.

Concerns around waste availability, changes in feedstock quality and quantity over time, and the consequences were cited as weakness to achieving constant feedstock efficiency overtime. These concerns were subjacent alongside the appraisal of efficiency for all pathways. The design of the plant and the calorific value and quality of the feedstock were cited as interrelated factors influencing the efficiency.

While the high calorific values of the fossil fuel derived materials used in both incineration and gasification pathways were seen as strength in terms of feedstock efficiency for these pathways, the reduced calorific value of organic food waste, and consequently low energy content, which would provide relatively lower amounts of energy was seen as weakness of the AD pathways.

The flexibility of the incineration technology with its design accommodating all types of waste, supporting mixed waste streams to build the desired calorific value, was cited as strength in terms of feedstock efficiency. This finding is consistent with previous strengths for incineration technology identified in the literature (Yap and Nixon, 2015). However, with legislation changes and the compulsory segregation of food waste, some participants (G5, G6, I2) felt that the BAU pathway could be adversely affected in terms of feedstock efficiency. For these participants, the use of food waste in incineration was seen as key to helping to achieve the defined calorific value, at which the technology by design works more efficiently. The segregation of food waste from the residual waste stream could, therefore, have a negative effect on achieving the desired calorific values for incineration technology. Participant G5 commented:

‘It [the segregation of the food waste from the residual waste] would push the calorific value out of the sweet zone where it incinerates properly, because it would move the calorific value from 9.8 to probably closer to 12. And the calorific value at which it incinerates properly is at 8.4 and 9.8.'

This could create an imbalance in feedstock efficiency for the BAU pathway, reducing its conversion process efficiency. This in turn could also have an adverse effect on financial and regulatory compliance. The latter were largely why participants objected to the diversion of food waste from incineration, a concern frequently raised by participants and further discussed in Section 5.3.1, and Chapters 6 and 7. Participant G5 commented that the solution would be to find another feedstock to reduce the calorific value which fits into the designed range. 'If food waste is taken out; another sort of ready humid/green waste would need to be fed into the incinerator' (G5). These two statements made by participant G5 should be interpreted with caution. Another alternative to balance the calorific value of the feedstock used for energy recovery and to make up for a loss of biogenic content, which could be directed into AD, could be to minimise the amount of plastics – of high calorific value and fossil fuel derived material – going into the EfW, and instead to support their recycling (DEFRA, 2014).

For gasification and AD pathways, feedstock efficiency was perceived as intrinsically linked to handling efficiency, and a positive trend in handling efficiency, could strengthen the availability of consistent feedstock for these technologies. This is consistent with views reported by Waldheim (2018) and CCC (2018).

Some participants (A1, G6, G4) considered that the feasibility and conversion efficiency of the pathways, especially for gasification, and AD technologies, due to their sensitivity to homogenous material, were not a matter of technology readiness or improvements, but a matter of designing the plant and technology properly around the consistent quality feedstock to be used. These findings correlate fairly well with Waldheim (2018) in regard to gasification, where it is explained that the design of a waste gasifier must be able to handle the varying fuel properties of the waste, which includes the variability in size and composition and the content in combustible and non-combustible material. This further supports the idea of improving the quality of feedstock handling for consistent, reliable, and controlled feedstock quality over time, appropriate for the plant design. This would result in improved availability and performance of the gasification technologies. Related to this, some participants identified plant design failure as why some gasification projects end up working as incinerators (G4, G2). As one participant argued: 'The UK is currently at this stage, where there is a good number of gasifiers that are not working. And then, they get unpicked and replaced by incinerators' (G4). This is the case, for example, of the Isle of Wight gasification plant which in May 2019, following technical difficulties and after several attempts to render the plant operational, the technology was finally switched to work as an incinerator (Letsrecycle, 2017a).

The type of feedstock used, the calorific value, and theirs mixes were cited as influential elements of the pathway feedstock efficiencies. As one participant argued in regard to the efficiency of feedstock in gasification pathways: 'If you were just doing the plastics and the wood went somewhere else, probably EfW; or to use it for chip, and the food waste streams to AD. Then it [the efficiency] would be higher. If you are saying we have to mix the stream then no, because we are not getting the same calorific value and efficiency' (G6).

Obtaining the desired feedstock efficiency from the food waste stream was seen challenging by some participants. The compulsory segregation of food waste could not be enough to secure the quality of the feedstock for the AD technology as it could be adversely affected by inefficient handling processes leading to feedstock contamination. This could be because of segregation inefficiencies of waste streams at kerbside level, for example, if segregation at household level was poorly understood or implemented, and other waste streams were mixed up with food waste. This would undermine the consistency of the waste and feedstock efficiency of the AD process. Likewise, the quality of the feedstock might be reduced due to collection inefficiencies driven by economic aspects. For example, if the garden waste stream was collected with food waste, the feedstock efficiency of the organic food waste could also be undermined. These findings are consistent with previous barriers identified in the literature (Ng *et al.*, 2019), and further support the urgent need for compulsory segregation of food waste at household level (ERA, 2020; Slorach *et al.*, 2020), especially in England where only 45% of the Local Authorities provide a food waste separation service to householders and can be practiced in voluntarily terms. The UK Government´s commitment to legislate compulsory segregation of food waste by 2023 (DEFRA, 2018b) should help to overcome some of these barriers.

The decline in waste availability, as a result of increases in handling and recycling, was cited by some participants as a weakness to building up the consistency of calorific value. This could lead to a reduction in terms of feedstock efficiency. This, in turn, could adversely affect both the quality of the syngas and biogas of gasification and AD pathways, and the production of the energy outputs to the desired standards for their usage. This would lead ultimately to the question of the feasibility of the pathway over time, as discussed further in Section 5.2.3.

5.2.3 Impact on Decarbonisation of the Heat and Transport Sectors

For some participants (G2, G4, G5, I2), concerns over waste availability and efficiency were also related to the feasibility and effectiveness of deployment of the pathways in relation to their contribution to the decarbonisation of the different energy sectors. These participants were concerned with: Would there be enough waste available over time to make an impact in the specific energy sector? How reliable would it be over time? This theme intersects with feasibility and economic issues.

Participants felt that the business case feasibility and practicality of any of these centralised and decentralised pathways would entail contextualised assessments of waste availability, feedstock efficiencies, heat demands specific to each area and liquid biofuels demand. These data would help to determine the size of plants needed, feasibility, practicality, and contribution of the specific pathway overtime. These assessments would also help to determine which pathway is most appropriate. As one participant argued:

'The amount of waste that people want for each of those [sectors] is really big, so we cannot possibly do everything. Because the amount of waste isn't there to do all the stuff… But what we need to think about is sort of post 2035, what are the options that there might be? Waste to jet-fuels, waste to chemicals, whatever it is, and see which technology in that time is ready to take over' (I2).

The uncertainty in terms of consistent waste availability over time, heat demand, and liquid biofuel demand over time were cited as weakness for any gasification and AD pathway deployment. Participants G2, G4 and G5 showed uncertainty about both the availability of enough food waste and the impact on the decarbonisation of the heat and transport sectors over time. Participants G2 and G5 showed more scepticism towards the deployment of and investment in AD facilities, if there was no certainty about the availability of food waste over time and its contribution. Participant G4 felt that, considering the environmental benefits of AD pathways, if the pathway worked, even with a small contribution, it would be worthwhile. Participants had the common view that the decarbonisation of the transport sector should not only rely on AD plants to produce liquid biofuels. Participant G2 suggested that a potential alternative could be to combine AD plants with gasification plants for the production of liquid biofuels, with gasification as the main technology for production. Participants G4 and G5 pointed out that the feasibility, practicality and efficiency of the long-term production and use of liquid biofuels from AD plants would emerge if companies supported their own fleet of trucks. These perspectives lend support to previous similar findings from the literature (Ng *et al.*, 2019).

Considering the large volume of liquid biofuels required for aviation and heavy good vehicles (HGV), producing liquid biofuels via decentralised pathways was seen as challenging. Participants felt that small plants to produce liquid biofuels might not make sense in terms of quantity production. Producing liquid biofuels from gasification would mean that power and heat would need to be produced from other sources. This was echoed by participant G1, and participant G4 who argued: 'A potential energy mix for the decarbonisation of the transport sector could be formed by hydrogen for HGV, electricity for small vehicles, and liquid biofuels for aviation.'

The possibility of using the heat and connecting the site to a heat network was cited as strength in terms of effectiveness for decarbonising heating systems. These findings support what has been previously reported in the literature (ETI, 2018; ERA, 2020; Cross *et al.*, 2021). This strength was limited by issues of feasibility and economic viability in the case of centralised pathways. The large scale and location of plants of centralised pathways, make it more difficult to use heat as it requires long pipelines to distribute the heat to where is needed. This has also been reported as a barrier to the uptake of heat networks in the UK by ERA (2020). Their deployment would entail high investment with a low degree of feasibility unless used in industrial sites.

Decentralised pathways were seen to be more favourable in terms of heat efficiency use, practicality, and feasibility. Despite these benefits, the consistency of feedstock which could affect the reliability of heat networks, and the lack of a control over feedstock consistency was cited as a weakness in terms of heat networks´ efficiency (G2, G4, G5, A2). Participants expressed concerns regarding the fact that heat produced by plants is a constant heat flow and 'cannot be turned off' (G4). Meaning that, as the heat is coming directly from industry into the district heating and buildings, at a specific high temperature, and it cannot be turned down manually by the consumer to their desired temperature. This might be a problem in the summer when consumers do not need buildings heated. This concern was echoed by participant G3. Participants expressed that a solution for the practicality and to increase efficiency of pathways with heat networks was to connect them to heat sinks, such as a swimming pool or a commercial centre, which require constant heat supply throughout the year. Participant G4 commented that if district heating were designed, managed, and deployed correctly to work well, the performance of the Decentralised Gasification pathway for decarbonising the heat network would be the best of the four thermochemical conversion pathways under appraisal. This is, however, blurred by concerns around public opposition and poor experiences of heat networks in the UK. This will be discussed further in Chapter 7.

The chart of the overall performance of the six pathways against efficiency issues, including handling efficiency, feedstock efficiency and impact on decarbonisation of heat and transport sectors themes, can be found in *Appendix 2.3. Figure 2.3.3*.

5.3 Economic Issues

The debate around economic issues focused on two main themes: 1) net financial cost of pathways (G2, G3, G4, G5, I1, I2, I3, A2, A4, CS1, CS2) and 2) UK economic impacts (G1, G3, G4, I2). The themes intersect with feasibility, efficiency, and environmental issues.

The two themes are discussed in further detail in the sections below.

5.3.1 Net financial costs of pathways

The net financial costs of pathways theme relates to the overall and underlying costs of the pathways. Concerns raised by participants related to the feasibility and practicality of delivering the pathways, when looking at them from an economic perspective. In other words, they assessed the pathways by addressing the question of how economically viable each of the pathways under consideration were. Participants addressed the financial cost aspects from different focuses/anchor points. Some participants focused on bankability, others focused on the pathways' CAPEX and OPEX; while others focused on the overall cost of the pathway, which included the revenues from the energy outputs. The theme intersects feasibility and efficiency issues. It was not surprising to note that themes discussed in previous sections on feasibility and efficiency, with their associated concerns, also appeared as features addressing economic concerns. The difference was that they were addressed in economic terms.

BAU with the incineration technology, which is proven, and deployed extensively, was seen favourable with minimum net financial costs, in comparison to the other pathways, also echoing views reported by Waldheim (2018). As one participant argued: 'The system [pathway] is set around what is needed '(G5). The certainty in terms of: CAPEX of the technologies and infrastructures used, OPEX, the waste management system costs, considered the least disruptive to public behaviours, and being the most cost effective, were cited as strengths. However, the financial performance of BAU could be adversely affected by additional handling, sorting, and processing costs associated with legislation changes on waste management systems, or by unforeseen circumstances such as budgeting problems in Local Authorities for waste management collection, processing and sorting systems (G4, G5, A4). The costs related to legislation changes were associated with handling and feedstock efficiencies, discussed in Sections 5.2.1 and 5.3.2. Budgeting issues related to the PFI contracts, mentioned in Section 5.1.1.

Some participants felt that implementing a scheme to sort and segregate food waste and other waste streams, would involve Local Authorities setting collection services, as well as communication, and education services to inform citizens about the new way of separating waste streams. These changes would incur additional handling, sorting, and processing costs. Likewise, as discussed in Section 5.2.2, for some participants removing food waste from the residual waste stream going into incineration could negatively impact on the calorific values for incineration technology. This could create an imbalance in feedstock efficiency for BAU, which would translate into lower economic efficiencies from running the technology with different calorific value parameters to the target range. Furthermore, the segregation of the organic fraction from the residual waste for incineration would exclude the plant from qualification for support by Renewable Energy Schemes. This would not just affect the efficiency and economic viability of BAU but also its regulatory compliance as a Renewable Technology. This, in turn, from an environmental point of view, could lead to questioning the legitimacy of its purpose. This will be further discussed in Chapter 6.

While PFIs contracts were perceived as assets for securing waste for centralised pathways, a reduction in terms of Local Authorities budgeting for waste management systems could lead to a collapse of the systems of PFI contracts. Some participants identified this as a major issue, arguing that available budget from Local Authorities to treat waste is continually decreasing (CS1, A4, G4, G5). This is consistent with previous findings reported in the literature (House of Commons, 2014; DEFRA, 2018b). Consequently, Local Authorities need to make cost-effective choices and currently BAU is considered as the most cost-effective alternative. This view was largely related to market forces and the need for sufficiently high gate fees for the pathway to work, which could have an adverse effect on the economic viability of a pathway. Through its RWS, the UK Government has committed to provide budget to Local Authorities, to ensure improvements in waste management systems are undertaken (DEFRA, 2018).

The three gasification pathways performed moderately against economic viability. Considerable costs associated with relatively high CAPEX due to technology readiness and shortage of technology suppliers and contractors were cited as reasons for concern. The reduced number of references to verify CAPEX and OPEX of these type of plants and reduced trust from investors in the gasification technologies were seen as strong weaknesses of the pathways´ economic viability. Similar observations have been raised by Waldheim (2018). Moreover, some participants (G4, I1) considered that with the sophistication of the gasification technology, even under better circumstances of bankability, the costs of the technology would always be higher than for AD or incineration. This corroborates previously published literature (Arena, 2012; Yap and Nixon, 2015; Waldheim, 2018; Cooper *et al.*, 2019). The shortage of suppliers was felt to affect both centralised and decentralised distributions, but with a greater impact on decentralised distribution, as a greater number of small-scale plants would be built. Participant I1 commented:

> ‘There is a massive shortage of technology suppliers, as well, as contractors to deliver them. Despite the number of French and Spanish engineering, procurement and construction (EPC) companies, as well as American, Italian, and Middle East companies working in the energy from waste sector, there is still a chronic shortage of contractors.’

This shortage of suppliers has also been identified in previous literature as a barrier (Cooper *et al.*, 2019), attributed to a vicious cycle; companies do not invest because of a lack of skilled operators and people do not train because of a lack of plants and investment.
Likewise, some participants felt that additional CAPEX would be required for the waste sorting and processing infrastructure to meet the selectivity of the technology. Despite these reservations, some participants noted that the implementation of political and legislation drivers on waste management systems were likely to reduce these costs. With legislation drivers pushing changes in waste management systems, investment costs for a sorting and processing infrastructure could be endorsed at political level. Some participants felt this could benefit the business case for gasification. However, as in the case of BAU, budgeting problems from Local Authorities to support waste management collection, processing and sorting systems could hamper the process (G4, G5, A4). The commitments and policies set out by the UK Government in the RWS, to support the delivery of waste management infrastructure, including recycling and energy recovery infrastructure, through the planning

system including a greater emphasis on the CE, should solve some of the budgeting problems, and promote the delivery of more efficient waste management solutions (DEFRA, 2018b, 2021b)

As each of the pathways deliver different energy products, depending on the final end product, additional costs for technology research and development, transportation and distribution, and storage infrastructure would also be incurred (G2, G4, A4). Thus, for example, the transportation of liquid biofuels produced in the gasifiers to the fuel stations, whether to airports if for aviation fuel, or ports if for ships, could be done by pipes or tanker trucks. This would increase costs for infrastructure and storage. Likewise, depending on where the plants were built, transportation might involve shorter, or longer transportation distances. Furthermore, the complexity of producing liquid biofuels could incur additional costs for technology research and development. These participants´ views are consistent with Waldheim´s conclusions (2018).

Similar additional costs for delivering heat would apply to the pathways dedicated to the decarbonisation of heat sector; however, in this case the heat technology was considered known, proven, and working, but there would still be infrastructure and distribution costs. The major issue for consideration related to heat decarbonisation pathways for gasification and AD pathways was that if the heat network infrastructure did not already exist, the pathway would incur extra infrastructure costs. These were considered additional drawbacks for the three gasification pathways in terms of economic viability. The £320 million Heat Networks Investment Project (HNIP), the £270 million Green Heat Network Fund (GHNF) scheme, and the Heat Networks Delivery Unit (HNDU) programme, aiming to support a shift from using high carbon gas generation to lower carbon generation in heat networks, should reduce these economic challenges of heat networks deployment. They should promote the economic feasibility of pathways aiming to decarbonise the heat sector, whether through incineration, gasification and/or AD, and facilitate operational, and under construction incinerators to make the most of their heat production potential, which is currently undermined by the lack of heat networks (BEIS, 2017a; DEFRA, 2018b, 2021b).

The best features for gasification pathways to be economically viable were held to be on account of its potential to produce higher value products, echoing conclusions from Waldheim (2018, p.16): 'It is the only waste management technology that can process all organic material in wastes, both fossil and biogenic, into fuels, and chemicals.' However, its potential economic viability, would be subject to market development (G3). This topic will be discussed further in Section 5.3.2.

As with BAU, the economic viability of AD pathways was seen favourable in terms of technology readiness and bankability. AD pathways were viewed relatively less intensive in terms of CAPEX: '[An] AD plant can be built for less than £10 million' (G4). However, OPEX is high due to the selectiveness of the technology and the need for highly consistent quality feedstock. Participants G5, I2 felt that the main drawback for AD pathways in terms of pathway costs was the extra costs required to segregate food waste from the residual waste stream. As already mentioned, the sorting, and segregation of food waste would incur additional labour, handling, sorting, and processing, public communication, and education costs, and transportation costs. Nonetheless, as in the case of gasification pathways, with legislation changes, these costs could be endorsed at a political level. The economic drawbacks to achieve food waste segregation for the implementation of AD pathways identified by participants should be considered with caution. Although Slorach *et al.* (2019) found that incineration had the lowest life-cycle cost (including CAPEX and OPEX) compared to AD, and other food waste treatment alternatives when implementing current ways of dealing with food waste, the authors also found that if all food waste generated in the UK was collected and sent to AD, AD could present the lowest cost to Local Authorities. While Slorach *et al.* (2019) study does not take into account costs associated with labour, public communication, and education, it does consider the costs associated with waste collection and treatment. Some of the economic drawbacks identified by participants G5 and I2 for the implementation of food waste segregation could therefore be dismissed, and instead might encourage political endorsement for compulsory segregation of food waste to increase the amount of segregated food waste from households and businesses. According to the RWS, these aims should be effective by the end of 2023. These measures aim to support and further develop AD (DEFRA, 2018b).

5.3.1.1 Economies of Scale: Centralised vs Decentralised

From the three gasification pathways, Centralised Gasification for the decarbonisation of the transport sector was seen as favourable in terms of economic viability, benefitting from economies of scale. The development of liquid biofuels was seen by some participants (G4, G5, I1) to be a more complex task in comparison to heat networks and gas to grid, and this would increase the pathways costs. Despite this, some participants (G2, G4, I1) felt that the extra capacity of the large scale in the centralised pathway would provide the budget to support more complex technology. The pathway would benefit from the economies of scale, by which the overall cost per unit of output would be less for Centralised Gasification than for Decentralised Gasification. In conclusion, there would be a greater chance for Centralised Gasification to be implemented.

Most participants (I1, G3, G4) converged on the idea that the economies of scale would negatively influence the Decentralised Gasification pathways in terms of net cost. This lends support to what has been previously published in the literature by Johansson and Warren, (2016) regarding that costs, both OPEX and CAPEX, are higher for small scale EfW plants. Decentralised pathways would not have the economies of scale savings of only requiring investment in one facility, whereas implementing several facilities would incur more CAPEX. In addition, from an operational point of view, with decentralisation, there would be higher number of plants around the country and more labour required in each of them, making it more expensive to operate them (I1, G3, G4).

Assuming the gasification technology works, participants argued that a potential solution to the economies of scale limitations would come with the adaptability of the specific decentralised pathways to the contextualised/community needs. In this case, the pathway could provide an energy source close to the needs of the community, keeping costs down (G3, G2, I1). Some participants (G1, G2, A4) felt that this could be limited by issues of planning permissions and land costs; planning and building in urban areas could be more expensive than at the edge of the cities.

Participants expressed concerns around waste availability for both Decentralised Gasification and Decentralised AD pathways. As discussed in Section 5.1.1, the PFI contracts between large waste management companies and Local Authorities could hamper the availability of waste for small-scale plants (A4). This supports previous findings by Hall (2014) regarding the lock-in mechanism in which Local Authorities are in debt due to long-term contracts, which prevents them from accessing waste management alternatives that promote greater resource efficiency. Related to this, participants G4 and G5 commented that a good attempt at economic viability could be achieved by looking at niche waste markets. For example, small-scale plants may work with supermarkets, from which they take the already pre-sorted waste. In this case, cost of handling, and transport could be reduced. Moreover, the energy produced would be used by the supermarket, either for heating, or for their own transportation fleet. The study from Ng *et al.* (2019) is a good example of how this can be done and how it can bring economic, social, and environmental benefits.

The chart of the overall performance of the six pathways against net financial costs theme, can be found in *Appendix 2.3. Figure 2.3.4*.

5.3.2 UK economic impact

The theme of UK economic impact relates to the contribution that each pathway could make to the UK economy. Participants concerns while appraising UK economic impact opportunities of the pathways related to the degree in which each of the pathways could enable the development of sustainable economic growth both at national and international levels. This raised matters around the possibility of accessing and broadening the markets of technologies (incineration, gasification and AD) and end products (electricity, heat, liquid biofuels) over time, and the capacity of the pathways to impact on the UK labour market through the creation of jobs. This theme intersects with the themes of technology readiness and bankability, handling efficiency, and feedstock efficiency.

The general idea among participants was that rising demand for more sustainable sources of energy would act as an opportunity for the development of economic growth opportunities in the UK. However, the lack of a sustainable waste management system, the lack of infrastructure for sorting and processing the waste in the UK, as well as the lack of reliable technologies to deliver high-value energy products were cited as weaknesses hindering the UK economic impact.

BAU was seen the least favourable in terms of UK economy impact, with limited margins in terms of economic growth and market opportunities in the medium to long term. The high number of operators and technological companies established around the world were cited as weaknesses for accessing markets for technology and energy products. Furthermore, participants felt that with the increase in renewable electricity generation and the decarbonisation of the grid, the use of incineration for electricity production would in the future start to decline. This is an important point to consider as in the transition to a lower carbon economy, as we approach the net zero target, the UK energy system will gradually change. Electricity coming from renewable technologies will gradually increase and the average intensity of CO_2 emissions of the grid will diminish. However, if we continue using incineration for energy recovery as we currently do – primarily dedicated to electricity production and with limited efficiency due to restrictions of heat usage – the CO_2 emission intensity coming from the EfW sector will remain the same as today. If MSW continues to be used as feedstock for energy recovery, we must look for alternative solutions to accommodate to the average grid intensity of the future and the continuously changing circumstances. This relates to points of controversy in the usage of incineration and EfW, which are exposed in the literature and will be further discussed in Chapter 6.

Centralised Gasification and Decentralised Gasification were seen as the most favourable pathways in terms of UK economic impact, with prospects of strong economic growth and market opportunities in the medium to long term. This was largely due to the potential economic opportunities in terms of access both to technology and high-value product markets. In the case of Decentralised Gasification pathways, there was also the potential strength of developing a more local economy. Participants G1 and I2 converged on the idea of markets of gasification and high-value products being widely deployed by the 2040s, by which time the challenges around gasification pathways´ feasibility and efficiency issues would have been overcome.

Gasification pathways´ performance was felt to depend on UK ability to develop the technology early enough to access the technology and end products markets both nationally and internationally, before other countries. In this regard, the technology readiness level (TRL) for gasification was viewed a substantial factor influencing the competitiveness. Uncertainty about the development of gasification technology in the UK played a key role in participants' arguments. As one participant argued: 'The stage of gasification at which the UK currently is, will not allow the development of any of the gasification scenarios [pathways] in the short term' (G1). Some participants (G1, G4) felt that developing gasification in the UK was challenging and there was the risk that other countries would develop the technology earlier. The TRL of UK gasification technology with its high investment risk and the lack of engineering skills for the technology (G1, G4) in the UK were cited as barriers to developing or accessing the technology market in the UK and ultimately internationally. However, assuming that the technology of gasification was developed in the UK, participants felt that the UK could have the power of skills in the technology, both, nationally, and internationally, accessing, and broadening the technology, and high-value product markets. This would deliver positive impacts on the UK labour market. Participants felt that the pathways would generate jobs along the whole supply chain, not only in the conversion process of the waste into end products. The pre-accession strategy to this point would have implied previous changes and investments in waste management systems, infrastructure, and technologies. This in turn would boost the UK economy growth. Hence, even if gasification technology struggled to progress steadily over time, for some participants, the pre-accession strategy of the gasification pathways was considered worth developing and a strength in terms of sustainable economic growth for the UK.

The versatility of syngas resulting from gasification was cited as strength for accessing high-value products markets. The market opportunity and deployment of the gasification technology for heat was considered to be lower than for liquid biofuels. Some participants considered that liquid biofuel production from gasification would be of global interests to decarbonise the transport sector, from which the UK could strongly benefit in terms of market opportunity and deployment of the gasification technology, and the creation of national and international market for high-value products. The UK currently has some gasification projects working on the production of liquid biofuels, which may give the UK a chance to enter the gasification technology and high-value product markets, including the Velocys Altalto project in Immingham and Kew Technology Ltd. project in Wednesbury, Birmingham. The Velocys Altalto project is developing a commercial plant to make jet fuel from MSW and C&I waste. The project started with the support of industry partners, including BA and Shell Aviation, and the Department for Transport (DfT). In January 2021, Shell Aviation withdrew from the Joint Development Agreement (Altalto, 2021). Likewise, the Kew Technology Ltd. project was selected in December 2019 as one of two projects to be funded under the government's £20 million Future Fuels for Flight and Freight Competition (F4C) and awarded a share of £6.5 million with Rika Biogas Technologies (AD for liquid bio-methane production) to provide fuel for heavy goods vehicles. Kew Technology Ltd. is also researching the production of low carbon aviation fuel (DfT, 2018a, 2019; Kew Technology, 2019b). Moreover, the Waldheim (2018, p.17) review states: 'Unlike WtE [Waste to Energy], for WtL [Waste to Liquid biofuels] there is no well-established competing conversion technology for gasification of wastes and biomass, such that the market introduction proceeds via waste and biomass gasification.' This again emphasises the potential market opportunity that the UK EfW sector has ahead.

Some participants expressed uncertainty in terms of job creation between centralised and decentralised distribution. Centralised pathways would create more jobs per plant, but in a smaller number of places as there would be fewer plants in the country. In contrast, decentralised pathways would create fewer jobs per plant, but plants would be widely distributed across the country. Participants felt that the distribution of decentralised pathways could be more beneficial for the country as there would be a more diverse and deployed spread of job creation; a more centralised distribution might force people to move to the areas where plants are located and jobs are therefore available.

In the short term, Decentralised AD pathways were seen as having limited potential in terms of UK economic impacts, with the prospects of better economic growth and market opportunities in the medium to long term once the technology had developed to be able to receive and process wider range of feedstocks, and the challenges around digestate quality standards and its utilisation had been overcome. Participants felt that the market opportunities of the AD pathway technologies with their respective impacts on the UK labour market, would be at a national level, as at an international level they would be hampered by the high number of expert companies around the world with better expertise, especially around AD, and heat networks.

At a national level, the two Decentralised AD pathways, were seen with potential to create economic activity from the production of fuels and energy products. Participants felt that with heat networks, there would be potential for job creation and local market development. Nonetheless, this optimism was hampered by the lack of heat network infrastructure in the UK, which is why some participants felt that Decentralised AD for the decarbonisation of the transport sector would have easier market access in comparison to Decentralised AD for the decarbonisation of the heat sector via heat networks. Whether there is enough food waste for liquid biofuel production via AD was also an issue. One solution to this constraint could be to create a local market where, for example, the liquid biofuels were used for the bus fleet in a city, or for the transport fleet of a supermarket company. Participants felt that the compulsory segregation of the food waste and consequently segregated collections would also create jobs on the waste management system side.

Several participants (G1, G2, G3, G4) considered that the best scenario would be a combination of gasification and AD, for the production of syngas and biogas together. This echoed what other participants had previously said when discussing issues around efficiencies.

The chart of the overall performance of the six pathways against UK economic impact theme, can be found in *Appendix 2.3. Figure 2.3.5*.

Conclusions

This chapter has analysed and discussed the results obtained from the MCM participants´ interviews and has begun to identify the different techno-economic issues, uncertainties, interests and values that are at stake when it comes to the sustainability of the six different EfW pathways under appraisal. The key findings are summarised below.

The techno-economic criteria addressed issues of feasibility, efficiency, and economics. Feasibility covered themes of waste availability, and technology readiness and bankability.

Regarding waste availability, gasification and AD pathways are less flexible than incineration, requiring selective feedstock, and consequently the need of extra-processing activities to achieve the appropriate consistency and quality of feedstock. Changes would be needed in waste management to make appropriate feedstock available for AD and gasification, which is challenging. Segregated collection of waste streams and sorting and processing infrastructure would make waste available for AD and gasification, but this requires infrastructure investment, policy intervention and legislation changes, as well as behavioural changes. Centralised pathways have better scope for sufficient and consistent capacity of feedstock due to their strategic-sourcing with multiple points of supply, and may also be supported by PFIs. Decentralised pathways can have issues of sourcing if there is not enough waste available locally. This would lead to challenges on self –reliance and dependency of other places waste streams. Nonetheless, the implementation of legislation changes and increase in recycling rates and segregation of waste streams will lead to a decline in waste availability for residual waste, which in turn could have impacts in the scale of operational plants needed, making decentralised pathways easier to deliver. Furthermore, if there were plans to build a gasification plant, it will be important to check if there is already an incineration plant in the area as, as reported by Waldheim (2018), with legislation changes and increase in recycling, there could be issues of overcapacity and therefore, lack of consistent feedstock for gasification.

Technology readiness and bankability are interrelated, with investors' confidence being influenced by the track record of proven technologies. Incineration and AD are proven technologies, but AD is disadvantaged by its selectivity to feedstock. Heat networks are proven and bankable, but only a few are available in the UK. Gasification is lacking on track record and must demonstrate its potential performance sufficiently to reduce the investment risk that currently exists. The progression from small/medium scale gasification plants to large scale plants can be a way to increase track records and gain trust in the technology. However, due to economies of scale making Decentralised Gasification scale plant economically attractive to investors may be more difficult relatively to large scale plants. The analysis of results reveal that there is a need to increase support on gasification technology, and that more evidence of technology success or failures with gasification are needed to formulate a supportive incentive scheme for the technology.

Efficiency issues include handling and feedstock efficiency, centralised vs decentralised, and the impact on decarbonisation of heat and transport sectors.
Handling efficiency related strongly to the selectiveness of the technologies requiring more or less front-end processing of the waste, and also to existing sorting infrastructures. Implementing new schemes involves Local Authorities arranging food waste collection, communication and education services. Introducing legislation to improve recycling and segregation would reduce handling efficiency of all pathways, which might benefit the business case for gasification and AD, (but would also decrease feedstock quantity available to all pathways). Although putting in more effort with pre-processing activities achieves more valuable feedstock appropriate for the selectiveness of the technology and it may not mean a less efficient process, but rather a potential increase in resource efficiency, for some participants, the need for extra levels/layers at the front-end of processing implied a reduction in process efficiency from a whole supply chain perspective. Hence, the findings suggest there to be a lack of appreciation of the concept of resource recovery from waste, which in this research, was found to be at governmental and industrial levels.

Feedstock efficiency related to energy acquired from materials in different pathways. The uncertainty in terms of waste availability and changes in waste quality and quantity over time was a key concern undermining the achievability of consistent feedstock, especially for gasification and AD pathways. Handling efficiency and technology design also impact on feedstock efficiency, with the AD pathway further disadvantaged by a poor handling efficiency. The flexibility of incineration to treat all heterogeneous materials was an advantage in feedstock efficiency terms. There was competition between incineration and AD for the use of food waste as feedstock.

Impact on decarbonisation of energy sectors was considered sceptically, with uncertainty over consistent waste availability (particularly with gasification and AD) versus heat and liquid biofuel demand, particularly as such large volumes are required for aviation and HGVs. However, heat distribution from decentralised pathways, connecting facilities to heat networks and using heat sinks such as swimming pools were considered feasible, but challenging, given the reduced number of heat networks in the UK.

The debate around economic issues centred around net financial costs of pathways, economies of scale, and economic impact on the UK.

Net financial costs related to CAPEX, OPEX and overall costs of a pathway. Pathways differed in costs with the energy product delivered, according to the research and development required, transportation, infrastructure and storage needs. BAU and AD pathways were perceived to have lower net financial costs; the three gasification pathways had relatively higher net financial costs. Liquid biofuels had higher costs for transportation, infrastructure and storage. Similar costs would be incurred with delivering heat to the decarbonisation sector. The put in place of heat network infrastructure for AD and gasification pathways would incur additional costs. The lack of budget for Local Authorities to put in place waste management infrastructure was identified as an economic barrier to manage the waste more sustainably. Through the WRS, the UK Government has committed to provide a budget to Local Authorities to ensure that improvements are made to waste management systems. This must be provided as soon as possible, and make sure it does not stay in the air.

Economies of scale would benefit centralised pathways through lower capital investment costs, lower employment costs, and the benefit of PFIs. However, decentralised pathways could be adapted to local community needs, helping to reduce costs. The findings suggest that to deploy small-scale plants adapted to community needs, and have waste available to supply to these EfW plants, it will be essential to correct the lock-in mechanism in which Local Authorities are found to be due to long-term contracts with large waste management companies, which prevents them from accessing waste management alternatives that promote greater resource efficiency.

Economic impact on the UK was considered in terms of how pathways could support economic growth, through accessing and broadening the markets of technologies (incineration, gasification and AD) and the final end products (electricity, heat, liquid biofuels), and improving the labour market through the creation of jobs. BAU was the least favourable in terms of economic growth. Centralised and Decentralised Gasification were the most favourable pathways for economic growth, although whether the UK was sufficiently competitive regarding technology development might threaten this.

In the following Chapter 6, the environmental dimension is analysed and discussed.

Chapter 6. Environmental Dimension – Results and Discussion

This chapter analyses and discusses the environmental issues identified by participants in response to their examination of the sustainability of the EfW pathways.

Section 4.1.1.2 provided an overview of the criteria identified by participants which were related to the environmental dimension. Of the 80 criteria in total identified across all sustainability dimensions, 18 were grouped under the environmental dimension. Except for participants G4 and A4, the other participants identified at least one environmental criterion as part of their appraisal. See Table 6.1 below.

Table 6.1. Environmental Criteria

Perspective	Code	Participant	Criteria
Government	G1	BEIS Energy Engineer Expert	Contribution to GHG emissions targets
	G2	DfT Advanced Biofuels Policymaker	GHG emissions
	G3	DEFRA Economic Advisor	Environmental impact of pathways delivered
	G5	Local Authority Waste Management Officer	Carbon impact (-)
	G6	EA Waste Management Planning and Strategy Regulator Advisor	Net GHG emissions (-)
			Environmental net gain *
Industry	I1	Energy from Waste Industry Sales Manager	Environmental performance (-)
	I2	ESA Executive Director	CO_2 emissions
	I3	Energy from Waste Industry Managing Director	GHG emissions (-)
			Landfill reduction (-)
Academia	A1	Sustainable Bioenergy Expert	Reduction in GHG emissions
	A2		Environmental performance

Table 6.1. Environmental Criteria

		Waste Management Process Engineer Scientist	Contribution to circular economy * (-)
	A3	Public Perceptions of Energy and Sustainability Scientist	Life cycle environmental (-)
Civil Society	CS1	UKWIN Environmental Campaigner	Decarbonisation
			Contribution to circular economy * (-)
	CS2	Sustainable and Strategy Developer	Air, land, water pollution
			GHG emissions reduction

* indicates corresponding criterion also addressed some social aspects

(-) indicates corresponding criterion also addressed some techno-economic aspects

Acronyms: Department for Business, Energy & Industrial Strategy (BEIS), Department for Transport (DfT) Department for Environment, Food & Rural Affairs (DEFRA), Environment Agency (EA), Environmental Services Association (ESA), United Kingdom Without Incineration Network (UKWIN)

The discussions around the environmental criteria focused on environmental efficiency in production processes, and in particular the decoupling of indicators of environmental pressure, especially waste and greenhouse gas emissions (GHG), and economic growth to develop a circular economy (CE). These two main themes: 1) waste management (G3, G5, G6, I2, I3, A2, A3, CS1, CS2) and 2) net GHG emissions (G1, G2, G5, I2, I3, A1, A2, A3, CS1, CS2) are discussed in detail below.

6.1 Waste Management and Circular Economy

The waste management theme relates to the capacity of the pathways to encourage more sustainable waste management systems, with the goal of improving waste management higher up in the waste hierarchy to contribute to a more CE.

Some participants (G3, G6, A3, CS1) were concerned with the capacity of the pathways and waste management systems to boost recycling and landfill diversion. Others (G6, A2, A3, CS1) were concerned with the inefficient use of waste materials due to the capacity of the technologies to treat materials which could otherwise be managed higher up in the waste hierarchy, especially in the thermochemical conversion pathways. Others (G5, I2, I3, A2, CS2) were concerned with the use assigned to end products and secondary products obtained from the processes. In some cases, the use of these products was seen as contributing to a CE.

Business as Usual (BAU) was viewed as having little to offer in terms of boosting sustainable waste management systems and a more CE (G3, A2, A3, CS1). Whilst the capacity of the incineration technology to treat all types of wastes was cited as a strength towards increasing landfill diversion and the discouragement of open burning (G3, I3, CS1), it was also cited as a barrier to improving recycling and moving the waste higher up in the waste hierarchy (G3, G6, CS1). These obstacles of incineration to developing more sustainable waste management systems have been previously identified in the literature (Zero Waste Europe, 2016; UKWIN, 2021). Incineration as a barrier to increasing waste recycling is also perceived by the UK Government, which through its Resources and Waste Strategy (RWS), has announced that if waste recycling and reduction ambitions over time are not achieved, a tax on incineration of waste may be introduced. Participants (G5, G3, CS1, I3) acknowledged the role played by incineration technology over recent years in terms of both diverting waste from landfill and increasing recycling. However, in the medium to long term, BAU was viewed as bringing limited advantages in terms of waste management. The lack of infrastructure available for sorting and processing waste in the UK was cited as a weakness that undermined potential long-term change and the need for more sustainable waste management systems. This lends support to previously published literature where the lack of infrastructure has also been identified as a barrier to more sustainable waste management systems and better recycling in the UK (House of Commons, 2014; Rhodes and Thair, 2017; Smith and Bolton, 2018). As one participant argued, ‘The recycling infrastructure of the system is plateauing, and the BAU system is probably not going to fix that ‘(G3). Legislation changes were seen as the key driver for boosting recycling in BAU. These results show once again that government action is critical to bring transformation and that it has an opportunity to lead the way. The political measures set out by the Government through its RWS include the introduction of plastic taxes, the deposit return scheme (DRS) for single use drink containers, and the extended producer responsibility (EPR) to be introduced from 2022 (for the former) and 2023 (for the latter two). Further, mandatory separate food waste collections will be implemented by 2023 and although still under consultation and as yet without an implementation date, there are plans for a core set of dry materials to be collected by all Local Authorities and waste operators. All these measures will potentially improve recycling rates and drive resource efficiency higher. Nonetheless, while the crux of the strategy is promising with all these potential legislations and schemes in the spotlight, it is discouraging that these measures have not been actioned immediately, but are instead being planned for later years.

At the risk of courting controversy, participants G5 and I2 considered that BAU and AD pathways were interrelated, when debating about the performance of waste stream management. The segregation of food waste, which reduces the amount of residual waste for incineration, was cited by participants G5 and I2 as a pathway weakness. This was because, the segregation/collection and sorting/processing of food waste could adversely affect BAU carbon impact performance by reducing availability of biogenic content for incineration. This will be discussed further in Section 6.2.

Centralised Gasification and the two Decentralised Gasification pathways were viewed more optimistically on the merits of improving sustainability of waste management and contributing to a more CE. The selectiveness of the gasification technology and the need for extra-processing to achieve the consistency of feedstock were perceived as potential drivers towards achieving higher recycling rates and more sustainable waste management systems (G3). As mentioned in Chapter 5, this would mean that more waste processing infrastructure/plants (Materials Recycling Facilities, MRF) would be needed. In the opinion of participant G3, even if the technology did not work, but the processing infrastructure was already in place, the pathway would bring important advantages in waste management.

Likewise, a failure in citizens' behaviour change to improve recycling was the main concern for achieving good performance of the gasification pathways in terms of waste management. This was viewed as likely to affect the segregation of food waste and the availability of waste for AD pathways. This means that robust education and awareness campaigns will be needed to change citizens' behaviour regarding waste management.

Participant I3 viewed the three gasification technology pathways as having the potential to achieve a 100% landfill diversion, as is the case in their own company. This is an interesting outcome considering participants repeatedly commented on how the selectiveness of the gasification technology was a weakness to feasibility of the Centralised and Decentralised Gasification pathways. Likewise, to achieve the 100% landfill diversion with gasification as they suggest would require all stakeholders involved in the sector to make the same decisions around waste management and ultimately opt for the same company gasification technology deployment, which is unlikely to be feasible.

The two Decentralised AD pathways were seen more favourably in terms of boosting sustainable waste management systems and a more CE. These were considered to be the pathways with the highest degree of compatibility with the CE. The compulsory segregation of food waste was seen as a key driver towards achieving more sustainable waste management systems (G2, G3, G5, G6, CS1, CS2). This would boost recycling rates and increase the diversion of organic waste from incineration and landfill (Ng *et al.*, 2019; Slorach *et al.*, 2019). In addition, producing digestate to the required quality standards and being able to make use of it as bio-fertiliser would entail the highest degree of compatibility with the CE (Fagerström *et al.*, 2018; Slorach *et al.*, 2019; ERA, 2020). The latter was subjected to concerns of waste availability and efficiency and will be discussed in Section 6.1.2. It seems worth noting here that these AD pathways were assessed in comparison to the other pathways but specifically for the treatment of food waste. Other waste streams, such as plastics, which cannot be treated by AD, were not considered in these AD pathways. Consequently, when these participants considered AD pathways to have the highest degree of compatibility to the CE, their views related specifically to food waste management. Alternative solutions need to be implemented to manage other non-organic waste streams. Deploying AD alone, therefore, cannot drive the uptake of the strongest recycling infrastructure, but only part of it. In other words, a suite of technologies will be required, of which AD may be one.

These identified benefits to the Decentralised AD pathways were hampered by concerns around inefficient segregation and collection of food waste or lack of citizens´ behavioural change to separate waste at source. This echoes barriers identified previously in the literature (Ng *et al.*, 2019). In this regard, participants G3 and G5 showed uncertainty about the capacity of the people to adapt to changes, achieving effective food waste segregation at household level, and collection by Local Authorities. As one participant argued:

> 'There are a lot of reasons why you would invest in the services, but you don't get the behavioural change that you want … Food waste segregation is the most kind of novel approach, because it is not as widely collected as other waste streams and it is a big step change. Enforcements [of food waste segregation] are tough. And food waste smell is an important barrier towards social acceptability' (G3).

This interlinks with the social issues to be discussed in Chapter 7.

Likewise, the competitive situation of incineration for food waste as feedstock was an additional concern undermining the performance of the pathways. This will be discussed further in Section 6.2.

6.1.1 Waste Hierarchy and Circular Economy: Inefficient use of material in thermochemical conversion pathways

Several participants raised concerns around the inefficient use of waste material in thermochemical conversion pathways. In this regard, the use of fossil fuel derived materials such as plastics, which could otherwise be treated higher up in the waste hierarchy, were considered to disrupt the progression towards both better sustainable waste management systems and a CE (G6, A2, CS1).

Some participants (G6, A2) felt that there could be place for thermochemical conversion pathways if they only treated waste that could not be recycled or re-used. This would, however, require greater attention to steps higher up in the waste hierarchy, from which energy recovery from waste would ultimately be considered. This lends support to previously published literature (Garnett *et al.*, 2017).

The view that waste should not be processed seemed to be partly shared by participant G5, who while discussing carbon impacts argued, 'The best way is not to dispose [of] it, the best way is to recycle it or to reuse it… The carbon impact of recycling is better than burning it' (G5). Nonetheless, participant G5 considered that BAU accomplished effective work in getting rid of large amounts of waste generated: 'If there was an increase in recycling, there would be an increase in carbon benefits, and it wouldn't really have a negative carbon impact on the incinerator'(G5), and added that 'if current recycling rates increased to 50%, there would still be waste going into the incinerator' (G5), so the process of burning waste would keep working. The arguments from participant G5, representing a local authority, echo previous findings published in the literature (Garnett *et al.*, 2017). Statements made in Garnett *et al.´s* (2017 p.216) study, also by a Local Authority representative, demonstrate support for EfW incineration as a way of managing the remaining waste after recycling. The interviewee claimed that after an optimum level of recycling is achieved, EfW incineration is the sensible option, always better than other alternatives such as landfill.

In contrast, participant CS1 discouraged the use and deployment of any activity that used high carbon intensive material, arguing it was a barrier towards a more sustainable management of waste and the CE: 'It [incineration] is a leakage from the system; where is the circle? If you burn something, then you have to extract again to make a new product.

From that point of view, incineration is a leakage from the CE' (CS1). In the case of the Centralised and Decentralised gasification pathways, CS1 further elaborated: 'You are still taking a resource and losing it' and while it does create some new resources it is 'very uncertain.' This view requires caution, however, serving as only one participant's feedback.

A somewhat intermediate view was articulated by participant A2, who viewed the production of added value products from gasification as an opportunity to contribute to the CE, with contributions to chemicals for manufacturing, liquid biofuels, and heat, which could offset the disadvantages of not recycling fossil fuel derived materials. It is interesting to find that from the 15 participants interviewed, only one participant (A2) clearly identified the added-value products from gasification pathways as potentially contributing to a CE. This could be due to the lack of trust in relation to gasification – identified in Chapter 5 – or it could be due to the fact that there may be a lack of appreciation of the gasification technology amongst stakeholders involved in the EfW sector.

Clear controversy is thus identified amongst participants around the development of the EfW sector. The most important result to emerge from the data reported here is how perspectives and understandings emerging from the three participants differ. Thornley and Prins (2009) and Thornley and Gilbert (2013) note that the sustainability of a particular energy system is inextricably linked to the stakeholders' perceptions, which in turn are linked to different priorities, values, and judgements. Consequently, understanding stakeholder perceptions becomes an essential element in the process of developing a sustainable system. The findings from this section seem to confirm their observations. It is possible to see that, depending on the context of work and discipline of the participant, a series of values, interests and priorities appear. This in turn, shapes the participants´ understanding, needs and expectations, as well as their ways of making decisions and/or defending them. Analysing the findings results in a number of observations. Participant G5 represents a Local Authority; one of the multiple priorities of Local Authorities is to avoid household waste piling up. In the absence of better recycling systems, incineration of waste, a well-established technology, is considered a useful practice of waste management for this purpose. Participant CS1 represents the UKWIN, NGOs, and the wider public associated with them. As shown in previous literature, their perspective is that further development of any of these thermochemical technologies should cease. Finally, participant A2 works in academia, in the engineering field. Participant A2's expertise spans waste and fuel characterisation techniques, waste treatment technologies, and energy recovery processes. With this knowledge in mind, it is easier to understand the different points of view, from where they originate, on what they are based, and whether such views can be changed, if necessary.

6.1.2 Anaerobic Digestion (AD) Digestate Quality and Utilization

The quality of digestate from AD and its utilisation was perceived as a main concern undermining the performance of the Decentralised AD pathways in terms of contribution to more sustainable waste management systems and a CE; which has also been identified previously in the literature (Garnett *et al.*, 2017; Fagerström *et al.*, 2018; ERA, 2020). In the view of participants G3, G6, A2, CS1, CS2, the environmental benefits and contribution of the pathways to the CE relied on the capacity to generate a good quality digestate to be used as bio-fertiliser. To this end, food waste needs to be carefully managed to ensure its segregation from other waste streams to avoid contamination. There must be strict quality controls on the digestate with the objective of meeting the digestate quality standards. This is, however, a problem nowadays. As technology improves (ERA, 2020) and more organic waste can be used as feedstock, the digestate will gain further strength and quality, opening up its path into the market.

Whilst the production of high quality digestate and its use as organic fertiliser to improve soil conditioning were cited as strengths, the difficulties in achieving the required segregation of the food waste and of the feedstock quality were cited as weaknesses. Constraints hampering the capacity to meet the digestate quality standards to be fully recycled to the land included inefficient behavioural change by citizens to separate the waste at source, inefficient segregation, and collection of food waste; further lack of available food waste could necessitate mixing with other waste streams.

However, even if digestate quality standards were not met, overall the two biochemical conversion pathways were considered better in terms of waste management, relative to the four thermochemical conversion pathways. In summary, this was firstly because compulsory segregation of food waste would boost recycling rates and increase the diversion of organic waste from incineration and landfill. In the case of other waste streams, such as plastics, there might be competing expectations between recycling activities and use in EfW. However, with food waste, apart from avoiding it, there are no other alternatives to reduce it. Consequently, its use for energy recovery was seen beneficial. Secondly, once challenges over the production of digestate are overcome, the AD pathways would be producing a nutrients rich product thus restoring nutrients to the land, so that AD would become fully compliant with the CE.

The chart of the overall performance of the six pathways against waste management and CE theme, can be found in *Appendix 2.3. Figure 2.3.6*.

6.2 Net Greenhouse Gas Emissions

The net greenhouse gas (GHG) emissions theme relates to the overall carbon impact of the pathways. It includes both, sources of emissions from the pathways as well as sources of avoided emissions.

Participants G1, G2, G5, G6, I2, I3, A1, A2, A3, CS1, and CS2 approached the overall issue of GHG emission impacts from different focusses/anchor points. Some participants focused on emissions from transportation, others on emissions from the handling and processing of the waste, and others on emissions linked to the construction of new infrastructures. A further focus was the value of the different energy outputs and the displacement of GHG emissions that could be achieved during their production and use. Finally, some participants also focused on the overall carbon impact of the pathways with others paying particular attention to the implementation and deployment of carbon capture and storage (CCS) technology to maximise and secure emissions reduction in the pathways over time. These different focuses are explained in this chapter by following the upstream/downstream of the waste to energy supply chain from waste management, waste transport emissions, through to waste processing and conversion, and product end-use. This chapter finishes with the focus around CCS technology deployment. CCS was not a technology included in this project. However, it has been added here as some participants considered it could have an important impact on future GHG emissions; consequently, it is explained and discussed last.

Some participants found the appraisal of pathways against net GHG emissions criteria challenging given the high number of interrelated factors to be considered and the need to quantify their response. As one participant argued, 'There are plenty variables to that. I have to say putting numbers on these things is really difficult … that is why you need the conversation around it.' (I3)

Different concerns were addressed by some participants for single criteria. However, in most cases the different concerns were used as counterfactuals reasoning or counter-arguments related to the same single criterion, especially when the discussion was centred around sources of emissions. This participants´ reasoning is illustrated throughout the following analysis. The displacement of fossil fuel GHG emissions from the production of gas and liquid biofuels with gasification and AD pathways were used as counterfactuals for the sources of emissions. This constant counterfactual use by some participants made the analysis and discussion of the results relatively complex. Thus, to simplify understanding of this theme, in Sections 6.2.1 to 6.2.4 below, the different sources of emissions are discussed individually, followed by a discussion of the sources of avoided emissions, in Sections 6.2.5 and 6.2.6.

6.2.1 Emissions from Waste Transport

Transport emissions from waste transport were seen as one of the key sources of emissions undermining the overall carbon impact of the pathways. Participants appraising the transport emissions of the pathways identified concerns including waste availability, proximity of the plant to waste sources and local traffic flow.

Several participants (G2, G5, A2 and I3) felt that the transport emissions from decentralised pathways would be lower than in centralised pathways. The reasoning behind this perception was that centralised pathways would need more waste which necessarily needs to come from a bigger supply radius. Consequently, the common view among these participants was that decentralised pathways would benefit from the proximity effect to waste sources, which reduces emissions in transport. This was, however, considered subject to the availability of waste in the area. If there was a lack of waste in the area, the pathway would be dependent on waste from other places to fulfil capacity of the plant. This would result in more waste transportation and, therefore, higher transport emissions.

Other participants (I2, G3) were more sceptical about the benefits of decentralised pathways in terms of transport emissions. For these participants, the proximity to urban areas was seen as a weakness. The transportation of waste within the urban areas could be more likely subjected to the use of smaller and busier urban roads, causing longer queue times, and increasing transport emissions overall.

Nonetheless, despite participants appearing to have favourable opinions in terms of transport emissions, their arguments also expressed uncertainty. Participants argued that transport emissions from the six EfW pathways could vary (G3, G6, I2), as there are many influencing variables, such as number of plants, traffic around the area, and type of vehicles used. As one participant argued: ‘We do model these things; we have quite a lot of models for the vehicle types and all that, but it is always very complicated too.’ (G3)

6.2.2 Emissions from Infrastructure and Extra-processing

Embodied carbon emissions in the construction of waste processing and heat network infrastructures were considered another source of emissions from the pathways.

With the exception of BAU for which the processing infrastructure is already established, so it is possible to ignore the embodied emissions; the rest of the pathways, Centralised Gasification, Decentralised Gasification and Decentralised AD pathways, were seen as adversely affected by emissions from the deployment of the waste processing infrastructure.

Decentralised Gasification and Decentralised AD pathways dedicated to the decarbonisation of heat via the deployment of a new heat network were seen as less favourable in terms of embodied emissions, if a new heat network needed to be built. The alternative of injecting syngas and biogas into the grid was seen by participants as a solution to the infrastructure issue.

Whilst most participants expressed concerns around emissions embedded within the construction of a new heat network, participant G5 felt that the carbon impacts from the construction of a new heat network could be offset by transport reduction with a decentralised system. The argument of this participant counters the aforementioned disadvantages: deployment of a new infrastructure would mean higher carbon emissions, which would affect the performance of the pathways dedicated to the decarbonisation of the heat network. Whilst this research cannot evaluate which participant offers the most accurate answer – for this a life cycle assessment would be best, case by case with the different business and process designs – what it reveals again is the different perceptions that exist around the same theme. This diversification of perceptions which leads to different opinions can complicate the decision-making processes. One more time the importance of understanding the stakeholders´ perceptions comes to light.

Authors in the published literature (ETI, 2018; ERA, 2020; Cross *et al.*, 2021), however, are increasingly insisting on the need to deploy heating networks in the UK, to optimise use of energy recovery from waste. This implementation will not only help to decarbonise the UK heat sector, but also make much more efficient use of EfW technology, and reduce emissions. Several authors (ERA, 2020; Cross *et al.*, 2021), strongly support the need to have a look at how Nordic countries are managing decarbonisation of the heat sector, and to adopt their strategies. It has been reported that emissions from UK incinerators producing electricity only, are four times higher than the most efficient European plants producing electricity and heat (ERA, 2020). This means that the UK has the potential to reduce emissions from incineration to a quarter if heating networks are deployed. Furthermore, as a national example, Nottingham district heating network saves up to 27,000 tonnes of CO_2 per year; founded in the 1960s, it now serves 5,000 houses and 100 commercial buildings (ERA, 2020). Although this study has the limitation that it has not quantified emissions of different pathways, and cannot therefore assess emissions of deployment of infrastructures, taking into account that a heating system works for decades – see Nottingham example – it could be argued that the accumulated reduced emissions per year could potentially counteract the emissions incurred during deployment.

Gasification and AD pathways would need extra-processing activities to achieve the appropriate consistency and quality of feedstock, and meet the selectiveness of the conversion technology. Changes in the collection and processing of the current waste management systems would be required to make the feedstock consistent and reliable for the technology. These activities were considered another source of emissions. This is an important finding, as these embodied emissions counter the benefits (stated previously Section 6.1.1) that these pathways could enhance recycling as a consequence of requiring more pre-processing. As previously argued, the best approach would be to undertake a life cycle assessment to evaluate the environmental impact of implementing the extra-processing infrastructure. However, the implementation of a better waste management system, increase in recycling and resource efficiency towards a CE (discussed in Section 6.1) and the deployment of Centralised Gasification, Decentralised Gasification and Decentralised AD pathways, are not feasible without these additional extra-processing activities. The waste sorting and processing infrastructure deployment thus becomes a necessity. Furthermore, some participants felt that the production of liquid biofuels could counteract emissions from the extra processing of waste, although this would be subject to technology readiness.

6.2.3 Emissions from the Type of Feedstock Used: Fossil Fuel Derived Material vs Organic Material

The waste is a mixture of fossil fuel derived materials and biodegradable waste - usually considered to be 50/50 mixture. The energy obtained from the waste is considered a partially renewable energy, and the energy derived from the fossil part of the waste seen as the problem.

Participants described fossil fuel derived feedstocks, such as plastics, as being high carbon intensive material and organic waste feedstock as being carbon intensive material and a source of renewable energy.

As one participant said: 'The more plastic is going into something, the more fossil fuels are being burnt. That is non-renewable and it is a GHG emission, that it is accumulative' (G6).

Some participants considered that the optimal alternative in terms of reducing CO_2 emissions in the atmosphere would be to use biogenic material, that would ensure the production of renewable energy source and neutral emissions.

The four thermochemical conversion pathways were seen to be adversely impacted on by emissions from the use of fossil fuel derived material. However, BAU was viewed relatively better in terms of emissions from the feedstock used (G5, I2, A3); because of the lower pre-treatment used in BAU, the organics fraction in the feedstock is higher than is usually for gasification, which has pre-treatment. Having a larger organic fraction in the feedstock for incineration, the emissions would be counted as lower. This result should, however, be considered with caution, as although in BAU the biogenic content is higher, and consequently fossil emissions lower per tonne processed, from energy efficiency and resource efficiency viewpoints, the amount of energy obtained per tonne of feedstock processed is lower in incineration than in gasification. In contrast, in gasification, due to the required pre-treatment, there would be higher resource efficiency, so the energy obtained per tonne of feedstock would be higher (Arena, 2012; Yap and Nixon, 2015; Waldheim, 2018; Foster *et al.*, 2021), and the CO_2 emissions would be lower (Yap and Nixon, 2015; Waldheim, 2018). These findings suggest that there is a lack of understanding about the technologies and a lack of appreciation of the value of waste as an energy resource.

6.2.4 Food Waste Segregation and BAU Carbon Impact

The diversion of the organic waste fraction from the residual waste going into incineration could lead to an increase in emissions from the BAU pathway. Driven by the fact that the biodegradable part of the residual waste stream is zero emissions rated, is considered to be a source of renewable energy and BAU pathway complies with regulations for generating energy from waste, some participants (G5 and I2) were hesitant about diverting food waste from incineration.

The carbon impacts depend on what is done with the biogenic content of the residual waste stream going into incineration. The diversion of organic waste away from the residual waste going into incineration would have a direct impact on the properties of the feedstock and calorific value. A lower degree of biogenic content in the residual waste going into incineration would translate into higher carbon emissions from BAU (G5 and I2). In the view of participant G5, the only solution for the BAU pathway to work in compliance with regulations, would be to find another organic source. Likewise, participant I2 considered that the only driving reason for segregating food waste and diversion from incineration would be to meet the recycling rates, as in terms of carbon emissions there would be no additional benefits from being zero carbon rated. Participants also expressed uncertainty about the overall benefits to carbon impact that the segregation of food waste would deliver, considering the increase in collection, sorting, and transport that would be required. These concerns intersect with the feasibility and efficiency issues discussed in Chapter 5.

6.2.5 Avoidance of GHG emissions: Displacement of Fossil Fuel GHG Emissions with the Production of Valuable Energy Products

GHG emissions avoidance relates to the emission savings from different pathways in accordance with the conversion processes and energy output produced. In other words, it values how producing a lower carbon output compared to the existing (counterfactual) way of making the product, would lead to emission savings. It also includes the emissions savings from the deployment and use of CCS technologies and heat networks.

For some participants, the most important aspect related to the capacity of the pathways to reduce greenhouse emissions by producing more valuable energy products. This in turn, was related to the capacity of pathways to contribute and to transition to lower carbon intensity energy systems.

Depending on the energy output produced, the contribution of the pathways to the displacement of fossil fuel GHG emissions would be varied. Participants G1, I3, A1, A3, and CS2 appraised the pathways by referring to the carbon intensity of the different energy outputs. The pathways replacing products with higher carbon intensity would generate a greater impact in the displacement of fossil fuel GHG emissions.

The pathways dedicated to producing electricity were seen as less favourable. This was due to the future competition that EfW for electricity will have with other lower-carbon energy technologies, such as wind and solar. In contrast, the pathways dedicated to producing heat and liquid biofuels were seen as more favourable, in particular those dedicated to the production of liquid biofuels.

Participant CS1 was reluctant to deploy any thermochemical conversion pathway, arguing this would be a barrier towards low carbon energy. This lends support to previous findings in the literature (Zero Waste Europe, 2019, 2021). However, participants G1, I3, A1, A3, and CS2 showed more optimism towards their deployment and implementation. The two Decentralised AD pathways were seen as the most favourably contributing to GHG reductions. Their better relative performance was related to their capacity to avoid methane emissions and use organic waste materials considered as low carbon intensive material and renewable; and to their capacity to displace GHG emissions coming from producing more valuable energy products. The latter was also cited as a strength for Centralised and Decentralised Gasification pathways; however relatively overall performance was undermined by the use of high carbon intensive feedstock.

BAU was judged the least favourable pathway in terms of GHG emissions reduction. Whilst participant A1 viewed BAU as relatively benign, because of its production of electricity from waste, participants G1, I3, and CS1 viewed the pathway as the most inefficient process in terms of GHG emission reduction. They converged on the argument that generating electricity from incineration was worse than burning natural gas; which echoes findings previously published in the literature (Jeswani and Azapagic, 2016; Zero Waste Europe, 2019). Participants G1, I3, and CS1 saw BAU as the least favourable pathway towards the transition and production of lower carbon intensive energy sources. Under current circumstances, the three participants were reluctant to deploy incineration. The reasons behind this were related to the fact that the average carbon intensity of the electricity grid will gradually fall over time. This has been discussed previously in Chapter 5, Section 5.3.2. As electricity coming from lower carbon energy technologies, such as wind and solar, will gradually increase over the future years, the average intensity of carbon emissions of the grid will be diminished. However, the carbon emissions intensity coming from the EfW incineration – if used as it is currently used – will remain the same as today. Therefore, these participants were reluctant to develop further incineration facilities. These findings lend support to previously published literature (Zero Waste Europe, 2019). However, assuming CCS technology would be deployed, participants G1 and I3 considered the BAU pathway might have potential to contribute to the transition towards lower carbon intensive energy systems. This will be discussed further in Section 6.2.6.

The three gasification pathways were seen more favourably than BAU in terms of GHG emission reduction. Centralised Gasification was perceived to have some potential to displace electricity grid emissions (A1, G1, A3). However, as with incineration, the pathway was seen as requiring of CCS. This will be discussed further in Section 6.2.6. Participants G1, I3, A1, and CS2 acknowledged that the greatest asset of gasification was its capacity to produce other products than electricity, not possible with incineration.

Participants G1, A1, I3, and CS2 agreed that the best outcomes from the Centralised Gasification, Decentralised Gasification and Decentralised AD pathways, in terms of contribution to GHG emission reduction, were the production of heat and liquid biofuels. The production of heat and liquid biofuels from waste could help reduce the consumption of fossil fuels and thus reduce GHG emissions. Both energy outputs were seen as having good potential in the displacement of GHG emissions. Electricity from EfW can do this too, but due to the above-mentioned reasons, it was seen as less favourable. However, due to the already low carbon intensity of natural gas, and the fact that liquid fuels are more carbon intensive than heat, the pathways dedicated to liquid biofuels production were seen as more favourable to the contribution of GHG emissions. In view of this, the production of liquid biofuels would generate a greater impact on the displacement of fossil fuel GHG emissions (G1, A1, I3, CS2). This result should be considered with caution, as the liquid biofuels produced are then burnt in cars, so that there would still be emissions from the transport sector. A life cycle assessment for each of the different pathways producing electricity, heat and liquid biofuels combined with CCS – with the different technologies – would be very useful to evaluate their environmental impact performance.

The flexibility of the liquid biofuels, for use with light and heavy good vehicles (HGV), aviation and maritime sectors, was cited as a strength. This could help to counter the complexity of decarbonisation of the transport sector. Participants G1 and I3 saw the inclusion of CCS as a great enhancer of emission reduction, which could provide gasification pathways with the capacity to deliver negative emissions. This will be discussed further in Section 6.2.6.

The use of heat from plants was seen as a major benefit for the development of lower carbon intensive energy systems, especially, in the domestic sector with the displacement of GHG emissions from the use of natural gas. Some participants (G1, CS2, A3) saw value in the availability and deployment of heat networks to use of heat, which would otherwise be lost. As one participant argued: 'Without the heat network, you have … huge amounts of heat generation that could not displace at the moment natural gas' (CS2). This lends support to what has been published previously regarding achieving full potential of EfW plants (Jamasb and Nepal, 2010; Wright *et al.*, 2014; Jeswani and Azapagic, 2016; ERA, 2020; Cross *et al.*, 2021; Foster *et al.*, 2021), and relates to the discussions in Section 6.2.2 This view was, however, hampered by issues of feasibility as heat networks are not common in the UK. A remarkable result to emerge from these findings is that while heat networks are identified in the literature as a way of decarbonising the heat sector and increasing efficiencies of EfW facilities, participants in this research failed to clearly support their deployment. Moreover, the debate on heat networks was directed to its unfeasibility. Notwithstanding the above, there is a strong argument for using EfW technologies, where physically possible, to produce only heat and no electricity (ERA, 2020). Indeed, the literature shows that EfW facilities in Northern European countries operating for the delivery of heat-only, extracts almost six times more energy per tonne of waste than the UK (ERA, 2020). Consequently, agreeing with suggestions made by ERA (2020) and Cross *et al.* (2021), it is argued that the UK should look to these countries' experience in the EfW and heat sector.

6.2.6 Maximising Emissions reductions through the Implementation of CCS

Participants G1 and I3 felt that achieving and maximising GHG emission reduction through the implementation of these pathways would be largely dependent on the deployment and implementation of CCS technology. Overall performance of pathways was perceived with a high degree of uncertainty and as dependent on implementation (or not) of CCS. Participants understood the benefits CCS could bring but had high levels of uncertainty around how and when CCS would be deployed and the impacts it would have on future waste to energy GHG savings and directions of technologies.

Incineration with CCS was seen as a potential alternative solution to natural gas plants – currently used as back-up technology for the production of electricity –. BAU with CCS could help in the transition of the power sector to a lower carbon intensive energy mix (G1). This matches with what Advisory Bodies are recommended for the transition to a low carbon economy towards reaching net zero (CCC, 2019, 2020). While renewable intermittent energy technologies, such as wind and solar are being established, incineration with CCS, could provide carbon savings from the electricity produced, while providing flexibility to the energy system. Likewise, if Centralised Gasification for the production of electricity were deployed, some participants felt that the opportunities of and barriers to decarbonising the power system would be similar to the incineration pathway, dependent on the feasibility of CCS technology put in place and deployed. As the electricity grid starts to decarbonise, the carbon intensity of the electricity grid will diminish over time. With this, electricity carbon intensity from incineration, gasification and combined heat and power (CHP) technologies will become higher than grid average. So, the capacity of the pathways to contribute via electricity to a lower carbon intensive energy system will become constrained. Therefore, unless CCS is deployed, the production of power from gasification will not be a better alternative to power from incineration, and none of the pathways will be superior to producing power from intermittent technologies, for which capacity is, and will increase over the years. The view, however, requires caution, as while wind and solar energies are intermittent energies, incineration and other EfW technologies can provide continuous energy. Consequently, it could also be argued that incineration and gasification for electricity would be more favourable alternatives when there is a lack of wind, and more favourable than solar during the night. Likewise, deployment of CCS for electricity production would provide further flexibility to the energy system, as there would be more technologies available to produce power (CCC, 2019). In other words, with CCS deployed, EfW would be delivering negative emissions, positioned in the energy system with wind and solar, which are low carbon technologies. However, if the CCS is not in place, then electricity from waste will compete with wind and solar as a low carbon technology, and it will not be able to compete as effectively, as it will be constrained as low carbon electricity. This means that EfW would not be deployed as often to make electricity, and the capacity to process waste would be reduced.

Participants G1 and I3 felt that the best alternative for decarbonisation of heat through gasification would be with the production of synthetic natural gas injected into the grid, which in the future, could be transformed into hydrogen. Participant G1 commented that in the medium to long term, the pathway would also depend on CCS deployment, especially for electricity produced from CHP, when the average carbon intensity of the power grid had decreased, with the increase in use of lower carbon intensive energy. Injecting hydrogen into the existing UK gas grid, for decarbonising the heat sector and to meet carbon targets forms part of the strategies set out in the UK´s Clean Growth Strategy (BEIS, 2017b), thus lending support to its implementation.

Centralised Gasification and Decentralised Gasification for the decarbonisation of the transport sector with or without the inclusion of CCS were seen as the optimal pathways for the objective of delivering GHG emission savings. This fits well with what has been reported by the CCC (2020). Participants G1 and I3 addressed several alternatives for these pathways: without CCS, the production of liquid biofuels from waste with inclusion of fossil fuel derived materials would still deliver GHG emission reductions, compared to the use of fossil fuels. Likewise, participants G1 and A3 considered the emissions could be neutral if the supplied feedstock to a gasifier was biogenic. With the inclusion of CCS, the pathways were seen as at their maximum capacity delivering GHG emission reductions to the point that they could potentially be delivering negative emissions. Moreover, if the syngas was transformed into hydrogen for use in the transport sector, then there would be the opportunity to capture the maximum amount of CO_2 from the EfW plant, since no carbon would leave the fuel production plant as a part of the fuel. This strategy of using hydrogen as transportation fuel aligns with the UK's Clean Growth Strategy and it is highly likely to be adopted in the near future (BEIS, 2017b).

Due to the research and development process still needed for transport fuel production, participant G1 considered that these pathways (Centralised Gasification and Decentralised Gasification for the decarbonisation of the transport sector) would require CCS in the long term run. This could be considered a point in favour for these pathways in their development, deployment, and adaptation towards the transition of a low carbon energy.

The use of biogenic material rather than fossil fuel derived feedstocks together with the deployment of CCS and the production of hydrogen from syngas was seen by participants G1 and I3 as the most effective combination for the reduction of GHG emissions, both for the decarbonisation of the heat sector and transport sector. This combination could potentially deliver negative emissions, which are reported by the Committee on Climate Change (CCC) to be essential in meeting net zero by 2050 (CCC, 2019, 2020).

The chart of the overall performance of the six pathways against net greenhouse gas emissions theme, can be found in *Appendix 2.3. Figure 2.3.7*.

Conclusions

Analysing the results obtained from the MCM participant´ interviews, this chapter has identified and discussed the different environmental issues, uncertainties, interests and values perceived to be at stake when it comes to the sustainability of the six different EfW pathways under appraisal. The key findings are summarised below.

The environmental criteria addressed issues of environmental efficiency covering themes of waste management, and CE and net GHG emissions.

The waste management and CE theme related to the capacity of the pathways to improve waste management systems, driving recycling rates up, improving resource efficiency and transition to a CE. The theme includes the sub-themes of waste hierarchy and a CE, and AD digestate quality and utilization.

Regarding waste management and a CE, the flexibility of incineration to treat all types of waste feedstock without pre-treatment provided the benefit of reduced waste going to landfill or open burning. However, there were concerns it could also hinder increased recycling and the transition to a CE. Participants agreed it would be best to increase recycling;

however, given the amount of waste produced, the lack of infrastructure and current waste management alternatives, some participants considered incineration as playing an important role in the waste management system. The selectiveness of gasification and AD technologies and the need for extra-processing to achieve consistency of feedstock would increase recycling and boost management of materials higher up in the waste hierarchy. The deployment of these pathways could boost the move to a CE. For this to happen, legislation drivers to change waste management systems and ensure increased segregation of waste streams are essential, and more waste sorting/processing infrastructure plants will be needed. Strong educational and awareness campaigns to change citizens' behaviour on waste management will also be needed.

Decentralised AD pathways were perceived as having the highest degree of compatibility with the CE. The segregation of food waste for utilisation in AD pathways to produce energy is a key driver to achieving more sustainable waste management systems, diverting organic waste from landfill and incineration, which have higher environmental impacts, while producing renewable energy. In addition, the production of the digestate and its use as bio-fertilizer will close the loop of the CE. However, for this to happen, concerns around achieving the required quality standards of the digestate and having consistent clean food waste feedstock supply will need to be overcome.

There was controversy between participants around the inefficient use of waste materials in thermochemical conversion pathways. From one perspective, the use of fossil fuel derived materials such as plastics, which could otherwise be treated higher up in the waste hierarchy, disrupt the progression towards both better sustainable waste management systems and a CE. Consequently, the deployment of thermochemical conversion pathways should cease. From another perspective, there could be place for thermochemical conversion pathways if they only treated waste that could not be recycled or re-used. This would, however, require greater attention to the steps higher up in the waste hierarchy, from which the energy recovery from waste would ultimately be considered. There is also the view that, gasification pathways producing added value products can contribute to the CE. Interestingly, this view was only stated by one participant. The findings suggest that together with the lack of trust – identified in Chapter 5 – there might also be a lack of appreciation of the gasification technology. Findings also reveal how the different perspectives are strongly related to contextual work, interests and values of the participants. This accentuates the need to understand stakeholders´ perceptions.

Net GHG emissions related to the overall carbon impact of the pathways; this included sources of emissions from the pathways and sources of avoided emissions. The sources of emissions included emissions from waste transport, emissions from infrastructure and extra-processing and emissions from the type of feedstock used. The effect of the segregation of food waste from the residual waste on the BAU carbon impact performance is also included.

Emissions from transporting the waste from the collection point to the EfW facilities were considered sceptically, with uncertainty over whether centralised or decentralised pathways would incur more or fewer emissions. At first glance, centralised pathways were perceived to introduce higher transport emissions from waste. This was because in order to fulfil capacity waste, will come from a larger radius and different points of supply, increasing miles of transport. The proximity of the plant to waste sources and the reduced amount of waste required were perceived to benefit decentralised pathways in terms of transport emissions from waste. However, uncertainty in terms of waste availability in the local area over time and local traffic flow were key concerns undermining decentralised pathways´ performance.

Except for BAU, with infrastructure widely deployed, the remaining pathways embodied emissions from infrastructure and extra-processing. Embodied emissions come from various sources, but could be offset by careful business and process design. The understanding around embodied emissions and how they could potentially be offset varied among participants. The diversification of understanding and opinions will influence the decision-making process. This highlights again the importance of understanding participant perceptions. Decentralised Gasification and Decentralised AD pathways dedicated to decarbonisation of the heat sector would have greater embodied emissions. This would come from the sorting and processing infrastructure required to achieve feedstock consistency and the construction of district heating networks. This falls outside the research scope, but the implementation of a life cycle assessment on a case-by-case bases, considering the different design alternatives, will help to comprehend the whole environmental impact of these pathways and technology deployments.

Results indicate there is competition between BAU and AD pathways for the use of food waste as feedstock. This is because the segregation food waste from the residual waste could adversely affect BAU carbon impact performance by reducing availability of biogenic content for incineration; the latter is what makes energy from incineration to be considered partially renewable.

The sources of avoided emissions related to the capacity of the pathways to displace fossil fuel GHG emissions with the production of valuable energy products. The implementation of CCS technology for maximising emissions reduction is also included. The future role of BAU in the transition to a low carbon energy system is contested. Constraints of adaptability to the grid´s average carbon intensity changes in the future undermine its performance. Similar constraints were perceived for gasification, if dedicated to the production of electricity. There was also controversy between participants as to whether incineration and gasification can be considered as low-carbon technologies. This was due to their ability to use fossil fuel derived materials.

The pathways replacing products with higher carbon intensity were perceived as generating a greater impact in the displacement of fossil fuel GHG emissions. Due to the fact that liquid fuels are more carbon intensive than heat, the pathways dedicated to the decarbonisation of liquid biofuels obtained stronger performance in terms of contributing to avoiding GHG emissions. It should be taken into consideration that the liquid biofuels are then burnt in the cars engines.

Whilst the use of heat from Decentralised Gasification and Decentralised AD plants was seen as a major benefit for the displacement of GHG emissions with the use of natural gas, support for its deployment was not obvious when analysing the participants' perceptions.

Overall, there is wide uncertainty over the pathways´ performance against GHG emissions reduction. This wide uncertainty is largely dependent on the deployment and implementation of CCS technology. To make EfW, all pathways will require CCS. The time scale in which they will required CCS will vary. BAU and Centralised Gasification for the production of electricity will require implementation of CCS urgently. Centralised Gasification and Decentralised Gasification for the decarbonisation of the transport sector would require CCS in the long term, once the technology has been developed. Likewise, in the case of CHP and heat networks, CCS will also be required, but for this, heat networks must be deployed. With CCS deployed, EfW would be delivering negative emissions, which positions it in the transition to a low carbon energy system, contributing to the decarbonisation of different energy sectors, due to its flexibility in energy outputs.

Particularly for electricity, without CCS, EfW might not be able to compete with the other low carbon technologies, to produce electricity as effectively. Consequently, the processing of the waste through thermochemical conversion processes could be constrained, making waste to power unfeasible.

The possibility of transforming syngas into hydrogen for both injecting it into the gas grid and for use in transportation, for the decarbonisation of the heat and transport sectors, respectively were identified as potential alternatives for reduction of GHG emissions. The use of biogenic material rather than fossil fuel derived feedstocks together with the deployment of CCS and the production of hydrogen from syngas was seen as the most effective combination for maximising the reduction of GHG emissions, both for the decarbonisation of the heat and transport sectors.

In the following Chapter 7, the social dimension is analysed and discussed.

Chapter 7. Social Dimension – Results and Discussion

This chapter analyses and discusses the social and political issues identified by participants in response to their appraisal of the sustainability of the Energy and Fuels from Waste (EfW) pathways. Section 4.1.1.3 provided an overview of the criteria identified by participants which were related to the social dimension. Of the 80 criteria in total identified across all sustainability dimensions, 18 were grouped under the social dimension. Except for participants G5, I1, I3 and A2, all other participants identified at least one social or political criterion as part of their appraisal (see Table 7.1 below).

Table 7.1. Social criteria

Perspective	Code	Participant	Criteria
Government	G1	BEIS Energy Engineer Expert	Air quality impacts ++
			Dependence of governmental policies
			Citizens´ engagement and behaviour change
	G2	DfT Advanced Biofuels Policymaker	Planning permitting
	G3	DEFRA Economic Advisor	Social acceptability (-)
			Resource security ++ (-)
	G4	Waste & Resources Specialist Consultant	Public acceptance
	G6	EA Waste Management Planning and Strategy Regulator Advisor	Net process efficiency (-)
Industry	I2	ESA Executive Director	Air quality
Academia	A1	Sustainable Bioenergy Expert	Appearance
	A3	Public Perceptions of Energy and Sustainability Scientist	Ease of development (-)
			Public acceptance
	A4	Waste Management Policy Advisor	Government incentives (-)

Table 7.1. Social Criteria

			Planning permission (-)
Civil society	CS1	UKWIN Environmental Campaigner	Community benefits
			Environmental justice and democracy
	CS2	Sustainable and Strategy Developer	Human Health ++
			Fuel Poverty (-)
++ indicates corresponding criterion also addressed some environmental aspects (-) indicates corresponding criterion also addressed some techno-economic aspects Acronyms: Department for Business, Energy & Industrial Strategy (BEIS), Department for Transport (DfT) Department for Environment, Food & Rural Affairs (DEFRA), Environment Agency (EA), Environmental Services Association (ESA), United Kingdom Without Incineration Network (UKWIN)			

Participant discussions of the social issues raised by the EfW pathways centred around three main themes: 1) social acceptability (G1, G3, G4, I2, A1, A3), 2) community benefits from the deployment of decentralised pathways dedicated to the decarbonisation of the heat sector (G3, CS1, CS2), and 3) air quality impacts on human health (G1, CS2). The two last themes could be understood as factors contributing towards more or less social acceptance of the pathways, whereby they could be identified as sub-themes of the social acceptability theme. These last two themes captured common beliefs about how plants´ scale could impact in society. Likewise, discussions of the political issues focused on one main theme: government intervention (G1, A3, A4).

Each of these themes and the key points raised by participants are discussed in detail below.

7.1 Social Issues

7.1.1 Social Acceptability

As mentioned in Section 4.2.1.3, three participants (G3, G4, A3) identified a ‘social acceptability’ criterion, and one participant (G1) identified a ‘public engagement and behaviour’ criterion. The ‘appearance’ and ‘air quality’ criteria identified by participants A1 and I2, respectively, focused on the physical size and visual image of the facility and public perception of air quality impacts. These criteria addressed aspects of public opposition. Consequently, they were considered additional criteria of the social acceptability theme.

Social acceptability was approached by participants G1, G3, G4, I2, A1 and A3 from different perspectives, albeit converging on the same goal: social acceptability towards the integration of the pathways. Whilst participant G1 approached the debate from the point of view of how much should the public change their behaviour to facilitate both the integration of the pathways and dispatchability of the energy in accordance with energy generation technology alternatives and demand needs; participants G3, G4, I2, A1, A3 approached it from the point of view of how socially acceptable were the pathways for the public. Public opposition was discussed with reference to the size and visual image of the plant, lack of trust, lack of communication and lack of awareness and understanding. To a lesser or greater extent, public opposition and the need for behaviour change and public engagement were cited as weaknesses in the development and uptake of the six EfW pathways under appraisal.

Participants G4, I2, A3 converged on the idea that there is a large amount of work to be done in terms of facilitating public communication, awareness and understanding. According to one participant, social acceptance is about showing the public what waste management facilities are for, why they are needed and what the issues are to 'make the public understand what is happening on that site; what the available alternatives are and what the hygiene alternatives are' (G4). By "hygiene alternatives", participant G4 refers to, for example, the management of waste via EfW technologies rather than landfilling or open burning. However, the public may be lacking an accurate understanding and knowledge of the differences between these management alternatives, so that they might oppose EfW without having the whole picture. Similarly, participant A3 argued that more and better communication with the public could help to combat opposition by reducing the lack of trust towards companies and the lack of awareness and understanding; a finding supported by the literature (Upreti, 2004; Upham and Shackley, 2006; Thornley and Prins, 2009; Evans and Newton-Cross, 2016). These results suggest that arenas of communication for sharing interests and concerns, develop understanding and exchange knowledge are needed to facilitate the alignment of objectives and values between stakeholders and citizens. Moreover, a common view among the participants (G4, I2, A3) was that a perceived feeling of gaining community benefits could potentially generate positive perceptions. In this respect, the decentralised pathways were seen more favourably, particularly those dedicated to decarbonising the heat sector. This will be further discussed in Section 7.1.2 below. These results concur with Welfle *et al.* (2014) who concluded that public opposition can be reduced by educating the local population on the air pollutant regulations in place and on the community benefits arising from the plant, and by providing direct local energy benefits such as district heating.

Business as Usual (BAU) was viewed as a pathway that did not require public behaviour change in terms of waste management to make it work but which nevertheless experiences significant public opposition that undermined its overall performance. Public opposition was identified by participants G3, G4, I2 to be due to two reasons. The first was the perceived health risks associated with air quality impacts from the incineration technology, widely noted in the literature (e.g., Upreti, 2004) and the second was the way in which waste is managed within the BAU pathway. Related to the second reason, participant G3 argued that there should be more focus and effort made at the top of the Waste Hierarchy ahead of making changes at the bottom. To make BAU work and be more accepted, the common view among participants G1, G3, G4, I2 was that people would need to change their perception of incineration technology. Participants G4 and I2 converged on the idea that there is lack of knowledge and understanding from the public towards the BAU pathway and incineration technology as a group, which drives this type of public perception issue. Implying that misleading information is being disseminated, participant I2 stated, 'People are persuaded by campaigns but actually these things aren't so bad.' Participants G4 and I2 argued that well-run, regulated incineration is not a significant risk to public health; otherwise, they would not be put in place at first. Participant G3 stated that incineration is seen by the public as a convenient excuse that conflicts with recycling and better waste management systems even though 'The amount of waste [going to incineration rather than being recycled] is very high at the minute in the public eye and staying as it is, is not acceptable for the public' (G3). Hence the possibility of changing public perception towards incineration was seen as challenging.

The population's tendency to form their opinion on the basis of information provided by NGOs has also been previously observed in the literature (Upreti, 2004). This further underlines the importance of creating public communication forums where all stakeholders involved can exchange knowledge and share opinions. On the one side, this type of practice could help to increase public awareness and understanding on EfW, on the other, it could teach government and industry stakeholders not only how to better communicate with citizens or communities but also how to better understand and be more knowledgeable of the interests and values of the citizens and communities involved. The latter should ultimately help to anticipate potential problems that may arise from lack of community familiarity or support of a EfW project, therefore enabling communication practices and decision making to be more aligned with the community context and perspectives.

Centralised Gasification and the two Decentralised Gasification pathways were seen as having slightly higher prospects in terms of social acceptability in comparison to BAU. The more compact size of gasification facilities and the selectiveness of waste streams of the gasification technology (G1, G3), which would require changes in waste management systems and higher recycling activities, were cited as strengths for their social acceptability. These strengths were limited by concerns around achieving the desired changes in public behaviour and engagement in recycling and separation of waste streams at the household level (G1, G3). Moreover, the changes in behaviour and increase in recycling could be adversely affected by loss of trust and motivation from the public towards recycling activities. Participant G3 noted, ‘The public are seeing that we are not recycling more, or we recycle but it is then ending in landfill anyway, so why should we even bother?’.

According to these results, the Government needs to show that it is developing policies in this area, and that its investments in energy recovery are targeting the problem of unrecyclable, unpreventable material. A long-term step change is needed to achieve this, which entails the need for a clearer focus and more effective efforts around re-use and recycling, with the aim of strengthening social confidence in the waste hierarchy. This will then provide confidence that waste, when processed in an incinerator, gasification or AD plant, is truly unrecyclable.

There were contrasting views on how gasification technology was perceived by the public. Participants G4 and I2, believing that gasification is more socially acceptable than incineration, argued that previous communication efforts have facilitated a more positive perception towards gasification technology. This perception has been reported in the literature (Garnett *et al.*, 2017). Moreover, in the view of participant G4, this public optimism towards gasification technology, implying lower public opposition, is one of the reasons why companies are trying to push gasification forward. In comparison, participants G1, G3 and A3 believed that people/citizens/the public do not distinguish between incineration and gasification, with A3 remarking ‘They are all seen as generating harmful greenhouse gas emissions.’ This view has also been reported in the literature, as Upreti (2004) and Upham and Shackley (2006) have identified similar public concerns and conflicts over different gasification and incineration facilities across the UK. Consequently, these studies suggest that the public does not really differentiate between these technologies when it comes to assessing their social acceptability. In light of these conflicting results, rather than assuming that one technology is more socially acceptable than the other, it is more likely that public perception differs according to community context, experiences, interests and values, which highlights the need for community engagement wherever a plant is being considered.

Participants G1, G3, G4, A3 maintained the need to raise public awareness and understanding of EfW technologies and processes; an approach also championed in the literature (Evans and Newton-Cross, 2016). A change in public awareness and understanding towards what the pathway is doing in the community, how waste facilities can contribute to the environment and a greener economy, and how they as consumers and waste producers can also contribute to greener renewable energy initiatives could generate increased acceptance and changes in behaviour. Participant A3 argued, ‘It is more than understanding the process itself. It is feeling a personal connection to it’, echoing the work of Devine-Wright and colleagues on place attachment (Devine-Wright, 2009; Devine-Wright and Batel, 2017). By knowing how the EfW plant is transforming their waste into something useful for their benefit, the community could feel a part of the circle. This in turn could lead to more positive public perceptions. In this regard, Decentralised Gasification and Anaerobic Digestion (AD) pathways were seen more favourably in terms of social acceptability. The smaller scale of decentralised pathways plants, which could deliver tangible and direct energy community benefits, reduce fuel poverty and increase public awareness, understanding and engagement, was cited as a strength towards achieving better social acceptance (G3, G4, A1, A3). This interlinks with the community benefits theme of Section 7.1.2 and the advantages mentioned match with those previously reported in the literature (Jamasb and Nepal, 2010; Johansson and Warren, 2016; Evans, 2017). In contrast, the proximity of the plants to populated areas with the associated ‘not-in-my-backyard’ (NIMBY) phenomenon of public opposition (Devine-Wright, 2009), was cited as a weakness of the Decentralised Gasification and AD pathways (G3, I2, A3).

The two Decentralised AD pathways were seen slightly more favourably to the rest of the pathways in terms of social acceptability. Whilst Participants G4, I2, A1, A3 converged on the idea that there was less opposition towards AD plants compared to thermochemical conversion processes, participant G1 felt that intrinsic to the social acceptability of the AD pathways was the capacity to achieve efficient segregation of food waste at the household level. To achieve this, participant G1 acknowledged that the compulsory segregation of food waste at home would involve significant behaviour change and engagement from citizens/the public/people underpinned by well-organised education and communication campaigns. Failing this, the social acceptability of AD pathways in terms of social acceptability could be undermined.

The smaller size of AD plants, their perceived reduced air quality impacts in comparison to thermochemical pathways, the possibility of producing both renewable energy and digestate, and the potential increase in public education and engagement leading to an increased sense of connection to the process, were all cited as strengths. The NIMBY phenomenon, the potential odour release from the process and the perception of explosive risks from methane were all cited as weaknesses.

Participants G3, G4, G1 also differed in their perceptions of which pathways may be more or less acceptable from a final end product point of view. Concerning both Gasification and AD pathways, the differentiation was due to the end products´ use and their manageable flexibility. Hence, whilst the use of a heating network was seen by participants G3 and G4 as a great opportunity to decarbonise the heat sector and increase both the community energy benefits and higher energy efficiencies of the pathways, under bad circumstances where the heating network would not work, participants considered it could have adverse long-term effects on the citizens' public perspective and acceptability. Participant G4 discussed problems that had arisen in the past, arguing that negative experiences of heat networks might considerably impact public acceptance. This kind of negative perception, due to bad experiences with heat networks has been reported in the literature (ETI, 2018). Participant G3 and G4 expressed concerns around the lack of control systems in district heating and the fact that heat produced by plants is a constant heat flow that 'can't be turned off' as the heat is pumped directly from the plant into the network at a specific temperature that cannot be adjusted manually by the consumer to their desired temperature. These particular arguments and perspectives need to be approached with caution: houses connected to heat networks will have heat exchanger units in place, allowing for the control of heat flows and temperature, and with the option of making use of the heat or, alternatively, letting it bypass (BEIS, 2018b). What these results suggest is a lack of awareness and/or understanding among participants regarding district heating technology. This is a remarkable finding because G3 and G4 participants represented the government perspective: although it cannot be assumed that this perception on district heating functioning is shared by the rest of the governmental departments' stakeholders, it reveals the existence of a certain lack of understanding/awareness of heat network technicalities in the departments where energy decision-making and policy developments take place. This kind of misguided understanding could lead to decisions based on mistaken assumptions, and such decisions, if not identified on time, could in turn lead to the development of deficient energy policies. This brings to light the need to share knowledge between stakeholders, which not only include the public, but also stakeholders of different technical knowledge, backgrounds and disciplines. Although stakeholders involved more directly within the EfW sector might be more familiar with the technologies under debate and the energy sector, they might also have misguided points of view, as indicated by these results.

Likewise, for the smooth functioning of decentralised pathways with district heating, a heat sink such as a swimming pool, a commercial centre or hospital, requiring a constant heat load throughout the year, is needed, as suggested by participant G4 who stated, ‘All people say that actually although people will use less heat in summer, a swimming pool is pretty constant for industrial heat load.’ (G4) Both participants G3 and G4 converged on the idea that the production and dispatchability of liquid biofuels would be easier to manage in that sense, reducing barriers in terms of social acceptability.

A different view was articulated by participant G1 when discussing behaviour change and public engagement as a matter of social acceptability, bringing to light concerns around the energy technology alternatives available. From participant G1´s point of view, if gasification and AD were dedicated to the production of liquid biofuels, electricity and heat would need to be produced from other energy technology sources, or from intermittent technologies like solar and wind, and would require storage. This could have an effect on the dispatchability of the energy as well as the flexibility of the system, and could affect the way in which energy would be consumed at home which may have an impact on public behaviour and engagement around the usage of the energy. For example, people may prioritise specific times of the day for energy storage or to switch on appliances. This could also ultimately be a cause of public opposition to the deployment and implementation of the Gasification and AD pathways dedicated to the decarbonisation of the transport sector. These results suggest that those pathways dedicated to more direct and tangible energy benefits, with less disruptive energy consumption behaviour, would be more socially acceptable.

7.1.2 Community Benefits

Several participants (G3, CS1, CS2) saw value in Decentralised Gasification and AD pathways emphasising community energy benefits from the deployment of heat networks. These views were expressed through criteria examining the degree of energy self-sufficiency and energy independency that the different pathways could help to achieve at a national and/or local level (G3), the capacity of the pathways to address fuel poverty (CS2), and the ‘community benefits’ that the different pathways could potentially provide (CS1).

Participants G3, CS1, CS2 converged on the idea that there would be higher direct energy benefits for society by producing heat rather than liquid biofuels. Whilst participant G3 raised it from the perspective that there are not many alternatives available to produce heat, arguing that 'Heat is a really tough sector to decarbonise, whereas the decarbonisation of the transport sector can be done in other ways'; participants CS1 and CS2 raised it from the point of view of which end product may more directly provide community benefits and alleviate local fuel poverty. Although both products, heat and liquid biofuels, would be generated in the area where the plant is located, these participants felt that the heat produced would have a better chance of being used locally. For this reason, participant CS2 emphasised the importance of heat networks, as the pathways would maximise their efficiency while reducing 'fuel poverty by using what is essentially a by-product of the process' (CS2). This argument is consistent with what has been previously emphasised in the literature (Jamasb and Nepal, 2010; Wright *et al.*, 2014; Jeswani and Azapagic, 2016; ERA, 2020; Cross *et al.*, 2021), and further supports the idea of enabling the full potential of EfW process in the UK with the use of the waste heat generated. In contrast, the liquid biofuels produced could be used nationally or even exported internationally, providing fewer benefits to the local community where the plant is located. As participant CS1 argued, 'With transport fuels [local] people don't really feel the benefits.' Hence, public acceptance of the plant was considered to be more likely if the energy products were to benefit the local community. On the other hand, export of the energy products could result in negative views towards the plant and an emphasis on the local disbenefits, such as reduced aesthetic appreciation, impact on air quality and heavy traffic. These concerns interlinked with others arguments related to social acceptability and potential concerns of public opposition.

Directing the heat produced to a heat network with the potential to increase self-sufficiency and community benefits and to lessen fuel poverty was cited as a strength. In the case of BAU and Centralised Gasification pathways, this strength was obscured by issues of feasibility. The large scale and location of the plants of the BAU and Centralised Gasification pathways makes the use of the heat more difficult as it requires long and more complex distribution systems to transport the heat to where is needed; which is consistent with what has been previously emphasised in the literature (ERA, 2020). Decentralised Gasification and AD pathways for the connection of the plant to heating networks and community buildings were seen more favourably. Nonetheless, the risk of lock-in mechanisms to updated systems was cited as a weakness for the development and deployment of heat networks in decentralised pathways. Participants CS1 and CS2 expressed concerns around the reliability of heat networks, the high capitals costs of investment and the lack of flexibility of the system due to lock-in mechanisms that would inhibit the possibility of introducing alternative energy technologies in the future. It is worth quoting at length some of the arguments from participants:

> 'If you are part of the heating network, that is a benefit… But there could be disadvantage because … what happens, like in Nottingham, when in Christmas the incinerator broke and then no-one had any heat at Christmas? … [Or] If something better comes along but you can't take advantage of it, because you are stuck as part of the existing network?... These new houses are being built with no boiler, they are completely dependent of the incinerator, [gasification or AD plant], so in a few years' time when there is cheap solar power, or wind power, they can't benefit from that. So, they are locked into a contract where they have to only buy the heat and electricity from the incinerator, [gasification, or AD, connected to the heat network].' (CS1)

> 'When it fails you would need an alternative, which would be probably more expensive… So, I have been involved in projects where we have put in biomass boilers, in which you put a lot of time and money, into install, to furnace, for everything… and then you think 'well we need a back-up boiler'. And you almost size the gas boiler to be as big as… so your capex cost is increased significantly by having to put back-up equipment. If it does fail, then you have got to use the back-up equipment. So it makes you doing two things. It is like having two hearts in your chest. The second one in case the first one fails.' (CS2)

However, these findings should be treated with caution. Although these participants discuss the issue as if it were a technical one, related to technology reliability, this might in fact be a problem of risk perception of new infrastructure with which owners are not familiar. This unfamiliarity, which was previously identified as a barrier to social acceptability (see Section 7.1.1), may lead owners to select another technology. Thus, these findings prove the need to increase awareness and understanding of new technologies entering the market, their benefits and barriers as well as the new ways in which energy may be produced.

7.1.3 Air Quality Impacts on Human Health

In terms of air quality impact on human health, the performance of pathways varied depending on a range of factors. Location of the EfW plant, its proximity to population areas, and population exposure to pollution along the length of the supply chain were identified as key elements to evaluate the impact on human health. Air quality impact was considered in relation to the location of the plant, the transport of waste from its collection point to its processing point, and the distribution and use of the final end product. The emission dispersal in relation to prevailing winds and the potential presence of vulnerable communities were additional elements identified by participant CS2: 'You would not put a waste incineration plant close to a hospital for example, because you might have people with a higher vulnerability to the effects of that waste incineration process.' Notwithstanding the accuracy of this argument, this finding is interesting: if participant CS2 perceives this to be a problem, it is likely that others involved in the development and planning of an EfW project will share a similar view. This brings to light the importance of understanding stakeholders' perceptions, interests and values, in line with what has been claimed in the literature (Thornley and Prins, 2009; Upham *et al.*, 2009; Thornley and Gilbert, 2013; Röder, 2016; Cross *et al.*, 2021). Overall, strategic planning emerged as the common denominator in the arsenal of arguments brought forward by participants.

Centralised pathways were viewed more favourably for reducing the effects of air quality impact on human health due to the remoteness of the plants from population areas, which reduced emissions exposure from both processing and transport in comparison to decentralised pathways. Large EfW plants tend to be located away from major population centres whilst small-scale plants of decentralised pathways would be located close to communities who are then able to benefit from them. As one participant argued, the 'farther away the plant is from population areas, less importance is given to the air quality impact.' (G1) Similarly, in terms of emissions from waste transport from collection to plants, participants G1 and CS2 reflected that in centralised pathways transportation is likely to take place around the edges of cities and not inside them, so the air quality of populated areas would be less affected.

However, as previously mentioned, the final use and distribution of energy outputs – which varies across pathways – emerged as another important factor in evaluating impact on human health. Hence, the pathways contributing to the decarbonisation of transport sector were also considered favourably, due to the observation that the carbon content of fossil derived liquid fuels is more intensive than heat from natural gas. Participant CS2 discussed the concept of carbon intensity and the displacement of GHG emissions from the production of different energy outputs. There was discussion, however, as to whether the emissions produced by these pathways would be too close to population areas, raised for instance by participant G1. Participant G3 felt that the emissions would be predominantly produced far from urban centres. Moreover, according to participant CS2, 'the biggest air quality problem in cities is from transport. It is not from processes. So anything that would improve air quality through transport would be much more positive' (CS2). One point raised is that the injection of synthetic natural gas or bio-methane into the gas grid would entail combustion of the gas in the home. Participant CS2, however, argued that 'gas is a cleaner fuel than diesel. So, it is probably better to heat your home with gas, than to drive a diesel car.' This intersects somewhat with the environmental theme of 'Avoidance of GHG emissions: Displacement of fossil fuel GHG emissions with the production of valuable energy products', which has been discussed in Chapter 6, Section 6.2.5. Attention should be given to the word "probably" used by CS2, which suggests that the participant is making an assumption without actual evidence to support it. In fact, this use of hedges – i.e. expressions such as "probably", "I guess that…", etc. – was common among the 15 participants interviewed in this thesis, suggesting that some ideas and perceptions were probably based on assumptions, rather than on evidence. These assumptions, in turn, could have derived from many different factors in participants' lives, including interests, values, past experiences, and the workplace.

Under the assumption that light vehicles were electrified, participant G1 considered the final end use of transport fuel – i.e. whether aviation, or heavy good vehicles (HGV) – as an important element for comparing the air quality impact of Decentralised Gasification and of Decentralised AD pathways dedicated to the decarbonisation of the transport sector. If liquid biofuels were used as jet fuels, the air quality impact produced from their combustion would be far from populated areas and would concentrate around airports, which tend to be at the edges of cities. If the liquid biofuels were used in HGV, the majority of transportation would take place between cities, and not inside them: even in this case the air quality impact would not affect populated areas.

The chart of the overall performance of the six pathways against social acceptability, community benefits and air quality impacts to human health themes, altogether, can be found in *Appendix 2.3. Figure 2.3.8*.

7.2 Political Issues

The debate around political issues focused on one main theme, that of government intervention (G1, A3, A4).

Political criteria were identified only by participants from Government and Academia. This is interesting as industrial and civil society participants were also interviewed. The six core pathways (Business as Usual (BAU), Centralised Gasification, Decentralised Gasification for the decarbonisation of the heat sector, Decentralised Gasification for the decarbonisation of the transport sector, Decentralised AD for the decarbonisation of the heat sector, Decentralised AD for the decarbonisation of the transport sector) scored relatively low with respect to political criteria and there was considerable overlap between the performance of all pathways when appraised against government intervention; especially between Gasification and AD pathways.

The different elements, key concerns and arguments articulated by participants, that have shaped these final pathways performances, are explained below.

7.2.1 Government Intervention

The theme of government intervention relates to the degree of intervention that is needed from the government to support the innovation and deployment of technologies as well as the production of the different energy outputs, for the pathways to become a reality.

Participants G1, A4 and A3 referred to different types of intervention instruments that the Government could implement in the different pathways. These were instruments of taxes, subsidies as well as instruments of regulation and influence, which were associated with the support of technology innovation and deployment, the production of energy outputs and the support of policies for reducing the waste sent to landfill as well as promoting the development of more sustainable waste management systems. The need for Government intervention instruments varied according to the different pathways and the different supply chain characteristics; particularly in terms of types of technologies and related technology readiness level, and the type of energy output produced. In this sense, this theme intersects with the theme of technology readiness and bankability discussed under the techno-economic dimension in Chapter 5.

BAU performed the most highly against government intervention because the pathway was seen as having relatively little dependence on government support. Incineration technology is a well-established technology that does not need government support for technology innovation and deployment, yet participants agreed that BAU would still require some government intervention in terms of waste management, such as the landfill tax, to stop diverting the waste into landfill which in the view of participants, without the landfill tax, would still be going into landfill. Moreover, the landfill tax was considered to be indirectly benefiting the use of incineration for the management of waste.

For instance, it could be argued that incineration does need, and actually has, government intervention. These are regulatory interventions in the form of gate fees that come through the landfill tax regulations. Since there is a fixed cost to landfill then there is a benefit to instead put the waste into an incinerator. Incinerator operators incentivise the waste to come to their facilities by taking a lower gate fee for waste tipped at their site. However, if there was no landfill tax, and in the absence of other rules to not landfilling waste, then it is very likely that most of the waste would end up in landfill. Consequently, the perspective of having little dependence on government support could be questioned. Despite the good performance of BAU, participants G1 and A3 expressed some scepticism towards the BAU pathway approach built over the years. As one participant argued: 'The rules around the market are not claiming a change … the system [pathway] is more likely to carry on unless it is subjected to shocks or pressures.' (A3). In this regard, participants G1 and A3 recommended the need for some type of regulatory intervention from the government. The government could intervene through regulation to, for example, reduce the amount of waste going to incineration, reduce waste exports and increase recycling (G1, A3); or through targets and policy statements, to influence the direction of the markets, such as for example, by 'tightening air quality impact limits on the incineration technology (G1); or by incentivising the entrance of new waste management players into the market system (A3). The latter relates to the waste management supplier companies. As previously discussed in Chapter 6, Section 6.1, some of these suggestions have already been placed on the table by the UK Government and are currently being consulted. Such is the case, for the introduction of plastic taxes, the deposit return schemes, or the extended producer responsibility. Not forgetting the potential introduction of a tax on incineration if waste recycling rates and reduction ambitions are not achieved rather than the waste kept being sent to incineration (DEFRA, 2018b).

For the three Gasification pathways, participants G1, A3, A4 expressed differing views resulting in a relatively wide uncertainty between the pathways. Whilst the optimistic performance relied on the assumption that gasification technology would become proven and deployed thanks to a range of interventions, the pessimistic performance relied on the assumption that this technology would remain at its current state, considered by most participants largely ineffective/unsuccessful in its attempts to make it work. The potential good performance of any of the three Gasification pathways was seen to be highly unlikely without government intervention (G1, A4). Participants G1 and A4 felt that there is an unquestionable need for government support for the development of gasification technologies and liquid biofuels production and their subsequent deployment, and for energy outputs generation (G1, A4). This lends support to previous findings in the literature (Thornley and Prins, 2009; Purkus *et al.*, 2015; Cross *et al.*, 2021). Government employee, participant G1 affirmed that the government is conscious that it will need to do something to push forward gasification technology, otherwise, 'Gasification without the support of the government will never happen, that is the problem.' (G1). Likewise, the deployment of heat networks as well as the development and deployment of technologies, whether gasification or other alternative routes to produce liquid biofuels will need high and long-term government support due to the high costs of investment. As in the case of conversion technologies, the production of energy outputs will also be dependent on government market intervention and support (G1, A4). Subsidies such as renewable certificates, renewable heat incentives, and feed-in tariffs would need to be available. The production of heat and power from wastes were seen to require less intervention than transportation fuels. This was because the development of combined heat and power (CHP) technology as an alternative to natural gas is less expensive than the development of transportation fuels through gasification and other routes. Moreover, CHP is part of the government-supported Advanced Conversion Technologies (ACTs) definition, such as the Renewable Heat Incentive and the Contracts for Difference, and for this reason, G1 stated that 'There is a clear commitment to keep supporting the outputs of heat and power from wastes with direct funding from the government.' Interestingly, whereas stakeholders' concerns around the uncertainty and/or lack of continuity of RHI have been reported in the literature (ERA, 2020; Cross *et al.*, 2021), no particular concern from the side of participants emerged from my results. Likewise, the UK Government investment programmes for heat network deployment, previously discussed in Chapters 2 (Section 2.3.1.1) and 5 (Section 5.3.1) respectively, should help reduce these high-cost investment risks and enhance their deployment and economic viability.

In terms of liquid biofuels produced from wastes, participants G1 and A4 addressed the existence of the Renewable Transport Fuel Obligation (RTFO) and how obligation targets are going to rise in the long term. Whilst participant G1 had some scepticism towards the effectiveness of the RTFO since it is just an obligation without subsidy support for liquid biofuels, Participant A4 saw that the introduction of aviation fuels into the RTFO could be beneficial. This change could have a knock-on benefit for the development of gasification in the production of aviation biofuels from waste. These results lend support to previous findings by Waldheim (2018), who also identified this introduction in the RTFO as a benefit for gasification. In addition, participant A4 expressed concerns around the timing and length of government support. These were identified as key elements to enable gasification pathways to have the time needed to develop and hence work satisfactorily. These types of concerns align well with what has been previously reported by Thornley and Prins (2009) and Cross et al. (2021), nonetheless according to the findings from those studies, this is just one barrier among many others.

AD technology was seen as a developed technology with no need for government support in technology innovation but with a strong need for government support for the production of energy outputs. Participants G1 and A3 agreed on the idea that the use of methane in transport would require more government support than the injection of methane into the gas grid. Although the latter would still require some type of incentive, this could help to displace natural gas and decarbonise the heat system.

Something that emerged from the exploration of the government intervention theme is the relatively small number of political barriers identified by participants. This is striking, since a wide variety of political barriers among stakeholders of the EfW and bioenergy sectors has been reported in the literature (Thornley and Prins, 2009; Purkus *et al.*, 2015; Cross *et al.*, 2021). An explanation might be found in the small number of participants who discussed political criteria: only three (participants G1, G3 and A4) out of 15. Further, this result might also be explained by the type of participants who discussed this theme. Two out of the three participants (G1, G3) represented the government perspective; hence, their opinion on the limitations of political interventions might have been biased.

The chart of the overall performance of the six pathways against government intervention theme, can be found in *Appendix 2.3. Figure 2.3.9*.

Conclusions

Analysing the results obtained from the MCM participant´ interviews, this chapter has identified and discussed the different social and political issues, uncertainties, interests and values perceived to be at stake when it comes to the sustainability of the six different EfW pathways under appraisal. The key findings are summarised below.

The social issues that were analysed included the themes of social acceptability, community benefits and air quality impact on human health.

Within the theme of social acceptability – which related to the public's perception of the social acceptability of the different pathways – public opposition was viewed as the main concern, with the potential to undermine the feasibility of EfW projects. Several factors were cited as important when assessing the extent of public opposition: size and aesthetic appreciation of the plant, lack of communication, of awareness and understanding from the public, and lack of trust towards companies. Participants also emphasised the need for a change in the behaviour and engagement of the public.

Results also underlined the need for arenas of communication in order to share interests and concerns and to allow for exchange of knowledge. This will help align the objectives of different stakeholders (including the public).

When it comes to evaluating the different pathways in terms of their social acceptability, participants seemed to perceive incineration as less socially acceptable than gasification. This is in contrast with other findings in the literature, which suggest that public perception of these two technologies is not so easily distinguishable. In light of these conflicting results, it would be premature to simply assume that gasification is more socially acceptable than incineration. Rather, it is more likely that public perception differs according to community context, experiences, interests and values. This highlights the need for community engagement wherever a plant is being considered.

Regardless of whether incineration was perceived as more or less acceptable than gasification, participants believe that the public lacks knowledge and understanding of incineration technology. Further, one reason why they view gasification technology as a more socially acceptable alternative is that this pathway requires a stage of waste pre-processing.

The challenges identified by participants in terms of social acceptability include achieving the behavioural change needed to increase recycling rates, and gaining the necessary trust from the public to promote such change. AD pathways were perceived to have less public opposition than any of the thermochemical conversion pathways. In particular, participants underlined the importance of implementing food waste segregation as this was perceived as a potential driving factor towards increased recycling, which in turn would provide renewable energy and digestate. It was also believed that implementation of food waste segregation would increase public awareness and engagement in waste management. However, a few drawbacks – the NIMBYsm phenomenon, possible odours derived from the process, and perceived risks of methane-induced explosions – could undermine its social acceptability.

As indicated from the results, the UK Government needs to show that it is developing policies in the waste management sector, and that any investment in better energy recovery is targeting the issues posed by unrecyclable unpreventable material. More targeted efforts and a clearer focus on re-use and recycling are needed to strengthen social confidence in the waste hierarchy. This will then provide confidence that waste, when processed in an incinerator, gasification or AD plant is truly unrecyclable.

Results also indicate the existence of a certain lack of understanding/awareness on heat networks technicalities in departments that are central in energy decision-making and policy developments. This kind of misguided understanding could lead to decisions based on mistaken assumptions. Such decisions, if not identified on time, could in turn lead to the development of deficient energy policies. These results indicate the need to share knowledge not only to the public, but also between stakeholders with different technical expertise and backgrounds and across different disciplines

Decentralised pathways with smaller scale plants were viewed as more socially acceptable compared to centralised pathways. In terms of community benefits, the pathways dedicated to the decarbonisation of the heat sector were perceived most favourably. These pathways were seen as delivering tangible and direct energy benefits to the community and reducing fuel poverty. Although concerns around NIMBYsm were raised, participants stressed the importance of informing the public on the process of community-based waste management and on the benefits associated with the EfW plant, as these elements were deemed important for building a sense of personal connection to the area and for increasing public awareness, understanding and engagement.

When participants evaluated benefits, they tended to perceive new infrastructure as riskier. This means that it is important to raise awareness of new technologies entering the market, in terms of their benefits, barriers, and energy production mechanisms.

Concerns also arose in terms of health issues associated with EfW plants. Whilst decentralised pathways were consistently deemed to be better in terms of community benefits and contribution to energy self-sufficiency, the performance of the various pathways under air quality impact on human health tended to be more variable, and to depend on a range of factors. In general, centralised plants were viewed more positively than other plants because they are usually located away from major population areas. This also meant that emissions from waste transportation were perceived as less of an issue in centralised pathways. Pathways dedicated to the decarbonisation of the transport sector were perceived to minimise air impacts to human health, in a greater level than the pathways dedicated to heat decarbonisation. This was due to the observation that the carbon content of fossil derived liquid fuels is more intensive than heat from natural gas, as well as to the counterfactual effect of creating a product with lower carbon intensity to the liquid fuels derived from fossils. In the discussion of this theme, it should also be noted that, in some cases, participants provided arguments based on assumptions, rather than evidence.

The political issues analysed covered the theme of government intervention. The government intervention theme focused on the level of government support that each pathway, with its technologies and energy output production, would need in order to be deployed. BAU was not believed to require any government support in terms of technology innovation and energy output production, although its feasibility is largely dependent on regulatory government interventions consisting of the landfill tax and gate fees. Conversely, the implementation of gasification technology was perceived to be completely dependent on government support, both for technology innovation and for the production of energy outputs. This was largely tied to bankability issues and technology readiness level, previously discussed in Chapter 5. In particular, gasification pathways are believed to require long-term government intervention to address the issue of high capital costs. In terms of energy output markets, pathways for heat and power production were perceived as requiring less government intervention as opposed to pathways dedicated to the production of transportation fuels. This difference was largely linked to the technology readiness level of the different technologies: since it would require government support only for its deployment, the use of CHP technology was perceived as less expensive compared to the production of transportation fuels through gasification and other routes, which would require high investment costs not only for its deployment, but also for research and development. AD pathways, on the other hand, were perceived as not requiring government support in technology innovation, but as requiring strong support in the production of energy outputs. The use of methane in transport would require more government support than the injection of methane into the gas grid.

However, it should be noted that political criteria were discussed only by three participants out of 15. These individuals represented perspectives from government and academia and, as suggested by my results, their views on this domain might have been slightly biased. This may explain the limited number of political concerns that have been raised.

In Chapter 8 that follows, the conclusions of this research are presented.

Chapter 8. Conclusions

The UK has the target of meeting net zero emissions by 2050. Energy and Fuels from Municipal Solid Waste (MSW) and Commercial and Industrial (C&I) Waste can have an important role to play in the energy mix system and transition to the lower carbon economy towards the 2050 target. However, the co-existence of the Energy and Fuels from Waste (EfW) sector, the low carbon economy, and the circular economy (CE) are not obvious bedfellows. The EfW sector is seen by some stakeholders as an essential component of renewable energy policies, waste management policies, and the development of sustainable integrated waste management systems. However, it also generates controversy among other stakeholders who see EfW as undermining the development of more sustainable waste management systems, the transition to a CE and lower carbon economy. Consequently, to date, there is still uncertainty about the long-term deployment strategy and role that the EfW sector can play in the national energy system and transition to a low carbon economy contributing towards UK net zero target by 2050. In this context of uncertainty, issues and interests of a very different nature compete: sustainable waste management and climate change concerns, technological, financial and energy market interests and social and political concerns.

This research aimed to contribute towards knowledge identifying which uncertainties, issues and interests are at stake, providing information for better understanding them, and to interpret the expectations of the role that the EfW sector can play in the UK in 2050. It aims to bring to light the technological, economic, social and political uncertainties, divergent values and social priorities that shape the competing expectations of the sector and lead to differing conclusions about the sustainability and opportunities of waste management, EfW technologies and different energy outputs from EfW in the UK. Given the strong interrelation with the waste management sector and the CE, this thesis also aimed to contribute and extend current knowledge of the complex "jigsaw" in which the EfW sector in the UK has become, and to show that there is potential for a symbiotic relationship between them to help the UK achieve its net zero target by 2050.

This research has assessed and described the perspectives and value-judgements of different stakeholders involved in the EfW sector in the UK. With the overall research aim of opening up the debate about the relative sustainability of six different EfW pathways, the overall research question has been to investigate '*How can energy and fuels from waste (EfW)* *technologies (Incineration, Gasification and Anaerobic Digestion) be integrated and contribute towards sustainable waste management and energy systems in the UK?'*

This overarching aim was put into practice through the following research questions:

1) To what extent can Energy and Fuels from Waste pathways contribute towards more sustainable waste management systems?
2) To what extent do Energy and Fuels from Waste pathways contribute towards both, more sustainable energy systems and achieving UK net zero target?
3) What have been the contributions of using the Multicriteria Mapping (MCM) approach to explore stakeholder participants' perspectives on the sustainability of different EfW pathways?

A comprehensive review of the literature helped to establish six core EfW pathways with potential for the future EfW sector in the UK. These pathways have been explained in detail in Chapter 3.

The MCM approach, an elicitation computer software, was used to answer the research questions. This allowed me to interview stakeholders from the UK government departments, industry and trade bodies, academia and NGOs, and to gather both qualitative and quantitative data around the relative sustainability of the six EfW pathways. The data were analysed thematically and interpretively, exploring emerging common issues and themes among the three sustainability dimensions – techno-economic, environmental and social – to capture the economic, technical, environmental, social and political opportunities and barriers that the different stakeholders perceive, value and prioritize for each of the pathways under appraisal.

This research has thus provided an overview of the divergent perspectives that have a bearing upon decision making processes in the UK EfW sector. The thesis provides transparency on unresolved issues and existing barriers in the UK EfW sector. It also provides transparency on what the future opportunities of the EfW sector are according to the opinions of a group of stakeholder participants involved in the sector. A deeper understanding of these opportunities will lead to a better chance of success for current and future EfW project deployment, helping the UK to develop a more sustainable and robust EfW sector, in line with sustainable waste management systems and the CE concept.

Section 8.1 of this concluding chapter first synthesises the key findings and conclusions from Chapters 4, 5, 6 and 7 on the overall performance of the six core EfW pathways. Research questions 1 to 3 outlined in Chapter 1, and repeated earlier in this chapter, are addressed in Sections 8.2, 8.3 and 8.4 respectively. Section 8.5 then discusses the limitations of the research, and presents a forward look to potential future research.

8.1. Summary of Findings

The quantitative and qualitative findings have revealed what techno-economic, environmental, social, and political issues and common themes exist. They bring to light what concerns, uncertainties, interests and values are at stake when it comes to the evaluation of the sustainability of EfW pathways. The results from the MCM show that, overall, there was a considerable overlap between all pathways performance, and no one EfW pathway emerged from this research as an outright winner.

The two Decentralised Anaerobic Digestion (AD) pathways were considered to be more sustainable compared to the thermochemical pathways. Their relative strong performance both under pessimistic and optimistic assumptions was due to the environmental and social benefits in terms of carbon emissions, waste management and contribution to CE (especially with the production of good quality digestate for use as bio-fertiliser) and social acceptability. However, they were the subject of concerns related to feasibility, efficiency, and policy, particularly in terms of waste availability, handling efficiency, feedstock efficiency, and government incentives. The performance of Decentralised AD pathways under waste availability and efficiency were to some extent linked to Business as Usual (BAU), due to matters of feedstock use competition.

In comparison to the two biochemical conversion AD pathways, the sustainability of each of the four thermochemical conversion pathways was more controversial. For example, the use of fossil fuel derived materials of high carbon intensity was a common concern to stakeholder participants for all four thermochemical conversion pathways. This has an important impact on the performance and likely sustainability of the different pathways. Likewise, the technology readiness level and bankability of gasification or/and the availability of waste and consistent feedstock appropriate for incineration and gasification technologies were other points of controversy, impacting on the performance and likely sustainability of the pathways. Regarding the latter, the findings suggest there is competition between incineration and AD for the use of organic food waste, as per the adverse effects that the compulsory segregation of food waste from the residual waste (for it to be sent to AD pathways) could have on the performance of BAU. Likewise, there is competition between energy and fuels recovery from incineration and gasification, as both technologies operate more efficiently with high energy content feedstock. Furthermore, there is a risk of diversion of waste from recycling towards incineration and gasification, which would disrupt progression towards better sustainable waste management systems and a CE.

BAU performed the most highly against waste availability, technology readiness, efficiency, net financial costs, and government incentives, but with some overlap with the rest of the pathways under its mean pessimistic assumption, i.e., its pessimistic performance against these different themes. This suggests that BAU against these themes would still be the worst performing if the rest of the pathways were considered optimistically. This was partly because of potential legislation changes concerning waste management systems, sorting, and segregation of waste streams. The segregation/collection and sorting/processing of food waste could adversely affect BAU waste availability, efficiency, economics, and carbon impact performance by reducing the availability of biogenic content for incineration. BAU's regulatory compliance regarding carbon impact and production of renewable energy could thus be compromised. Likewise, BAU was also judged to be the least sustainable pathway in terms of environmental and social performance, largely because of concerns about GHG emissions, waste management, and social acceptability. In general, participants maintained the need for some type of regulatory intervention from the government to reduce the amount of waste going to incineration or being exported, for there to be an increase in recycling. There were concerns around the role that BAU could play in the transition to a low carbon economy in the long-term. For some participants, BAU was seen as a supporting technology in the transition to a lower carbon economy, with perceived limitations on its longer-term viability once the capacity of electricity produced from renewables has increased rendering the emissions from incineration higher than the average of the grid. With the implementation of carbon capture and storage (CCS) technology, incineration could have a greater margin of manoeuvre; nonetheless, as incineration plants are already widely deployed and operational, the need of CCS for BAU is already critical.

Centralised Gasification and the two Decentralised Gasification pathways performed relatively similarly to each other. The sustainability of the three gasification pathways was strongly subjected to concerns of waste availability, handling efficiency and feedstock efficiency, technology readiness and bankability, net financial costs, waste management, social acceptability, and government incentives. The uncertainty over these pathways was greatest, overall. There was significant scepticism about achieving the required technology readiness level for reliable operation and ensuring the availability of consistent feedstock to make the gasification for added value products feasible. This undermined the performance and likely sustainability of each of the three gasification pathways, and to a greater extent, the good performance of those gasification pathways dedicated to the decarbonisation of the transport sector. The need for government intervention for the development of gasification technologies and liquid biofuels production, subsequent deployment, and for the generation of energy outputs, is unquestionable for gasification pathways. As with AD, there were technological, and infrastructure barriers, as well as educational, and public behaviour barriers hindering the availability of consistent feedstock for these pathways. Consistency of feedstock supply will require infrastructure investment, policy intervention, and legislation changes, as well as behavioural changes.

The relative strong performance of gasification pathways, as with AD pathways, was due to the environmental benefits from lower carbon emissions and their contribution to the CE as well as their UK economic impact. This reflected the potential benefits of low carbon fuel production displacing fossil fuel emissions and the potential benefits in terms of UK economic impact, with the production of high added-value products and access to EfW technology and energy product markets. In the case of gasification, there was the additional possibility of producing hydrogen.

However, there was strong controversy around the inefficient front-end management and usage of fossil fuel derived materials´ waste streams, with which the gasification technology operates most efficiently. The use of fossil fuel derived materials such as plastics, which could otherwise be treated higher up in the waste hierarchy, is a disruption to the progression towards improved sustainable waste management systems and a CE. Some participants considered that the best alternative would be to use biogenic material; this would ensure the production of renewable energy resource and neutral emissions, contributing towards the transition to a lower-carbon energy intensive economy. As with BAU, for some participants the deployment of CCS in gasification pathways would also be needed for the transition to a lower carbon economy. Nonetheless, in comparison to incineration, CCS would be required at a later stage, after the gasification technology has been deployed and become operational. In addition, since technology for the production of liquid biofuels has yet to be developed, pathways dedicated to the decarbonisation of the transport sector would require CCS at a later stage compared to those dedicated to the decarbonisation of the heat sector, for which technology is already developed.

Gasification and AD pathways dedicated to the decarbonisation of the transport sector were seen more favourably in terms of carbon impact, as they would be replacing products with higher carbon intensity. Therefore, they would generate a greater impact on the displacement of fossil fuel GHG emissions. Nonetheless, because of the higher number of alternatives available to decarbonise the transport sector, some participants felt that the use of the gasification and AD would have a more significant role to play in the decarbonisation of the heat sector rather than the transport sector.

As with BAU, under proposed legislation changes for waste management systems, increased sorting and processing, there were also uncertainties about the scale of operation of the gasification plants. This hindered the performance of centralised pathways as well as those producing liquid biofuels, where the large amount of fuel required could be challenging to produce if feedstock consistency became a constraint.

Due to economies of scale, the two Decentralised Gasification pathways presented greater challenges in terms of feasibility and economic issues than Centralised Gasification. Nonetheless, the findings also revealed a relative greater performance of Decentralised Gasification pathways in terms of social issues. This was largely related to the potential greater benefits that decentralised pathways could provide to recipient communities. Some participants highlighted the possibility of designing Decentralised Gasification pathways to the contextual needs and social priorities of the area, while driving the transition to a lower carbon economy. This would help to increase social acceptance based on the potential benefits, increasing public awareness, understanding, and engagement.

Concerns about waste availability over time highlighted a risk to the scale of operation for Decentralised Gasification and AD pathways. Considering the large amount of liquid biofuels required for aviation and HGVs, the purpose of decentralised pathways for the decarbonisation of the transport sector was seen as challenging to achieve. Some participants considered that a good attempt of efficiency and economic feasibility for long-term production and use of transport biofuels, especially for AD, would be deploying them in niche markets, such as supermarkets. For example, small-scale plants may work with local supermarkets, from which they would take the pre-sorted waste; the biofuel produced would be used for their own business transportation fleet, while at the same time delivering associated benefits to local areas.

Yet, concerns about perceptions of direct benefits to the community were a hotly debated point by the participants. Liquid biofuels produced locally could be used nationally or even exported, and would thus provide fewer benefits to outweigh any burdens imposed on communities where the plants were located. In contrast, use of heat could help address local energy poverty, thus providing a tangible, and direct benefits to the community. In this regard, the pathways dedicated to the decarbonisation of the heat sector were seen favourably in comparison to those dedicated to the decarbonisation of the transport sector. However, the non-existence of heat networks in the area, potential feedstock efficiency constraints, and limits to costs effectiveness and infrastructure offered several technological and economic barriers to the implementation of Decentralised Gasification and AD pathways for the decarbonisation of the heat sector. Under such infrastructure constraints, the injection of synthetic natural gas or bio-methane were seen as better alternatives, as they could use existing infrastructure. Nevertheless, if the heat networks were already in situ and gasification and AD technologies were ready for deployment, these same pathways were perceived to perform relatively well in terms of net financial costs and social acceptability, with particular relevance in terms of providing community benefits and alleviation of local fuel poverty.

Key conclusions

Participants recognised a wide range of situations in which EfW via gasification and AD pathways could be less sustainable than the current BAU pathway. These were particularly related to concerns over waste availability, technology readiness, net financial costs, and government incentives. Nevertheless, gasification and AD pathways were considered as having potential strengths to encourage and deliver sustainability advantages related to a wide range of issues, which BAU is currently unable to achieve, particularly in terms of feedstock efficiency, UK economic impact, GHG emission reduction, waste management, and social acceptability. For example, gasification and AD would require an increase in the sorting and processing of waste streams due to the selectiveness of the technologies. Further, the production of high-value products can contribute to the displacement of fossil fuel GHG emissions. This will be explained in further detail by addressing the research question in the sections below.

There was significant uncertainty in terms of feasibility, efficiency, environmental efficiency, and social issues. These uncertainties have important impacts on the likely sustainability of the different pathways. In particular, there were techno-economic uncertainties concerning the availability of waste over time (Section 5.1) and obtaining consistent feedstock over time appropriate for the selectiveness of gasification and AD technologies (Section 5.2), the cost of gasification, liquid biofuels and heat network technologies and the infrastructures associated with each of them (Section 5.3). Likewise, there was significant uncertainty concerning environmental efficiency and social issues. Particularly related to waste management (Section 6.1), GHG emissions (Section 6.2) and social acceptability (Section 7.1). Chart displaying of the overall performance of the pathways under the different themes can be found in *Appendix 2.3*.

The appraisal of the different pathways brought to light a wide range of arguments encompassing both descriptive and normative statements. On various occasions, these arguments were based on value judgements and opinions of participants about the way in which society currently works and how it has been working for the last decades. In this regard, some participants approached the debate around EfW based on what has always been done, supporting the reasons why it was done that way and supporting in some way continuity in its current way-of-doing. Other times, the value judgements, and opinions of participants were based on how the pathways could work in the future, if subjected to changes. In this regard, participants approached the debate looking at a wider picture. These changes could involve political implications, changes in behaviours and perceptions of the public, and/or deeper understanding, awareness, and collaboration between stakeholders of the pathways´ supply chains. These changes in turn would affect the likely sustainability of pathways' performance.

The above has summarised the findings related to relative performance of the EfW pathways under focus. The following sections will address the research questions in turn.

8.2 To what extent can Energy and Fuels from Waste pathways contribute towards more sustainable waste management systems?

The UK need to transition towards the use of efficient resources in line with the CE is imperative. In terms of achieving more sustainable waste management systems through the deployment of EfW pathways, the findings reveal that gasification and AD pathways can have a role to play in the transition to more sustainable waste management and contribution to a more CE. For this however, legislation changes, the deployment of sorting and processing infrastructure, as well as strong educational and public awareness campaigns, are required.

Key messages from the findings are discussed in this section.

The UK Government needs to show that it is developing policies in the waste management sector and that any investment in improving energy recovery truly deals with unrecyclable unpreventable material. More open and effective focus and effort around re-use and recycling are needed so that from a social perspective, confidence in the waste hierarchy is strengthened. This will then provide confidence that waste, when processed in an incinerator, gasification or AD plant is truly unrecyclable. Compulsory segregation of waste streams, both for food waste and standardization of recyclable collections by local authorities, as announced by the UK Government in their Resources and Waste Strategy (RWS) (DEFRA, 2018b), should be implemented as soon as possible. The tax strategies on products containing less than 30% recycling plastic material and schemes promoting greater circulation of plastic products must also be implemented as soon as possible. As schemes and reductions in the use of virgin plastic are achieved, stronger targets to reduce virgin plastic usage should be set. The announced commitment made by UK Government through the Resources and Waste Strategy to fund Local Authorities to implement changes in their waste management systems and put in place the sorting and processing infrastructure required must be provided. This commitment must not be left hanging in mid-air.

New sorting and processing infrastructure deployment is a must to meet the targets in recycling, increase resource efficiency, and move towards the CE. The lack of infrastructure available for sorting and processing waste in the UK hinders improvement to sustainable waste management systems and, consequently, blocks the potential benefits of improved sustainable EfW production. The selectiveness of the gasification and AD technologies requires extra-processing to achieve consistent feedstock. In the absence of budget to support changes in the front-end activities of waste management for sorting and processing waste streams, investment in gasification and AD plants can be the driver of investment and deployment of sorting and processing infrastructure and improved waste management at the front-end of the pathways. Consequently, gasification and AD technologies would be the drivers towards achieving higher recycling rates and more sustainable waste management systems. In contrast, there was also a fairly general opinion among stakeholder participants about the need to move away from incineration. The ability to treat all types of waste, without waste segregation requirements at the front-end of the BAU pathway, constrains the transition to more sustainable waste management systems and CE.

AD pathways were perceived as having the greatest capacity to promote more sustainable waste management and the highest degree of compatibility with the CE. The environmental benefits and contribution of the AD pathways to the CE relied on the capacity to generate a good quality digestate to be used as bio-fertiliser. To this end, the food waste must be managed carefully to ensure its segregation from other waste streams to avoid contamination. Some participants raised concerns about inefficient segregation and collection of food waste or citizens´ failure to adapt behaviour and separate waste at source. To alleviate these potential barriers, well-organised education, and communication campaigns on sustainable management and efficient segregation of waste must be launched. Likewise, there must be strict quality controls with the objective of meeting quality standards of digestate. Funding should be provided for research and development of technologies to achieve the upgrade of the digestate for its use as fertiliser. AD pathways would then support the CE 100%.

The production of added value products from gasification is also an opportunity to contribute to the CE by means chemicals for manufacturing, liquid biofuels, and heat. However, the possibility of producing high quality added-value products is linked to the availability of consistent feedstock. This once again brings to light the need for better management and more sorting and processing of waste streams.

Cooperation amongst policy departments of waste management and energy and fuels from waste for the development of sectoral policies is required to ensure that the developed policies in the various sectors are complementary. This will help to solve the following two points, identified in the findings:

- There is competition between energy and fuels recovery from incineration and gasification, as both technologies operate most efficiently with high energy content material. Likewise, there is the risk of diversion of waste towards incineration and gasification instead of recycling, which would be a disruption to the progression towards more sustainable waste management systems, and a CE. Recommendations to alleviate disruption from recycling have been alluded to earlier in this section: only truly unrecyclable material should be sent for energy and fuels recovery. If incineration disrupts recycling over time, a tax on incineration as considered by the UK Government, and as already demanded by UKWIN on the emissions generated from the incineration of waste, should be introduced (DEFRA, 2018b; UKWIN, 2018b). Similarly, if gasification technology is developed and deployed and disrupts recycling, a tax on this might also need to be considered. Since gasification is still in development, it is essential that as the technology is developed, the recycling infrastructure is also developed. This will help prevent any possible recycling disruption. Likewise, as a result of greater strategies in waste management, the amount of waste should also be reduced, so we should also aim for decentralised pathways. This will be discussed further in Section 8.3.

- There is competition between incineration and AD for the use of organic food waste, as compulsory segregation of food waste from the residual waste (for it to be sent to AD pathways) could have adverse effects on the performance of BAU. While the majority of participants advocated changes in waste management legislation to support compulsory segregation of food waste from the residual waste stream, participants G5 and I2 were reluctant to support these changes. Although segregation of food waste streams was identified by these participants as a good way to increase recycling and move towards meeting the recycling targets, it was also identified as a hindrance to continued use of incineration. It is interesting to note the area of work of participant G5 to further understand this participant's perspective. Participant G5 works for a Local Authority, the duty and responsibility of which is to manage the waste as effectively as possible. Although this participant may have an interest in a more efficient management of waste and resources, his duty as Local Authority and decision-maker is linked to availability of economic resources as well as availability and investment in reliable technologies. The stipulation at legislative level that food waste must be segregated by all local authorities and sent to AD for the production of energy and digestate, should solve this competition.

8.3 To what extent do Energy and Fuels from Waste pathways contribute towards both, more sustainable energy systems and achieving UK net zero target?

In terms of contribution to more sustainable energy systems and achieving the UK net zero target, the findings reveal that each of the EfW pathways can have an important role to play in the transition to a low carbon economy and progress towards achieving UK net zero targets by 2050. For this to happen, however, several aspects of the EfW sector will need to change.

Looking forwards, policies have increasing emphasis on creating a CE. This includes proposals to reduce waste production (specially plastics waste), and to increase recycling rates both by increasing rates of separate dry-recyclable collections, as well as separate food waste collections to be delivered to AD. These changes could significantly alter the current waste management and disposal landscape. Concerns over waste availability for EfW pathways over time were common among participants, and were associated with these political drivers, which would reduce waste quantities over time; there were also concerns regarding achieving consistent feedstock for the selective technologies such as gasification and AD. However, it is argued here that even with reduced waste and improved waste management, there is still likely to be a large residual waste stream to deal with, as suggested by the inclusion of EfW plants in the net zero assessment of the Committee on Climate Change (CCC, 2019). Moreover, opportunities associated with the production of EfW in the UK should be seen in light of international developments, including countries´ decisions to restrict imports of certain types of waste streams. It is expected that these restrictions will be further tightened as importing countries improve their own waste management systems. The UK needs to find ways to manage its own waste, and increase resource efficiency, while recovering energy, and fuels from it.

The findings reveal that overall there is strong agreement that the six EfW pathways can have a role to play in the transition to a low carbon economy. Only one participant (CS1) out of 15 was completely opposed to the development of any of the four thermochemical conversion pathways. This participant´s view was that any of the four thermochemical conversion pathways undermine both the transition to a lower carbon economy and the transition to a CE. Consequently, he argued that the deployment of any of these pathways has to cease. It should be noted that this participant represents an NGO group that opposes the deployment of such technologies. Likewise, under current circumstances in the EfW sector, two additional participants (G1, I3) also showed reluctance towards the use of incineration.

Key messages from the findings are explained in the following lines.

Decentralised pathways should be prioritised as they offer advantages over centralised pathways; they can better match local availability of waste, demand for different forms of energy, and align with local interests and priorities. The deployment of EfW pathways should be contextualised according to availability of waste, community interests and priorities, and energy demands of the local area where the plant will be located. This will ensure feedstock availability and energy supply over time. The waste management and energy benefits from using waste and energy locally will be directly experienced in the community. This should potentially increase public understanding and awareness of the EfW sector and increase social acceptability for this type of project. It could also increase public engagement in the development of this type of project, whereby the community has a greater level of participation in the decision-making process.

Compulsory segregation of food waste for AD pathways deployment must be implemented, as stated in previous Section 8.2. Funding must be provided for Local Authorities to implement new schemes, arrange compulsory segregation of food waste, food waste collection, communication and education services. Constant government support is needed for heat and methane production through AD. Participants from this research did not identify many barriers in terms of governmental support for production and use of renewable heat (Section 7.2); however, they did acknowledge the importance of government support for renewable energy technology development and deployment, and production of energy. Other studies found in the literature (ERA, 2020; Cross *et al.*, 2021) have addressed that uncertainty and instability of UK Government policy are perceived as barriers for EfW deployment. In April 2021, the Renewable Heat Incentive (RHI) was extended until March 2022 (Ofgem, 2021), but it is not known if it will continue afterwards. This uncertainty around RHI should cease, and a clearer direction on future government support for renewable heat should be set to prevent reduction of activity and investment in technologies such as AD, for the production of heat.

AD pathways deployment can be the first step to increasing awareness and understanding about waste management, and especially to gain a better appreciation of waste as a resource for energy and fuels recovery. Deployment will contribute to the decarbonisation of the heat and transport sectors, while reducing GHG emissions by avoiding landfill, increasing recycling rates, and contributing to the CE. Participants agreed that AD pathways alone would not decarbonise the energy sectors. Several participants considered that the best scenario would be a combination of gasification and AD pathways for the production of syngas and biogas, respectively. Gasification would be used for the treatment of unrecyclable fossil fuel derived materials such as plastics; and AD would be used for the treatment of food waste. A gasification and AD combination was suggested for the decarbonisation of both heat and transport sectors.

AD pathways were perceived to have less public opposition than any of the thermochemical conversion pathways. Food waste segregation could be perceived by the public as a driver towards increased recycling, which in turn would provide renewable energy and digestate. This would increase public awareness of and engagement in waste management. The deployment of AD pathways, with a strong educational campaigns at a local and national level, on waste management, EfW technologies, and their role in the transition to a low carbon economy, could potentially smooth the path to acceptance of deployment of thermochemical conversion pathways. For this, it will be important to gain trust from the public, to keep them recycling.

The decarbonisation of the power sector via EfW technologies is largely dependent on the implementation and deployment of CCS. The findings reveal that EfW pathways dedicated to the production of electricity could play a short-term role in the transition to a low carbon economy, unless they are combined with CCS. There is a general concern about the role that EfW pathways dedicated to the production of electricity will play in the future. The reason behind this concern is linked to the average carbon intensity of the grid in the future. As the electricity grid starts to decarbonise, the carbon intensity of the grid will have diminished over the years. By then the carbon intensity from incineration, gasification and combined heat and power (CHP) technologies will be higher than grid average – e.g., due to incineration/gasification of plastics content in waste stream. So the capacity of the pathways to contribute via electricity to a lower carbon intensive energy system will be constrained. Some participants felt that any of the pathways dedicated to the production of electricity will require CCS at some point to continue using plastics waste as feedstock in EfW, and achieve negative emissions from EfW.

As the incineration technology is already widely deployed, it will need CCS earlier than the rest of the pathways dedicated to the production of electricity. Centralised Gasification and Decentralised Gasification pathways producing power only, or heat and power via CHP, will also be dependent on the feasibility and deployment of CCS technology. However, since the technology still needs to be developed, there is potential for a greater degree of manoeuvre. Similarly, according to the CCC (2020), any EfW technology combined with CHP and using biomass feedstock will have potentially limited roles in contributing to achieving net-zero emissions by 2050, if they cannot be fitted with CCS.

There is broad support for the pathways using existing infrastructure. For instance, BAU, for which the infrastructure is already deployed, combined with CCS could play the primary role in helping with the transition of the power sector to a lower carbon intensive energy mix. While renewable intermittent energy technologies, such as wind and solar are being established, incineration with CCS could provide carbon savings from the electricity produced, providing flexibility to the energy mix systems, while still processing the waste generated in the UK. Moreover, CCS could lead the EfW sector to deliver negative emissions.

For the deployment of any of the EfW pathways to happen in a sustainable way, due care must be taken at the front-end of the pathways with the sorting, and processing activities of waste, to ensure that only unrecyclable materials are sent to these pathways. There are a series of controversies with respect to thermochemical conversion pathways in regard to whether they can lead to achieving sustainable waste management systems. This links with the second research question, addressed in Section 8.2. If incineration disrupts recycling and CCS is not deployed, an exit strategy for incineration facilities may need to be considered.

Government support for gasification technology to achieve higher technology readiness level is needed. The three gasification pathways were perceived completely dependent on government support, both for gasification technology to achieve higher TRL, and also for the development of the technologies which will enable to convert the syngas into advanced biofuels, such as liquid biofuels and hydrogen. Otherwise, the pathways will never become a reality. The findings reveal that gasification pathways could play an important role in the transition to a low carbon economy, especially in the decarbonisation of the transport sector. Participants expressed strong support for its implementation if the technology was realised, especially for the production of advanced biofuels, such as liquid biofuels and hydrogen, as this could enable an increased displacement of GHG emissions from fossil fuels. The production of hydrogen combined with CCS could deliver negative emissions. Development of the technology could also allow access to transport sectors difficult to decarbonise, such as maritime and aviation. Decarbonising these sectors is of global interest but not possible with currently available technologies, which makes gasification an even more attractive technology to develop. Hydrogen from gasification could also have an important role to play in the decarbonisation of the gas grid and displacement of GHG emissions from natural gas. If combined with CCS, the production of hydrogen from syngas was perceived as the most effective combination for contributing to net zero emissions, for the decarbonisation of both the heat and transport sectors.

The findings also reveal that the UK could strongly benefit in terms of UK economic growth and market opportunity. If the UK manages to develop gasification technology early enough to access the technology and end products markets nationally and internationally before other countries, it could become a worldwide leader, provider, and developer of the technology. The UK currently has some gasification projects working on the production of liquid biofuels, which may give the UK a chance to enter the gasification technology and high-value product markets. For this to happen, however, the UK needs to overcome challenging techno-economic barriers which are largely related to concerns over technology readiness level, economic viability and poor reputation from previous projects´ failures. Gasification is lacking on track record and must demonstrate its potential performance sufficiently to reduce the investment risk that currently exists. Long-term support from the government to develop the technology, gain trust, and develop a successful track record on the technology will be indispensable. A clear strategy of support from the government could also help to promote research and development from the industry sector.

The progression from small and medium scale gasification plants to large scale plants was identified as a good strategy to improve track record and gain trust in the technology. However, due to economies of scale making Decentralised Gasification small scale plants economically attractive to investors may be more difficult relative to Centralised Gasification large scale plants. Government investment to support small scale plants could alleviate these risks. Given gasification flexibility in scale and production of energy outputs, this progressive development is feasible. Gasification could start to be deployed at a decentralised level, providing heat, and power to local areas. This is what the Kew Technology plant in Wednesbury is currently doing and has successfully achieved in three trials, as informed in Chapter 1. Successful development of gasification for the production of heat and power will help to generate confidence and gain attraction from investors to the technology. Moreover, the plants deployed can be adapted to expected feedstock availability in the local area, once targets in recycling are achieved. This may solve some of the constraint identified by participants in terms of waste availability. As gasification is deployed for the production of heat and power, research, and development on technology for the conversion of syngas into liquid biofuels and chemicals could be undertaken. By the time syngas conversion technologies for advanced biofuels are developed, the capital costs of the gasification technology will potentially have reduced, and the business case for gasification pathways will potentially be more economically attractive. Furthermore, the findings also revealed that one of the greatest issues in terms of gasification projects and failures is the lack of transparency around what led to projects being unsuccessful. To make the strategic progress mentioned above more easily become a reality, arenas of communication between gasification companies for sharing interests and concerns, exchanging experiences, understanding and knowledge are needed. We must share the know-how gradually built up, identify best practices, and learn from mistakes. This should help to speed-up and facilitate the strategic progress of developing gasification technology and deploying the pathways.

Heat networks should be deployed at domestic, community, commercial, and industrial level. Decentralised pathways dedicated to the decarbonisation of the heat sector with CHP and heat networks could play an important role in enhancing community resilience. The deployment of heat networks emerges as bringing important technological, environmental, and social benefits to both the EfW and heating sectors. Deployment of heat networks and decarbonisation of the heat sector will increase EfW efficiencies while reducing emissions, and provide community benefits while alleviating fuel poverty. The need to look into the Nordic countries´ experience in the use of the heat is emphasised. EfW plants in Nordic countries generate four times less CO_2 emissions than UK EfW plants (ERA, 2020). Deploying heat networks in the UK would mean a significant reduction in emissions.

Gasification and AD technologies can be delivered at small scale, which is challenging for incineration technology. Small scale gasification plants of 5-20 MWe could be deploy, for example, at town level, as suggested by the Energy Technologies Institute (ETI) (Evans, 2017; ERA, 2020). The deployment of Decentralised Gasification and Decentralised AD pathways offers greater opportunities for the development and deployment of heat networks in the UK. Being small scale plants, they will be closer to community areas, and it will be easier to deploy district heating networks. Moreover, if at some point electricity from EfW were to be constrained – it is expected average carbon intensity of the power grid to diminish over time –, these small scale plants could operate for heat-only, which is a common practice in the Nordic countries (ERA, 2020; Cross *et al.*, 2021). This would enable to continue processing waste and recover energy from it. Electricity could then be produced with other lower-carbon energy technologies. As the feedstock use in gasification and AD requires of pre-processing, the pathways themselves will lead to higher recycling rates and more sustainable waste management systems, as already discussed in Section 8.2.

Notwithstanding the above, the findings reveal that heat networks deployment is highly challenged, with only a small number already existing in the UK; there are high investment costs, and a high number of interested customers is required for it to be economically viable. Other concerns were related to negative perceptions people might have of them, due to previous poor experiences, and potential perceived risks of new infrastructure development. These were important barriers that strongly conditioned the performance of the pathways for heat decarbonisation, although they can be solved.

- The UK Government has launched over the last years a series of investment programmes aiming to reduce economic barriers and boost the deployment of heat networks in the UK. These are: the Heat Network Investment Project (HNIP), the Heat Networks Delivery Unit (HNDU) programme, and the Green Heat Network Fund (GHNF) (BEIS, 2017a; DEFRA, 2021b). The ERA (2020) report recommends that more should be invested. Currently only 2% of British domestic and non-domestic buildings are connected to district heating networks. However, according to the CCC, to decarbonise the heat sector by 2050, this percentage should be increased to 18% (BEIS, 2017a). Since participants identified investment as one of the main barriers, a conclusion from this research is the recommendation of further investment.

- There is a need to increase understanding, awareness, and knowledge among stakeholders. The findings reveal that two participants from the government perspective had a misunderstanding of the functioning of heat networks. This misunderstanding could also exist among other stakeholders who may also be engaged in energy decision-making and policy development. For instance, this misunderstanding could lead to decisions based on false indications and ultimately lead to the development of ill-defined energy policies. It is therefore important to ensure a clear understanding and awareness about the technologies under consideration. Education campaigns on how technology works should be delivered at all levels. This, in turn, should help to reduce perception of risk related to new infrastructure development, and should help change negative public perceptions based on previous poor experiences. All this in turn should increase social acceptance, and facilitate the availability of customers and the demand for technology.
- The Nottingham heat network connected to the EfW facility is a good example of how this infrastructure can work for decades. For example, in the future, if CCS cannot be deployed and electricity from incineration becomes a constraint, towns such as Nottingham with their incineration plant connected to a heat network will be able to work on heat-only.

There are several additional key conclusions largely associated with social concerns that must be considered for the sustainable development and deployment of any of these pathways.

Before any facility is deployed, stakeholder communication activities, and public perception studies should be carried out in the community where a plant is considered to be developed. This will help to anticipate potential social acceptability issues. Likewise, strong educational and awareness campaigns will be needed to change citizens' behaviour regarding waste management, and especially the segregation of food waste for use in AD pathways. Furthermore, educational campaigns are also essential around the functionality of technologies – both old and new technologies to reduce perceived risks – and to make people understand the role they play in energy supply and the low carbon economy.

Understanding the process of how waste is managed at local and national level, and the benefits from sending waste to an EfW plant could help to increase public acceptance of EfW facilities. Issues such as NIMBYsm, perceived risks of new infrastructure development or of explosions, and air quality impacts on human health could be minimised if people were well informed and educated about the functionality of technologies and the conversion processes.

There is a need to increase awareness and understanding among all stakeholders of new technologies arriving to the market, their benefits, and barriers as well as the new ways in which energy may be produced. The findings reveal that the statements of some participants are based on past needs, when waste was considered a nuisance. However, there is a need to look forward and shift towards what is currently needed to transition to a low carbon economy, make more efficient use of materials and reach net zero emissions by 2050. This change of mentality must reach everyone.

Stakeholders, including the public, will need to make low carbon choices, both in terms of behavioural changes (e.g. segregation of food waste by the public, separate collection services of food waste and recyclables by Local Authorities) and by adopting low-carbon technologies (e.g. heat networks, the deployment of hydrogen to replace natural gas heating, or the selection of gasification – which is a new technology – instead of incineration – which is an old technology –). Some of the challenging decisions will only be possible if stakeholders are engaged in a coordinated and sustained societal effort to reach net zero emissions, understanding the choices, opportunities, and barriers.

8.4 What have been the contributions of using the Multicriteria Mapping (MCM) approach to explore stakeholder participants' perspectives on the sustainability of different EfW pathways?

The use of the Multicriteria Mapping (MCM) approach has allowed the systematic exploration of different perspectives towards the sustainable development of different EfW pathways in the UK.

As a method, the MCM has leveraged the strengths of both qualitative and quantitative approaches to document perspectives and value-judgements of leading stakeholders involved in the EfW sector in the UK. The MCM approach supported the identification of technological, economic, environmental, social and political uncertainties, divergent values, and social priorities that shape the competing expectations of the sector and lead to differing conclusions about sustainability, opportunities and barriers of the waste management, EfW technologies, and energy outputs in the UK.

The implementation of the MCM has thus supported data collection within a single study on the different technological, economic, environment, social, and political opportunities, and barriers that in the literature are reported on independently from different studies. This is an important contribution to knowledge since, to date no previous studies have appraised the relative sustainability of different EfW pathways in the UK. The few studies that attempt to provide sustainability appraisals of different EfW pathways have done so by assessing the environmental sustainability of the pathways and/or the economic sustainability of the pathways; however, the social and political analysis in such studies is lacking (Slorach *et al.*, 2019, 2020). The closest study to a sustainability analysis of EfW pathways incorporating an economic assessment with an environmental assessment and including some social aspects is by Ng *et al.* (2019). However, there is no single study that engages different stakeholder perspectives for assessing the relative sustainability of different EfW pathways.

The ways in which participants are able to open-up the framing/scope of EfW appraisal through their unconstrained problem definitions, pathways, criteria, and weightings with the MCM, allowed issues to be raise and debated, which would not have been possible to explore with other narrower approaches. This is a positive benefit of the MCM methodology.

The ability to elicit quantitative and qualitative data simultaneously, while making relative comparisons between pathways according to their optimistic and pessimistic performances, not only allows discussion of opportunities and barriers, but also identifies interactions between different dimensions of sustainability – techno-economic, environmental and social –. This has enabled the complexity of the EfW sector debate to be explored and presented in a transparent manner, as seen in Chapters 4, 5, 6 and 7; which, in turn, has provided in depth understanding of the perspectives and motivations behind the arguments put forward by the different participants.

Some participants stated that the ability provided by the MCM process to debate the 'quality' of the issues raised by the different pathways was of great value, since the quantitative data on its own would not reflect the complexity of the subject. They argued that there were many variables that could influence the performance of a pathway, and a single number would not reflect that variability and the reasons behind it. Likewise, the findings suggest that some of the arguments brought forward by participants were based on assumptions rather than evidence, which can be identified from expressions such as "I guess" or "probably", which are gathered through the qualitative data.

The MCM also highlighted linguistic nuances around commonly used terms, which depending on the participant using the term might be addressing different concerns. Different ideas existing among participants regarding the term "efficiency" (discussed in Chapter 5, Section 5.2) can be highlighted here. Some participants evaluated the efficiency of pathways as a function of the number of waste sorting and processing layers required in each of them. While others evaluated it on the basis of the amount of energy per waste stream and feedstock efficiency as well as conversion efficiency of the different technologies and pathways. This emphasises the complexity of language and terminology. Depending on the participant background, context, or discipline of work, they may use and understand a term differently. The MCM shows how conversation is not only important when it comes to understanding quantitative data, but also to understanding in greater depth the arguments and messages a person is transmitting, which based on a single technical word, may be mis-, or poorly understood. Consequently, it is important that the meaning of specific terms used by stakeholders of the EfW sector from different disciplines and/or backgrounds are known and understood. This will facilitate dialogue between stakeholders, which will be useful when negotiating, making decisions, and setting energy policies. The previously suggested arenas of communication for exchanging knowledge and understanding, and sharing interests and concerns among stakeholders (including the public) may help to solve these linguistic barriers.

The MCM also helps to identify how participants' perspectives are built upon contextual interests, knowledge, and values. This information helps to understand in further detail participants´ perspectives. For example, participant G5, representing a Local Authority, has the responsibility of managing waste for a city. As has been repeatedly discussed in Chapters 5, 6 and 7, participant G5´s perspective is that BAU does the work that needs to be done. For instance, participant G5´s interest in a new technology, such as gasification, that may have reliability problems for treating local waste on time, is compromised. Participant G5 would prefer to rely on what is already known to work rather than take a risk with a new technology. Likewise, participant I1, belongs to an international company focused on large-scale plants; his perspective on overall performance of pathways reflects a preference for centralised pathways over decentralised pathways (see *Appendix 2.2 Figure 2.2.7*). Participants I1´s perspective may be conditioned by his context of work. Furthermore, participant CS1, represents an NGO opposed to any thermochemical conversion processes. The chart reflecting overall performance of pathways from participant CS1´s perspective (see *Appendix 2.2 Figure 2.2.14*) shows clear reluctance for the four thermochemical pathways and strong optimism for the two biochemical conversion pathways.

In conclusion, the implementation of the MCM approach has allowed to:

- Assess and understand the perspectives of different stakeholders involved in the EfW sector in the UK.
- Bring to light the different interests, values and priorities of the stakeholder participants involved in the sector.
- Identify what issues and uncertainties exist within the sustainable development of the different EfW pathways and that consequently require further debate, support, and/or analysis.
- Evaluate synergies between the waste management and EfW sectors in the UK.
- Identify opportunities and barriers to sustainable waste management, the development and deployment of EfW technologies and the production of EfW in the UK.
- Assess and interpret participants' expectations of the role that different Energy and Fuels from Waste pathways can play in the transition to a low carbon economy towards net zero target, as well as in the development of more sustainable waste management systems.

This thesis has shown that there is clear potential in the use of the MCM approach to explore and map stakeholders' perspectives, uncertainties, and issues around the development of sustainable future energy pathways. While this thesis has focused on the appraisal of EfW pathways, the MCM approach (as previously proved and concluded by McDowall and Eames, 2006) could be effectively implemented for exploring other energy contexts.

8.5 Limitations and Future Research

Due to the necessarily tight focus of a thesis and constraints imposed by available time and resources, this research has some limitations. One main limitation stems from the lack of time and the large amount of data produced by the MCM approach: that is the scale of the research.

The research involved interviewing 15 stakeholders from the EfW sector in the UK. Although the research was not intended to involve a statistically representative sample of stakeholders, but rather to undertake an exploratory mapping of the issues and themes under deliberation in the EfW sector in the UK; a greater sample size would have brought together a greater diversity of perspectives. Potentially with this, a greater number of issues and themes would have also emerged among the different sustainability dimensions.

Having said that, it must be noted that this research has been conducted by a single researcher and that the amount of data that is generated in an MCM interview is vast and to some extent unwieldly. The results that are presented in this thesis do not represent the full extent and depth of the analysis carried out. The possibility of increasing the sample of participants and the data captured would have been an enormous challenge for one single researcher, in terms of both the amount of data and time.

Likewise, this research did not interview lay people. The 15 stakeholders participating in this research are in some way engaged in the EfW field. Therefore, they had a certain level of knowledge about the technologies and pathways characteristics under consideration, as well as some knowledge about the most common concerns among citizens. This enabled some participants to identify concerns associated with public opposition and to provide potential reasons behind those concerns. However, it would have been interesting to receive this information first-hand by carrying out some focus groups with citizens to capture public perceptions and bring to light the different issues and concerns that citizens encounter in their appraisal of these EfW pathways. Taking into account that public opposition is an important barrier to the development and deployment of energy technologies, it would have been interesting to undertake field work research in communities/towns, where these different technologies are in place or proposed. For instance, a focus group with citizens from the town of Wednesbury, where Kew Technology Ltd. has the gasification plant, could have been a place to assess public perceptions to gasification technology. Lack of time as well as budget constraints undermined the possibility of undertaking a focus group with citizens.

Focus groups in different geographical locations with these types of EfW facilities in place, or under consideration, should be carried out in future research. It could be interesting to carry out an investigation similar to that of Upreti (2004) which analyses the public perception of different energy technologies from biomass in different locations. This will allow deeper understanding of community issues towards the development of these EfW projects. The more information there is on the UK public perception of the different EfW technologies and projects, the easier it will be to get ahead of potential conflicts that could arise when launching a project. Of course, the investigation of public perceptions in different geographical locations must go beyond the narrow questions of technology and its acceptance. The social benefits, the energy preferences of the community, as well as the way in which they want society to develop and more specifically their local area, may be all important. This will enable EfW companies to have a clearer knowledge on how to proceed in communication and dialogue with the communities.

Perhaps less of a limitation and more of a reflection point is the framing of the six different pathways adopted in this research. The six pathways under appraisal are directed towards the production of EfW through three different EfW technologies. Since the main research question of this thesis was to answer and evaluate '*How can energy and fuels from waste (EfW) technologies (Incineration, Gasification and Anaerobic Digestion) be integrated and contribute towards sustainable waste management and energy systems in the UK?*', the frame of appraisal of these six EfW pathways is fully justified. The frame has certainly worked well and has provided a rich map of opportunities and barriers, driving and undermining, respectively, towards the development of the EfW sector in the UK, in sustainable integration with the waste management sector. Nevertheless, given the strong interrelation of the EfW sector to the waste management sector, the sole appraisal of pathways fully dedicated to the production of EfW could in itself be seen as narrowing the frame of the debate, rather than opening it up. A possibility to further open-up the debate towards the waste management sector might be to include few "core pathways" fully dedicated to the waste management sector, without any energy and fuels recovery element. This could include some pathways addressing specific waste management systems that lead to a maximum reduction of waste generation and increase in recycling, or even the inclusion of a utopian pathway where waste is fully eliminated. The latter is a pathway completely opposed to the generation of EfW that could be interesting to appraise together with the other pathways to explore both individual and overall perceptions among stakeholders. The inclusion of pathways as contrasting as these would certainly open-up the debate further, and may bring to light new discussions, issues, and themes related to how to manage waste, manufacture products, or change social behaviours to reach those utopians states. As one of the key features of the MCM is the possibility of making relative comparisons between pathways, the comparison between utopian waste management pathways with EfW pathways may bring to light new issues and interrelationships otherwise missed.

The appraisal of the six EfW pathways in itself, however, led one participant to open-up the frame by including additional pathways for appraisal. This was participant CS1, who included two additional pathways for appraisal. These were: Add3. Zero Waste and Add.4 Incineration Exit strategy (See *Appendix 2.1* for further information). These two additional pathways are aligned more towards the waste management sector rather than the EfW sector. Since these were "additional pathways", they were not appraised by the rest of the participants. There is, therefore, no aggregated general overview of these two pathways.

The overall environmental impact of each of the six pathways, with the implementation of Life Cycle Assessments (LCA) should be explored in future research. This will help to further clarify the sustainability of each of the pathways in terms of environmental impacts and, enable the role that each of the pathways can have in the transition to a low carbon economy towards meeting net zero target to be stated more accurately. Participants discussing the environmental impacts of the pathways in terms of GHG emissions identified multiple variables influencing pathway performance. Each of these variables made the pathway perform better or worse in terms of GHG emissions. On multiple occasions, the variables identified were used by participants as counter factors to another variable. Many of these impacts vary according to the scale of development, as well as the combination of variables and technologies considered for a pathway. It would be interesting to undertake environmental impact assessments for each of the variables identified by participants, combine them for the different pathways where they were taken into consideration and obtain an overall LCA for each of the pathways, once all parameters had been considered.

Future research should continue to promote and open-up the debate among stakeholders (including the public) around the EfW sector. As suggested earlier, this could be pursued by interviewing more stakeholders from different disciplines and organisations, or by undertaking focus groups with both experts from the EfW field and citizens from different geographical locations of the UK. The scale of the project could be opened-up to an international level. Given the repeated references made in the literature to the Nordic countries and their efficient way of producing and using heat from EfW facilities (ERA, 2020;

Cross *et al.*, 2021), it would be interesting to capture the benefits and advantages that the Nordic countries identify for each of the EfW pathways. A larger-scale study should be complemented by a larger team of researchers. Another advantage of MCM is that several researchers can collaborate on the same project (Coburn and Stirling, 2016). The scope of the research could also be extended to include further pathways for appraisal.

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Appendices

Appendix 1. Research Design and Methods

Appendix 1.1 Expert Booklet

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20th March 2019

Dear participant,

Thank you for agreeing to participate. We believe this study is very important and we appreciate your willingness to help us tackle the question: ***How can energy and fuels from waste (EfW) technologies (incineration, gasification, anaerobic digestion) be integrated and contribute towards sustainable waste management and energy systems?*** This will involve multicriteria sustainability appraisal of potential future Energy and Fuels from Waste pathways for the UK. In this interview brief we provide a short overview of the process and define the pathways to be appraised.

You are one of a number of experts and stakeholders participating in a transparent, participatory, multicriteria pathway appraisal process, called Multicriteria Mapping. Experts and stakeholders will independently participate in a face to face interview to conduct an initial multicriteria appraisal of pathways for tackling sustainable Energy and Fuels from Waste futures. If you agree, you may be contacted again some weeks later to elicit any changes in your initial appraisal results.

The Multicriteria Mapping interviews will be conducted with a dedicated software program called Multicriteria Mapper, provided by the researcher. Using this program, the researcher will guide you through the multicriteria pathway appraisal process, which you will be asked to complete in a personal capacity:

1. Identify pathways for appraisal.
2. Obtain criteria by which those pathways will be appraised. You, as participant, will be providing a set of criteria.
3. Appraise the performance of the pathways against those criteria.
4. Review the outputs.

A comprehensive review of the literature has established 6 ‘core’ pathways for responding to potential future pathways of the Energy and Fuels from Waste sector in the UK. These will be appraised by all participants (see next pages). You are also free to identify and appraise additional self-defined pathway, be they pathway combinations or pathways not already included.

You will then be asked to develop a common set of criteria by which to appraise the pathways relative to one another. The relative ‘best case’ and ‘worst case’ performances of each pathway under each criterion should then be given score on a scale of 0 to 10, where high scores are always better than low scores. This will produce a visual output of the different pathways´ performances, where each criterion can then be given ‘weight’ according to their relative importance.

Your Multicriteria Mapping interview will produce both quantitative and qualitative results: quantitative scores of pathway performance and a qualitative audio transcript of the reasoning underpinning those scores. These data will be analysed alongside those of the other experts and stakeholder participants, producing an overall dataset that seeks to provide a comprehensive snapshot of the divergent perspectives that bear upon decision making process on Energy and Fuels from Waste. You will receive a copy of the project report if you wish.

Thank you again for your participation. I look forward to meeting with you. In the meantime, if you have any questions about the interviews process, please do not hesitate in contacting me.

Kind regards,

Lola Vazquez Peraita
Research Engineer
E: Lola.VazquezPeraita@nottingham.ac.uk

Industrial support provided by the ETI until 31st December 2019, Kew Projects Ltd & BeaconTech Ltd.

CORE PATHWAYS TO BE APPRAISED BY ALL PARTICIPANTS

Pathway 1: Business as Usual. Centralised Incineration EfW Pathway.

Recycling rates on waste streams improve slowly towards the legally binding targets set out in the EU Directives (recycling 50% of municipal waste by 2020, 55 % to be achieved by 2025, 60 % by 2030 and 65% by 2035; recycling 75% of packaging waste by 2030; and reduce landfill to maximum of 10% of municipal waste by 2030). Waste exports continue to be the primary management strategy for recycled waste streams. Waste disposal rather than waste valorisation remains the priority, due both to the large amount of waste generated and modest recycling rates. This drives strong investment in ongoing deployment of incineration plants; an established technology.

Gasification technology remains a niche technology, which struggles to come to commercial scale deployment due to weak support from government, few financial incentives for new demonstration plants, poor performance of existing demonstration plants, absence of technology-specific policy and lagging market developments.

The UK Energy from Waste sector is focused on conventional incineration technologies for the production of electricity (Figure 1). This electricity is supplied to the domestic and non-domestic sectors. Limited recovered heat is used for industrial facilities closely located to the plant. The heat that could be supplied to the domestic sector via heat network deployment is not a widely available option: heat network deployment over large distances from energy recovery facilities to houses and city services involves high investment costs as well as important efforts changing on planning and design. Therefore, heat for industrial, commercial and domestic use continues to be supplied by the national gas grid, and possibly in the future more electrical heating (for example through heat pumps).

If demand for power and heat remains much as it is today, this future would contribute 2% and 0.25% of UK power and heat respectively.

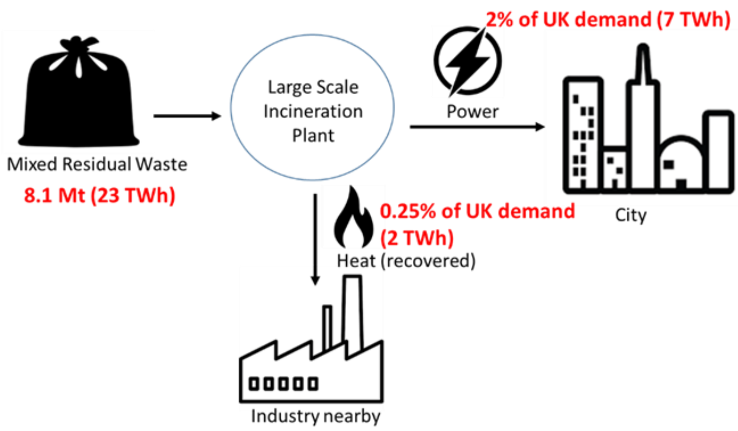

Figure 1. Centralised Incineration EfW Pathway

Pathway 2: Centralised Gasification EfW Pathway. Displacement of Incineration.

There is a significant change in perceptions and attitudes towards the management, added value and efficient use of national and local waste streams. Accordingly, the EU waste management targets are met and waste exports are drastically minimised.

Under this pathway, waste valorisation in terms of energy content and efficiency, end-products generation, flexibility and adaptability to contextual needs, becomes the priority, rather than waste disposal. This drives strong and rapid investments in gasification for the production of electricity, chemicals and liquid biofuels. The high calorific value waste streams are sorted and processed individually in gasifiers to maximise the product outputs.

Large and medium-scale gasification plants located outside cities, displace large incinerator plants, producing electricity as well as higher value liquid biofuels for the road, air and marine transport sectors and chemicals of high commercial importance including plastics precursors, cosmetics, agricultural chemicals, paints and adhesives (Figure 2).

Gasification contributes to the production of electricity for domestic and commercial services. Heat for industrial, commercial and domestic use is supplied by the natural gas grid. If demand for power and liquid fuel for transport remains much as it is today, this future would contribute 2% and 1% of UK power and liquid fuel for transport respectively. The contribution on the transport sector becomes more significant if focused on heavy good vehicles or jet fuels.

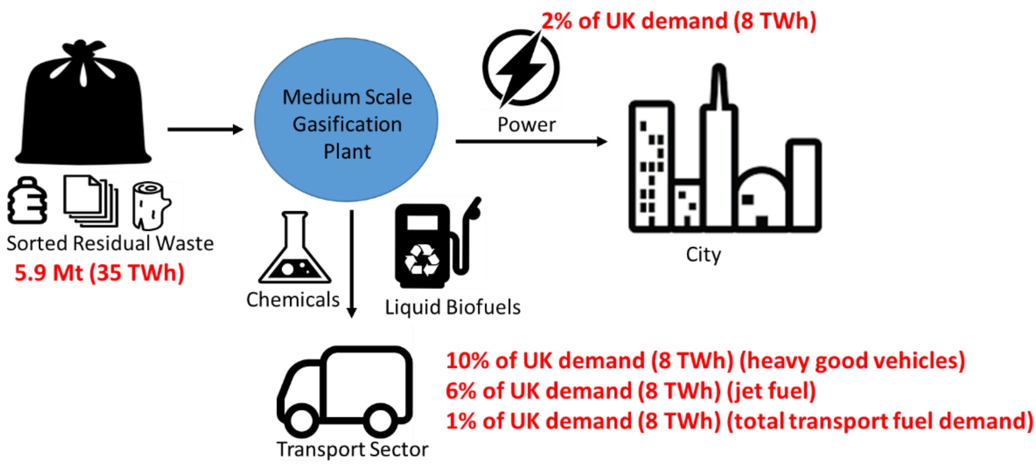

Figure 2. Centralised Gasification EfW Pathway. Displacement of Incineration

Pathway 3: Decentralised Gasification EfW Pathway. Decarbonisation of the heat sector.

Similar to Pathway 2 in terms of waste management, the EU waste management targets are met; waste exports are minimised, local waste is managed and recovered locally. Waste valorisation is the priority.

The decarbonisation of the heat network is seen as a high priority by the UK Government. Local heat networks enable the use of local renewable energy sources at a larger scale. Fuels and heat generated at Energy from Waste facilities are a key element contributing to this decarbonisation goal. This drives strong and rapid investment in small-scale urban gasification plants, which allow the adaptability of scale to local planning needs, embedding them within cities.

The clean syngas produced from the gasification is combusted on-site to generate heat and electricity. The heat is used locally in an integrated district heating network. This entails the construction of district heating infrastructure to make use of the heat recovered. As an alternative, the clean syngas can be upgraded to synthetic natural gas and/or hydrogen for its use as a natural gas renewable equivalent, injected and stored into the gas grid (Figure 3).

Small-scale gasification plants provide electricity and heat to domestic and non-domestic services such as universities and colleges, leisure, arts and community sectors; contributing to meeting the energy demand in the local areas.

If demand for power and heat remains much as it is today, this future would contribute 3.4% and 1.5% of UK power and heat, respectively. Alternatively, 2.5% of heat demand.

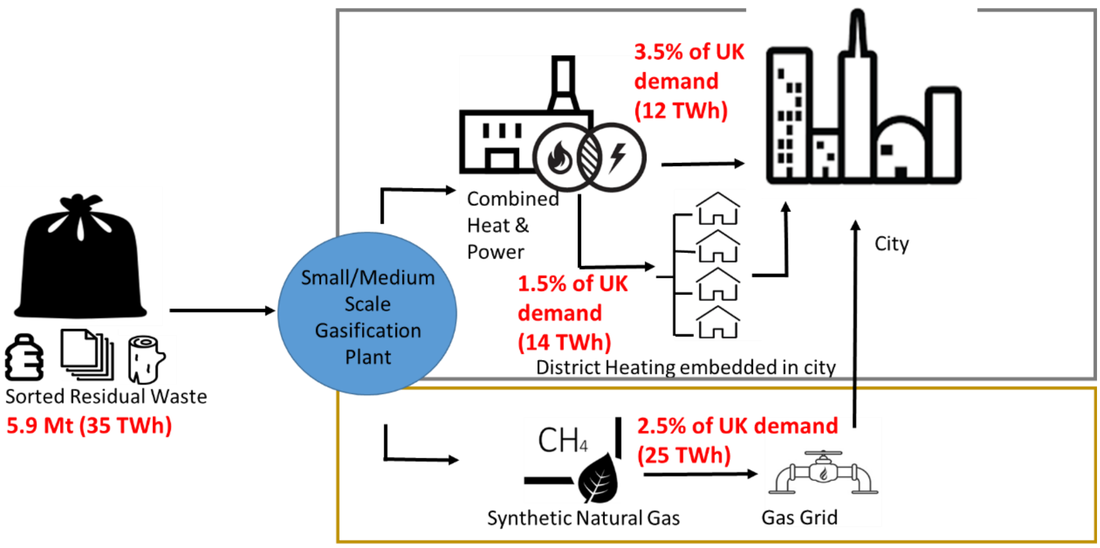

Figure 3. Decentralised Gasification EfW Pathway. Decarbonisation of the heat sector

Pathway 4: Decentralised Gasification EfW Pathway. Decarbonisation of the transport sector.

Similar trade-offs to Pathways 2 and 3 in terms of waste management are followed in this pathway. The EU waste management targets are met; waste exports are minimised, local waste is managed and recovered locally. Waste valorisation is the priority.

Gasification is exploited as a technology for the production of transportation fuels and/or higher value chemical products from waste. Liquid transportation fuels derived from waste are used within the road, aviation and marine transportation sectors. Deploying medium-scale gasification plants embedded within cities enables the recovery and use of the waste heat in district heating networks (Figure 4), while also reducing potential transport constraints that would be associated with larger scale facilities.

Large waste incineration plants located on the fringes of cities, with limited heat recovery, contribute to the supply through the generation of both electricity for domestic and non-domestic areas and heat supplied only to buildings near the plants.

Heat and power for industrial, commercial and domestic use continues to be supplied by electricity and the natural gas grid.

If demand for heat and transport liquid fuels remains much as it is today, this future would contribute 1.5% and 2.5% of UK heat and liquid fuel transport respectively. The contribution on the transport sector becomes more significant if focused on heavy good vehicles or jet fuels.

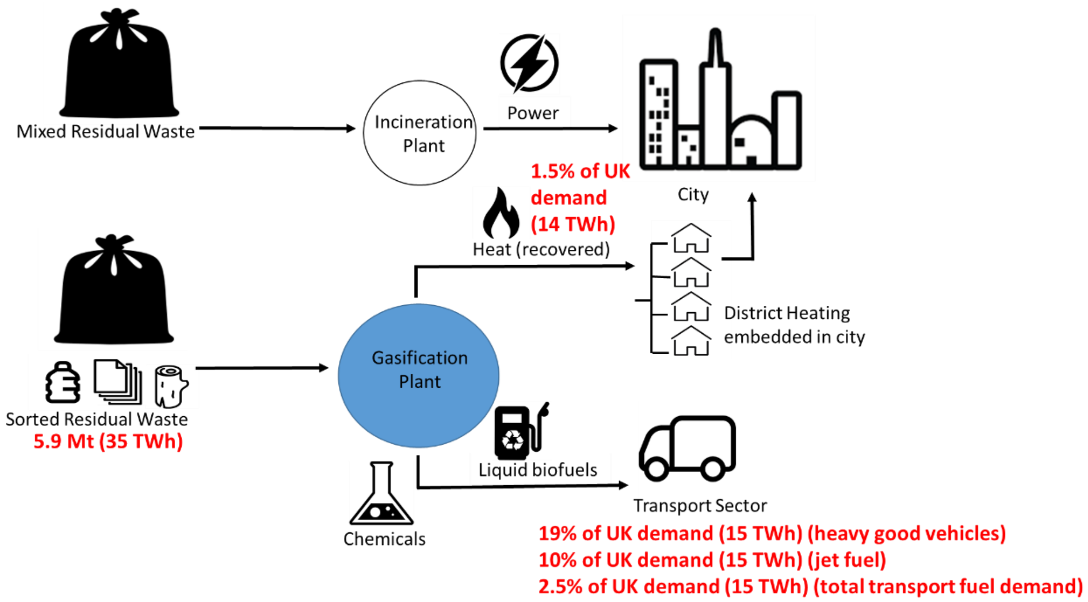

Figure 4. Decentralised Gasification EfW Pathway. Decarbonisation of the transport sector

<u>Pathway 5. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the heat sector.</u>

The segregation and collection of waste food in separate bins becomes mandatory at a household level. Food waste is no longer going to landfill or incineration plants. Food waste is used as feedstock in anaerobic digestion (AD) plants for the production of biogas.

The biogas produced is used locally for the generation of electricity and/or heat for the domestic and non-domestic sector. With an integrated district heating network, the biogas is burned in a combined heat and power (CHP) process, producing electricity and heat which is then exported to the national grid. This entails constructing district heating infrastructure to make use of that heat. Alternatively, the biogas can be upgraded to bio-methane for its use as a natural gas renewable equivalent, injected and stored into the gas grid (Figure 5).

Heat, electricity and bio-methane from AD plants, embedded within cities, contribute to meeting energy demand in the local area, leading to less dependency on fossil fuels for energy generation.

The digestate produced from the AD process is used as compost and beds as a soil conditioner.

Heat and electricity from AD contributes to meeting energy demand in the local area, leading to less dependency on fossil fuels for energy generation.

If demand for power and heat remains much as it is today, this future would contribute 0.8% and 0.4% of UK power and heat respectively. Alternatively, 0.7% of heat demand.

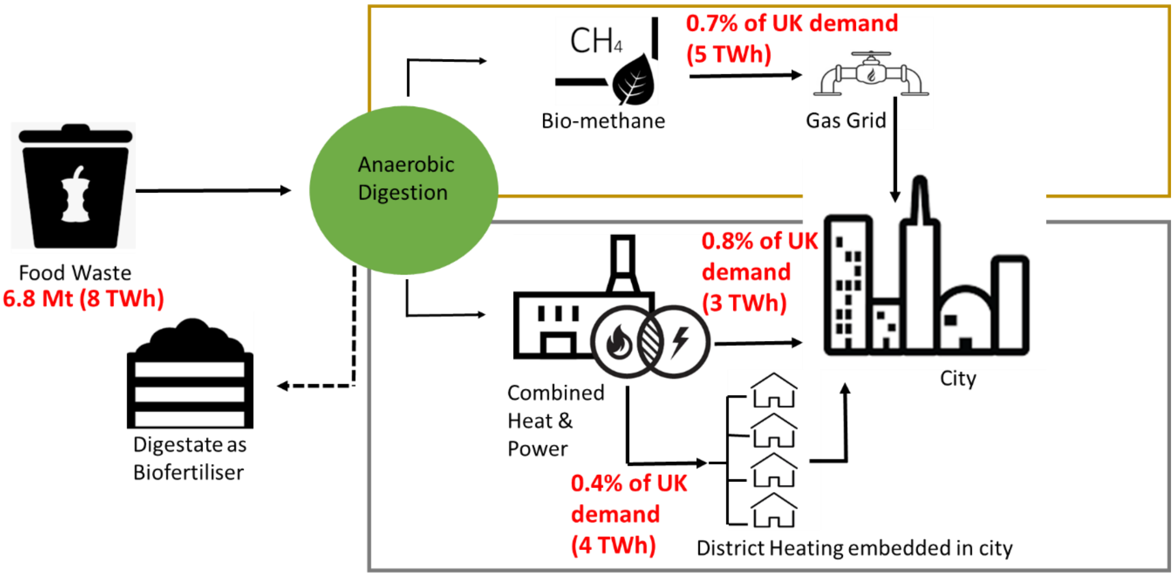

Figure 5. Decentralised Anaerobic Digestion Pathway for Segregated Food Waste. Decarbonisation of the heat sector

Pathway 6. Decentralised Anaerobic Digestion Pathway. Decarbonisation of the transport sector.

As in Pathway 5, food waste is segregated at household level and used as feedstock in anaerobic digestion (AD) plants for the production of biogas. Food waste is no longer going in to landfill or incineration plants. The deployment of AD around urban areas is dedicated to the decarbonisation of the transport sector.

The biogas obtained from the AD process is upgraded in to bio-methane for its use as transport biofuel (Figure 6). The deployment of AD around urban areas is dedicated to the decarbonisation of the transport sector.

Heat and power for industrial, commercial and domestic use continue to be supplied by electricity and the natural gas grid.

If demand for liquid fuels for transport remains much as it is today, this future would contribute 0.9 % of UK liquid transport fuel.

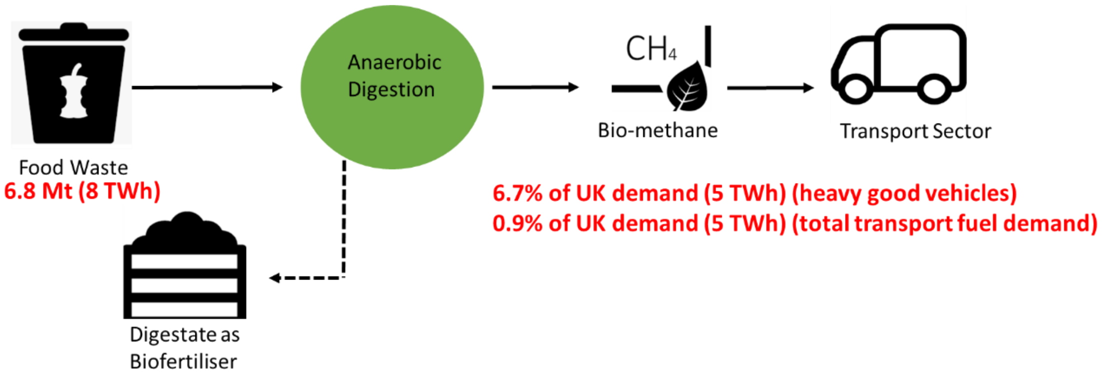

Figure 6. Decentralised Anaerobic Digestion Pathway for Segregated Food Waste. Decarbonisation of the transport sector

Appendix 1.2 Participant Consent Form

PARTICIPANT CONSENT FORM
Project title: Sustainability of Energy and Fuels from Waste pathways in the UK

Lola Vazquez Peraita
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School of Engineering and School of Sociology and Social Policy
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E: Lola.VazquezPeraita@nottingham.ac.uk

Please read the following carefully and mark an 'X' in each box:

I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason. ☐

I agree to the interview being audio recorded. ☐

I agree to the use of my position / organisation / anonymous quotes in publications arising from this study (delete as appropriate). ☐

I agree that my data gathered in this study may be stored in a secure data centre. ☐

I agree that my data gathered in this study may be used for future research. ☐

I agree to take part in the above study. ☐

------------------------------------- -------------------------- ------------------
----Name of Participant Date
Signature

------------------------------------- -------------------------- ------------------
----Name of Researcher Date
Signature

Appendix 2. Results

Appendix 2.1. Additional Pathways

Additional Pathway 1. Central Advanced Combustion. Identified by Participant I1. In Appendix 2.2 Figure 2.2.7 it appears as “Add1. Central Adv. Comb”.

> Description: ‘Large scale grate combustion gradually replaced by large and medium scale advanced fluidised bed combustion using RDF instead of residual MSW. Use of fluidised bed support knowhow and expertise with respect to developing advanced type 2 which in turn leads to type 3 which both systems require advanced control process and syngas cooling and cleaning systems. Good quality syngas only comes from fluidised beds.’ (I1)

Additional Pathway 2. Small Scale CHP Combustion. Identified by Participant A1. In Appendix 2.2. Figure 2.2.10 it appears as “Add2. Small Scale CHP Comb”.

> Description: ‘Electrical efficiency of 15%, heat efficiency of 70-75%.’ (A1)

Additional Pathway 3. Zero Waste. Identified by Participant CS1 in Appendix 2.2. Figure 2.2.14 it appears as “Add3. Zero Waste”

> Description: ‘Elimination of residual material. Stricter application of the waste hierarchy. Circular economy package. Incineration tax to internalized externalities.’ (CS1)

Additional Pathway 4. Incineration Exit Strategy. Identified by Participant CS1 in Appendix 2.2. Figure 2.2.14 it appears as “Add4. Inciner Exit Strat”

> Description: ‘Moratorium on new waste incineration capacity. Phased shut down of exciting facilities starting with oldest and least efficient. Identify areas of concentrated overcapacity where incineration is harming recycling. Tax incineration to internalize externalities.’ (CS1)

Appendix 2.2 Final Overview Performance of Pathways per Stakeholder Participant (G1-G6, I1-I3, A1-A4, CS1-CS2)

Figure 2.2.1 to 2.2.15 show the final overview of pathways performance per each Stakeholder Participant. On the vertical axis, the chart displays all the “core” pathways that were defined for use by all participants in the MCM process, as well as any “additional” pathway that were defined by this individual participant alone. Participants I1, A1 and CS1 defined “additional” pathways.

In order of appearance in the vertical axis, the core pathways are: Business as Usual, Centralised Gasification, “Decent AD HN” refers to Decentralised Anaerobic Digestion for the decarbonisation of the heat sector, “Decent AD TF” refers to Decentralised Anaerobic Digestion for the decarbonisation of the transport sector, “Decent Gasification HN” refers to Decentralised Gasification for the decarbonisation of the heat sector, “Decent Gasification TF” refers to Decentralised Gasification for the decarbonisation of the transport sector.

The additional pathways are: “Add1. Central Adv. Comb” identified by Participant I1 (see Figure 2.2.7 below), “Add2. Small Scale CHP Comb” identified by Participant A1 (see Figure 2.2.11 below), “Add3. Zero Waste” and “Add4. Inciner Exit Strat” identified by Participant CS1 (see Figure 2.2.14 below).

If a pathway was not appraised during the MCM process, there will be no data displayed for that pathway. An orange circle icon of warning appears in the chart on the right side of the pathway name. This is the case of Participants I3 and A4 for the two Anaerobic Digestion pathways (see Figure 2.2.9 and Figure 2.2.13, respectively).

On the horizontal axis, the chart displays an arbitrary scale from 0 to 100 expressing the ranks assessed for each pathway by the participant in question. Higher values indicate higher performance.

The orange bars in the chart indicate the ranks assessed for each pathway by the participant in question. The left-hand end of the bar indicates the rank assessed under the most pessimistic assumptions. The right-hand end of the bar indicates the rank assessed under the most optimistic assumptions. The length of the bar indicates the degree of uncertainty or variability associated with the ranking of each pathway (Coburn and Stirling, 2016).

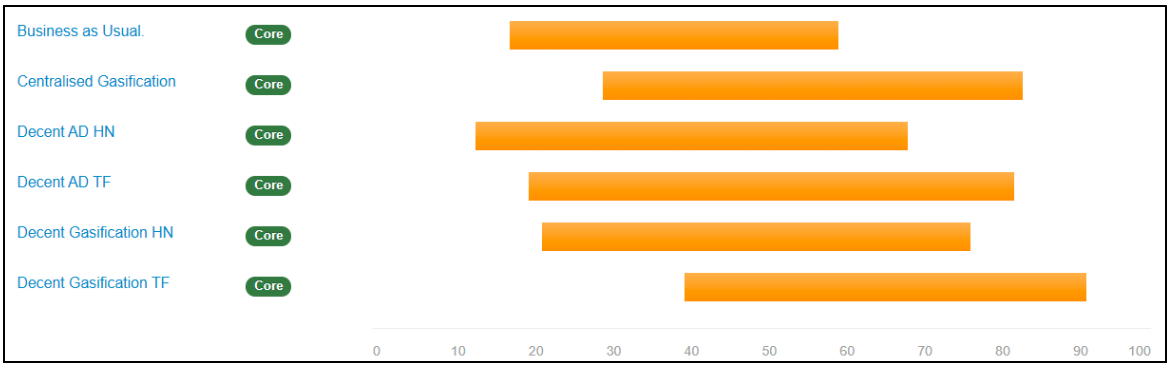

Figure 2.2.1. Participant G1: Overall Performance

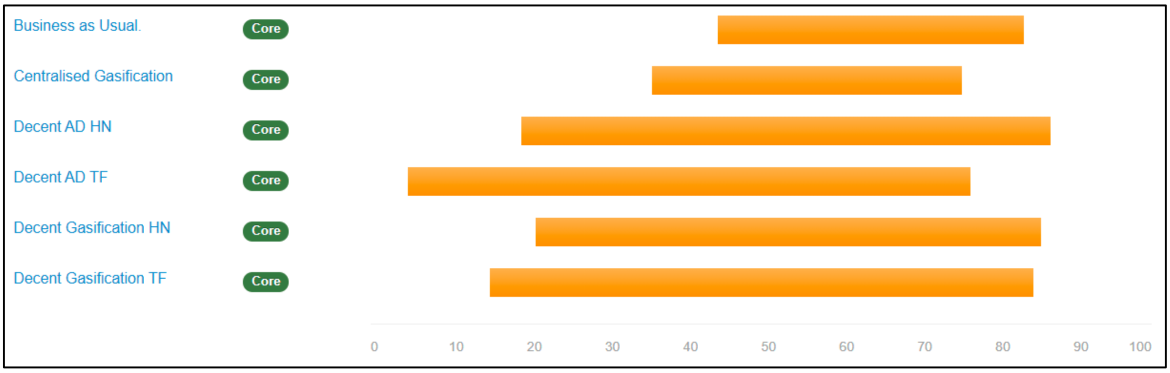

Figure 2.2.2. Participant G2: Overall Performance

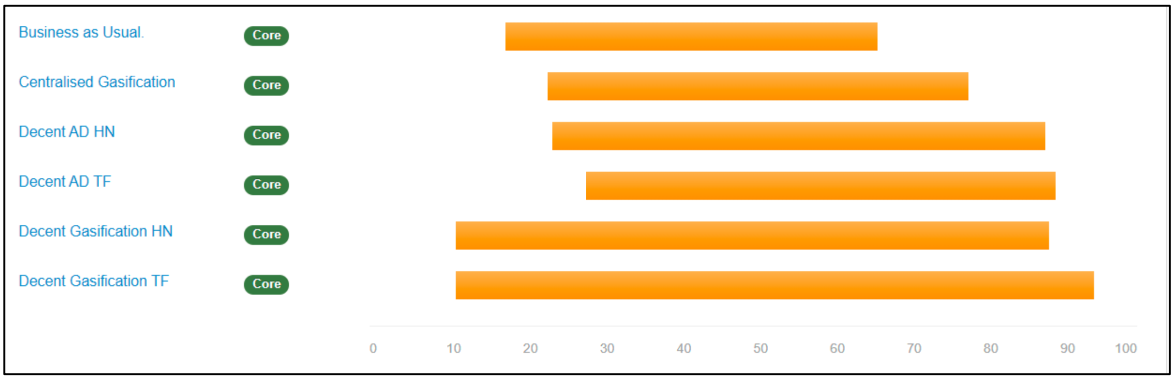

Figure 2.2.3. Participant G3: Overall Performance

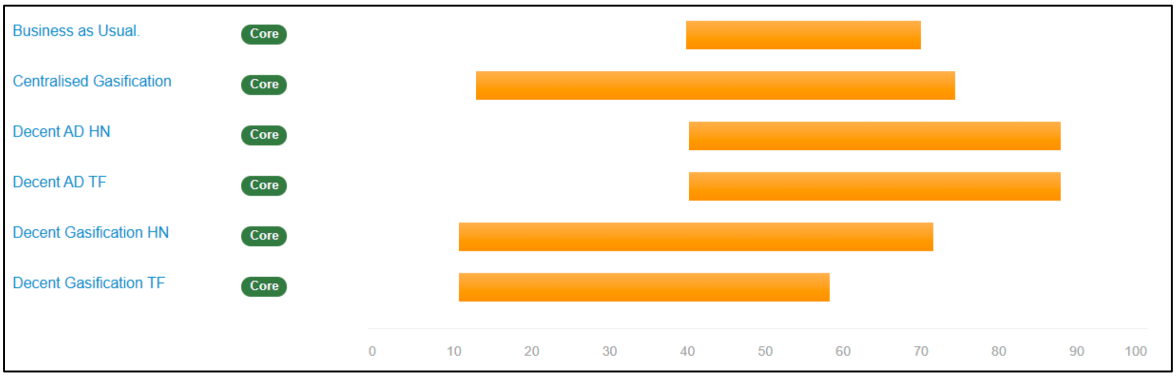

Figure 2.2.4. Participant G4: Overall Performance

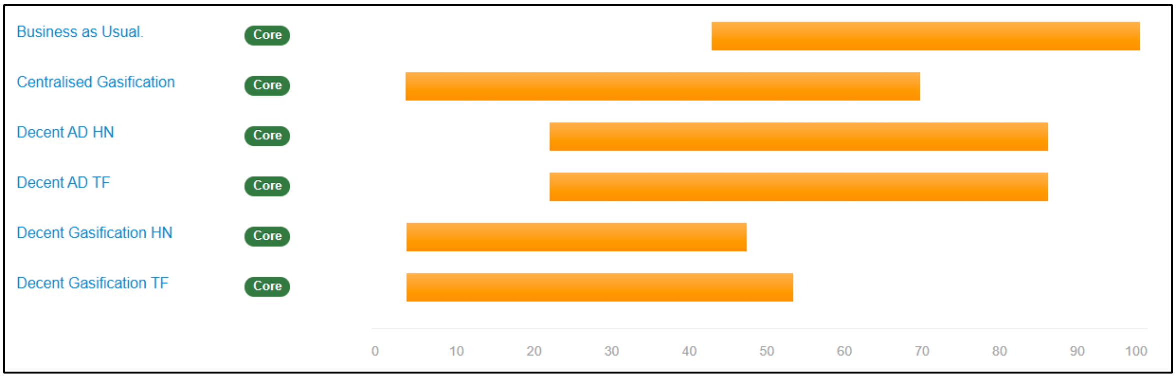

Figure 2.2.5. Participant G5: Overall Performance

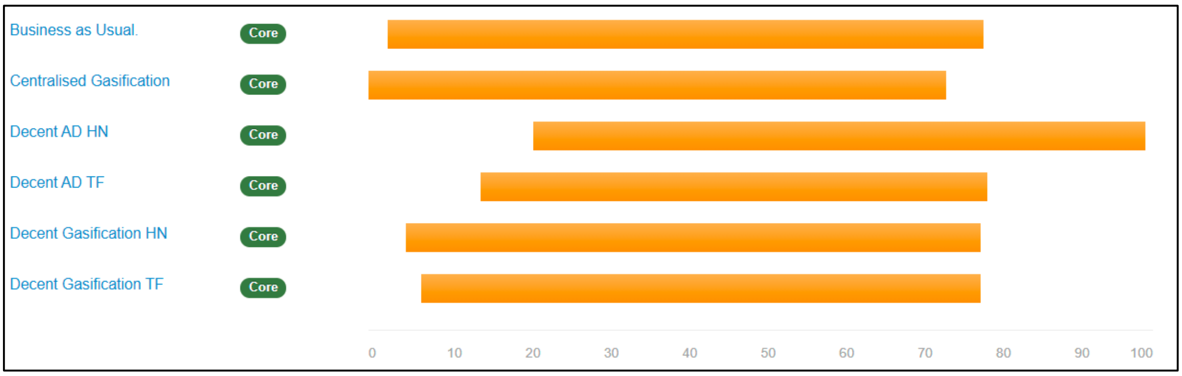

Figure 2.2.6. Participant G6: Overall Performance

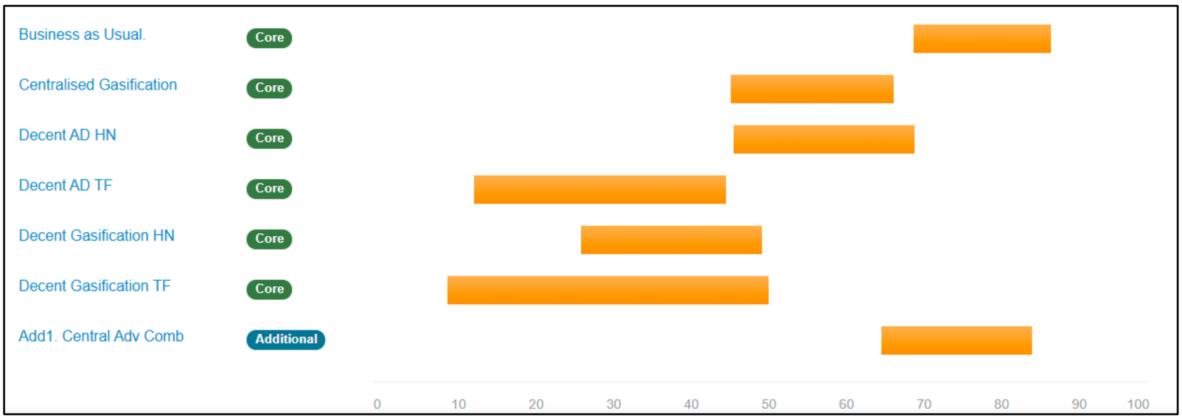

Figure 2.2.7. Participant I1: Overall Performance

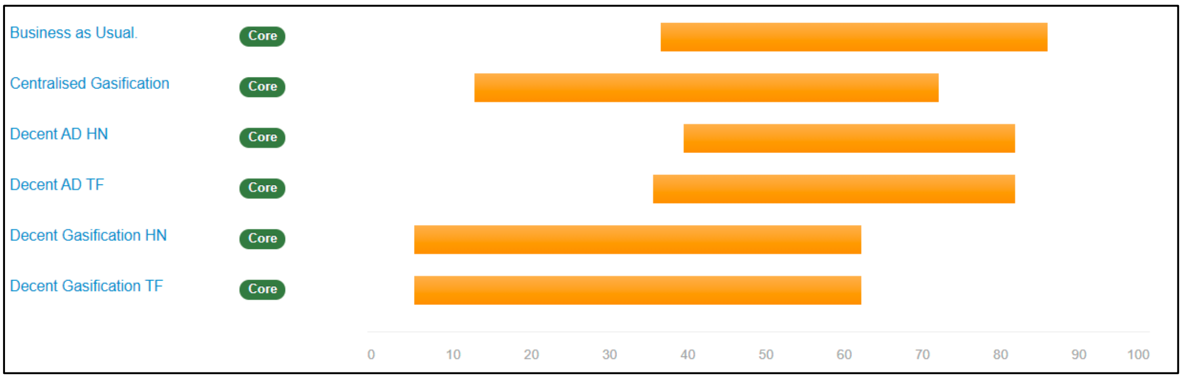

Figure 2.2.8. Participant I2: Overall Performance

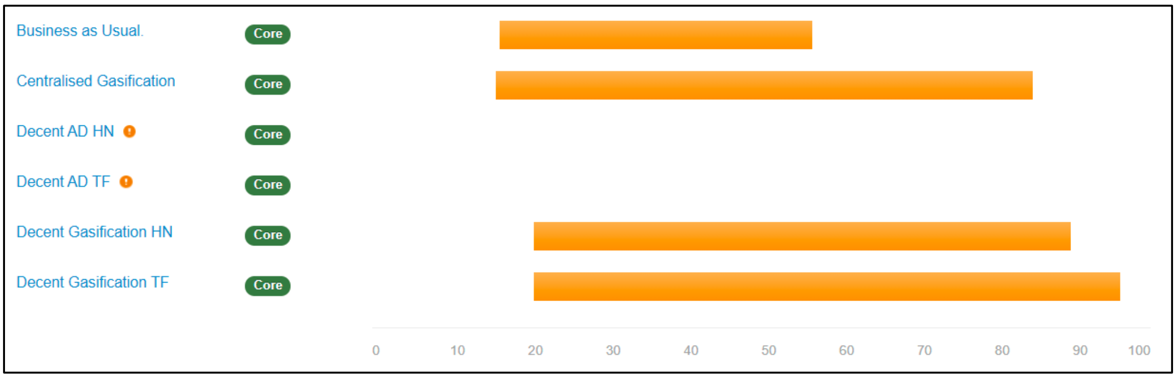

Figure 2.2.9. Participant I3: Overall Performance

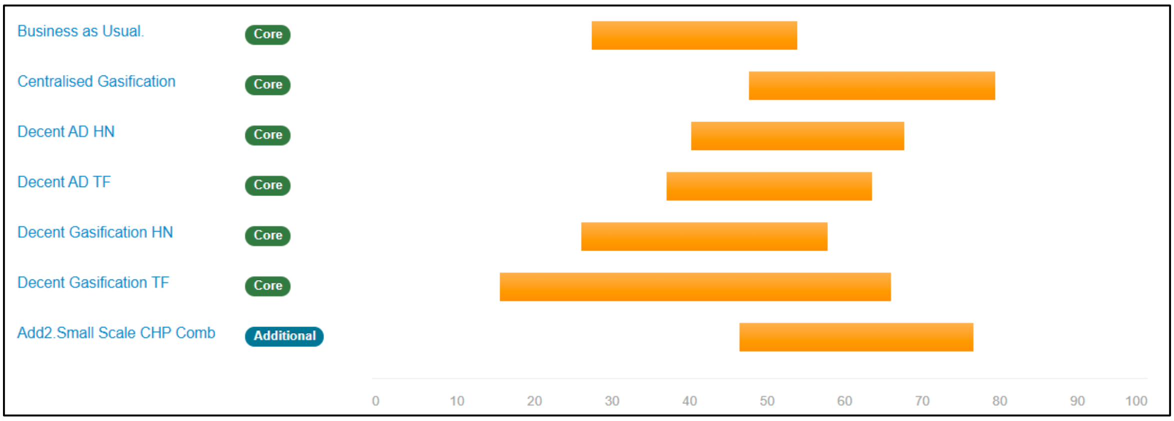

Figure 2.2.10. Participant A1: Overall Performance

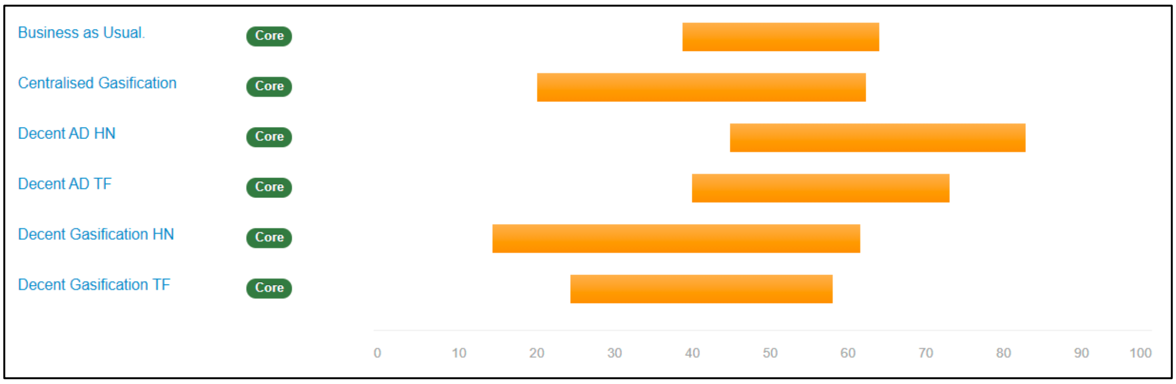

Figure 2.2.11. Participant A2: Overall Performance

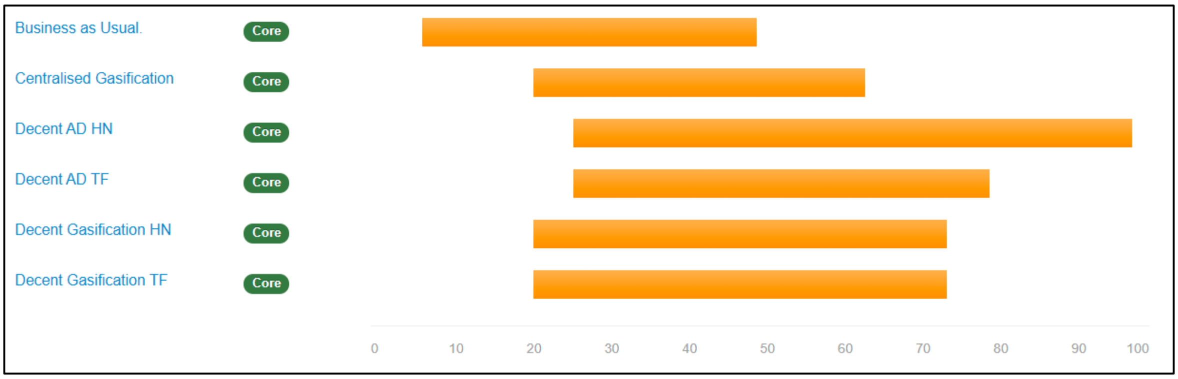

Figure 2.2.12. Participant A3: Overall Performance

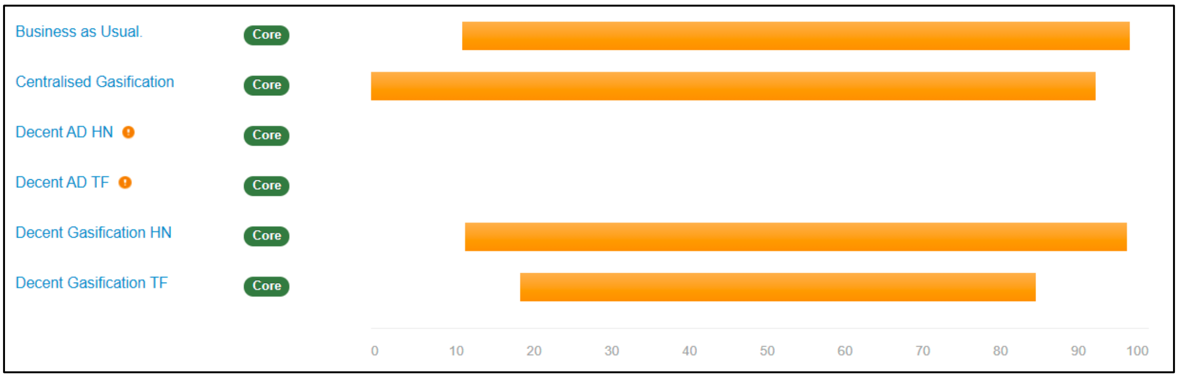

Figure 2.2.13. Participant A4: Overall Performance

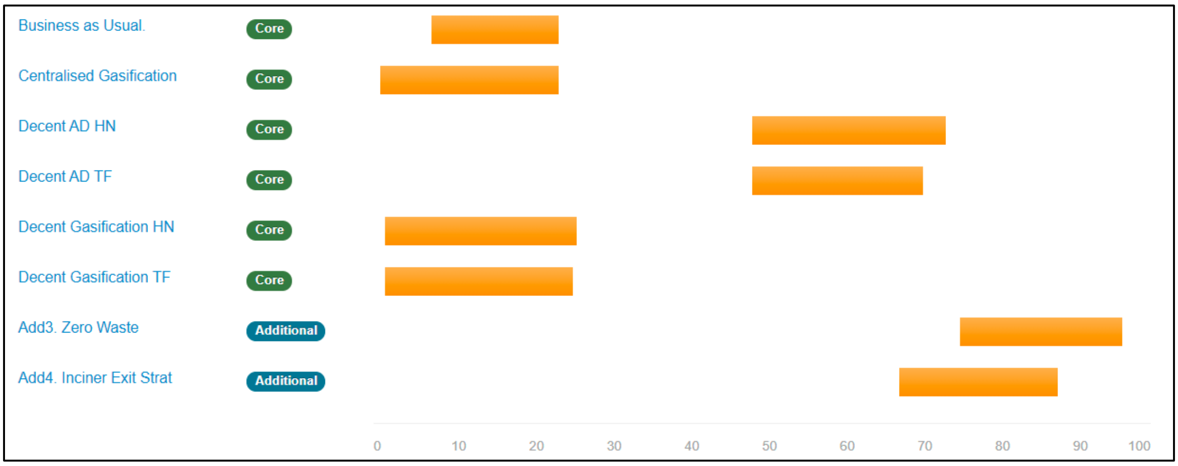

Figure 2.2.14. Participant CS1: Overall Performance

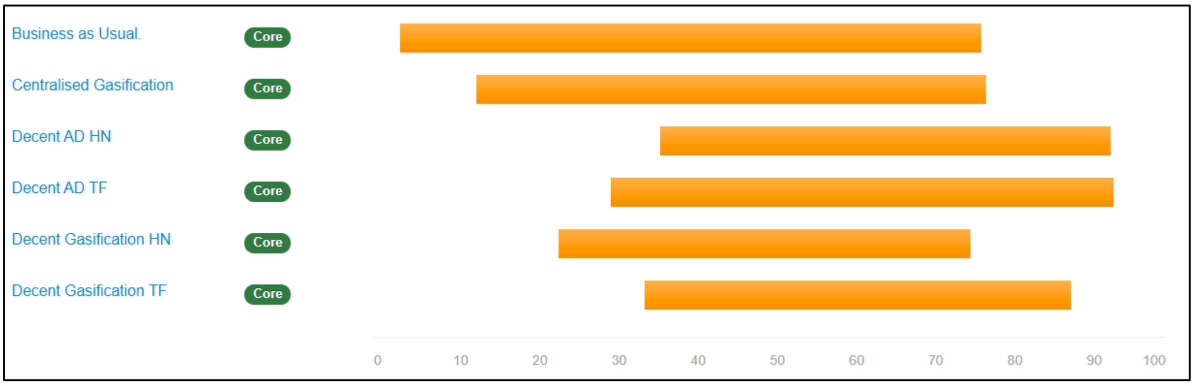

Figure 2.2.15. Participant CS2: Overall Performance

Appendix 2.3 Pathways performance by themes identified in each dimension

Figures 2.3.1 to 2.3.9 display the pathway performance by identified theme in each dimension. The charts of pathways performance for themes aggregate what it is called the pessimistic and optimistic sub-ranks for the selected perspectives and criteria included within the theme under analysis. The criteria were grouped per themes identified from the qualitative data (Chapter 5, 6 and 7). All participants' perspectives were included in the charts of themes under analysis. Each chart displays the overall performance of the pathways against each theme.

The charts take into account both of the scores and weights for each criterion selected for inclusion in the theme in question. Both scores and weights are normalised automatically by the MCM software tool. The detailed description of the normalisation process of the MCM can be found in Annex A of MCM Manual (Coburn and Stirling, 2016).

The orange horizontal bars indicate the interval between the lowest and highest aggregate weighted scores for the theme in question. The left side end of the blue lines indicates the lowest aggregate weighted score assessed across the selected theme by any participant. The right side end of the blue lines indicates the highest aggregate weighted score assessed across the selected theme by any participant (Coburn and Stirling, 2016).

On the vertical axis, the chart displays all the "core" and" additional" pathways under appraisal during the MCM process. The additional pathways have not been appraised by all participants, therefore their performance will not have appeared in the chart unless the theme under assessment included a criteria identified by the participant who included the additional pathway.

If a pathway was not appraised during the MCM process by any of the participants, there will be an orange circle notation at the front of the pathway name. This is the case for the two Decentralised AD pathways, that participant I3 and A4 did not appraised.
On the horizontal axis, the chart displays a 0 to 100 scale, in order to express the relative magnitudes of aggregate weighted scores for all criteria included under the theme in question. Higher values indicate higher performance (Coburn and Stirling, 2016).

In order of appearance in the vertical axis of the charts below, the core pathways are: Business as Usual, Centralised Gasification, "Decent AD HN" refers to Decentralised Anaerobic Digestion for the decarbonisation of the heat sector, "Decent AD TF" refers to Decentralised Anaerobic Digestion for the decarbonisation of the transport sector, "Decent

Gasification HN” refers to Decentralised Gasification for the decarbonisation of the heat sector, “Decent Gasification TF” refers to Decentralised Gasification for the decarbonisation of the transport sector.

The additional pathways are: “Add1. Central Adv. Comb” identified by Participant I1, “Add2. Small Scale CHP Comb” identified by Participant A1, “Add3. Zero Waste” and “Add4. Inciner Exit Strat” identified by Participant CS1.

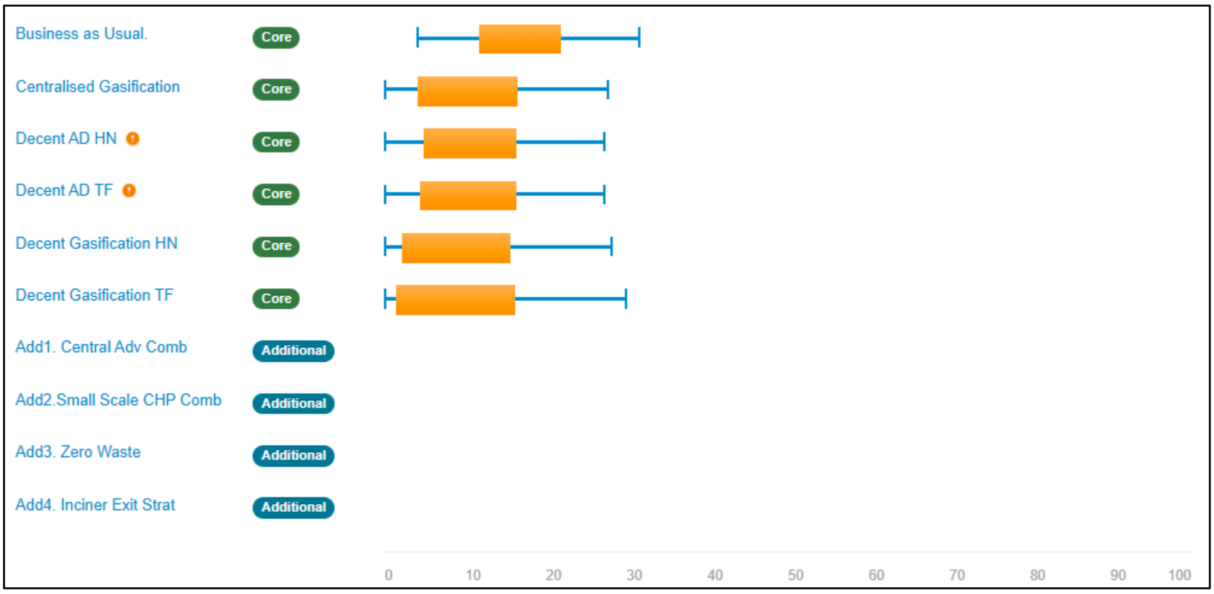

Figure 2.3.1. Pathways performance against Waste Availability

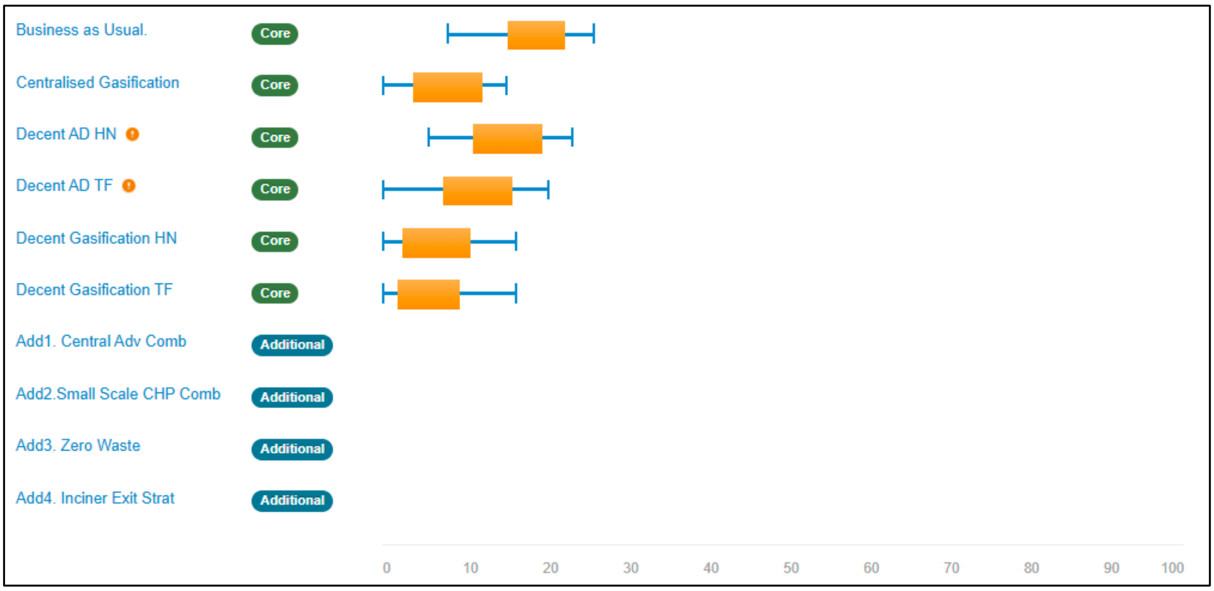

Figure 2.3.2. Pathways performance against Technology Readiness and Bankability

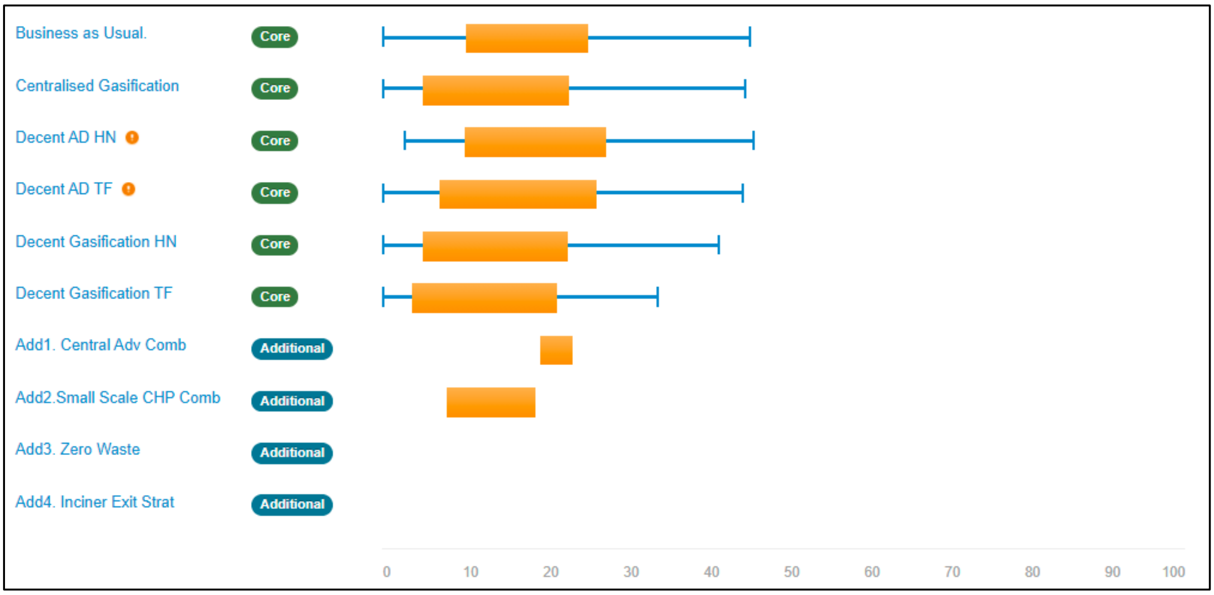

Figure 2.3.3. Pathways performance against Efficiency, including Handling Efficiency, Feedstock Efficiency and Impact on Decarbonisation of Heat and Transport Sectors

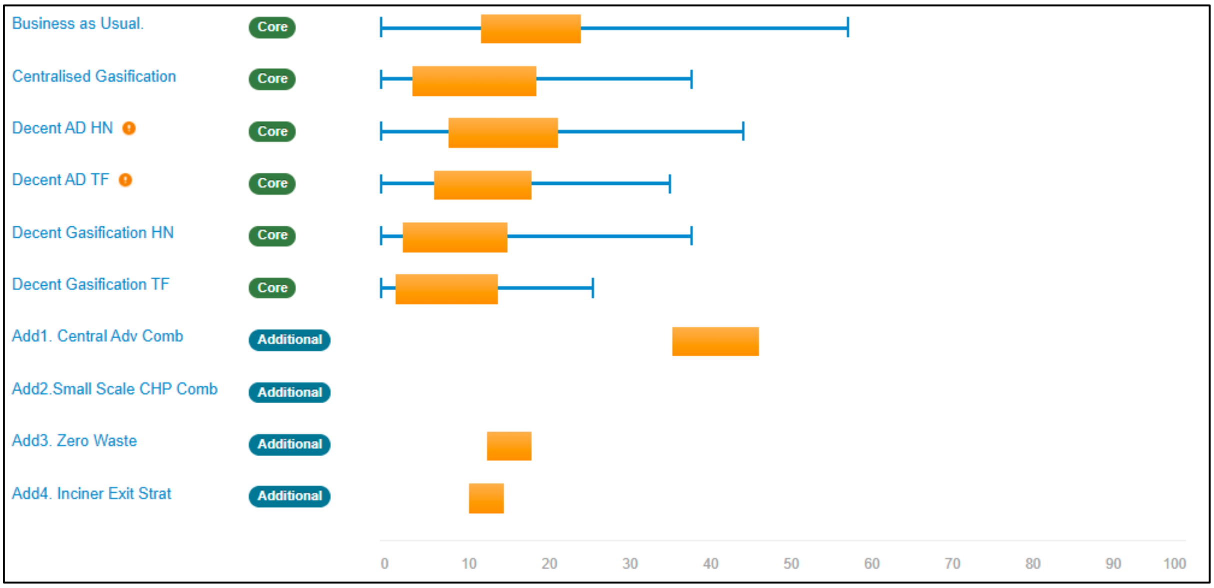

Figure 2.3.4. Pathways performance against Net Financial Cost

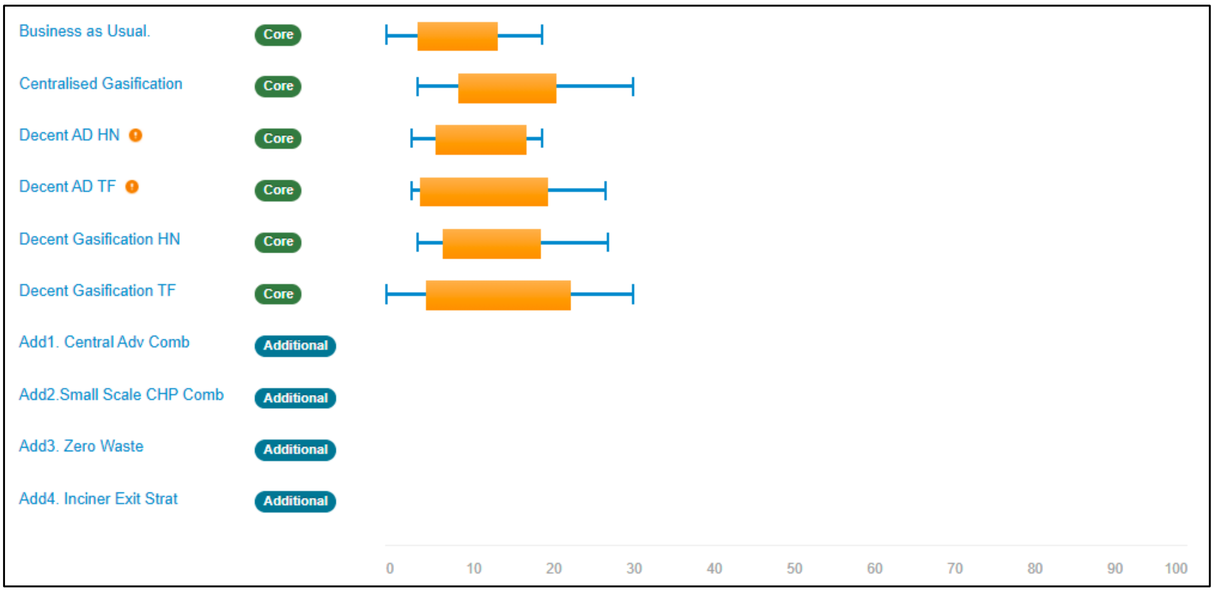

Figure 2.3.5. Pathways performance against UK Economic Impact

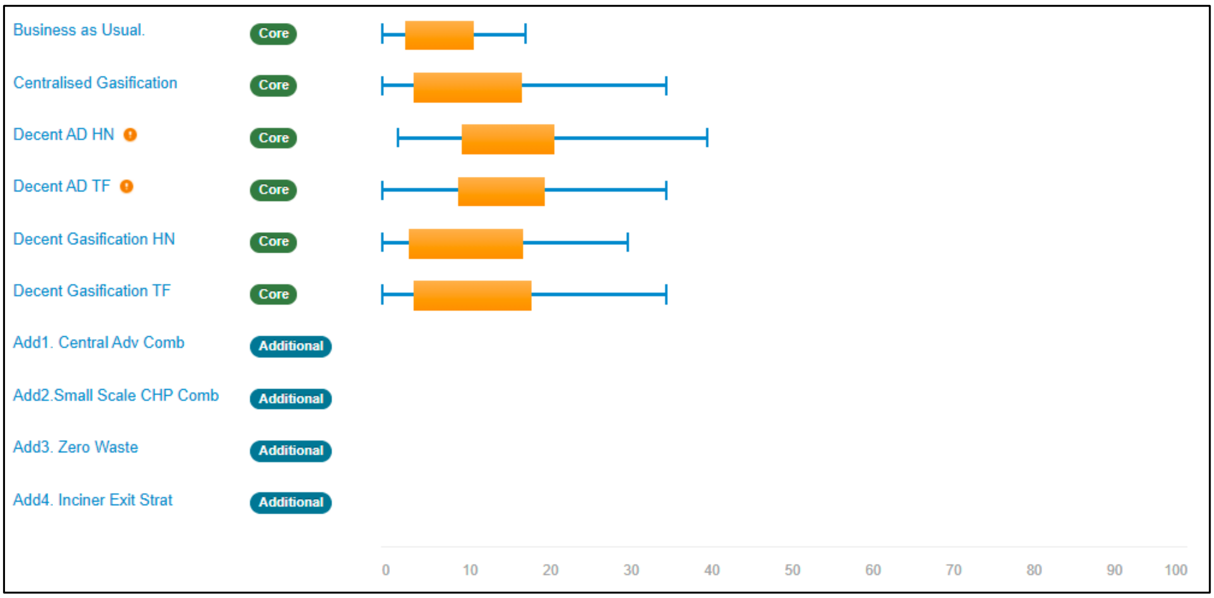

Figure 2.3.6. Pathways performance against Waste Management and Circular Economy

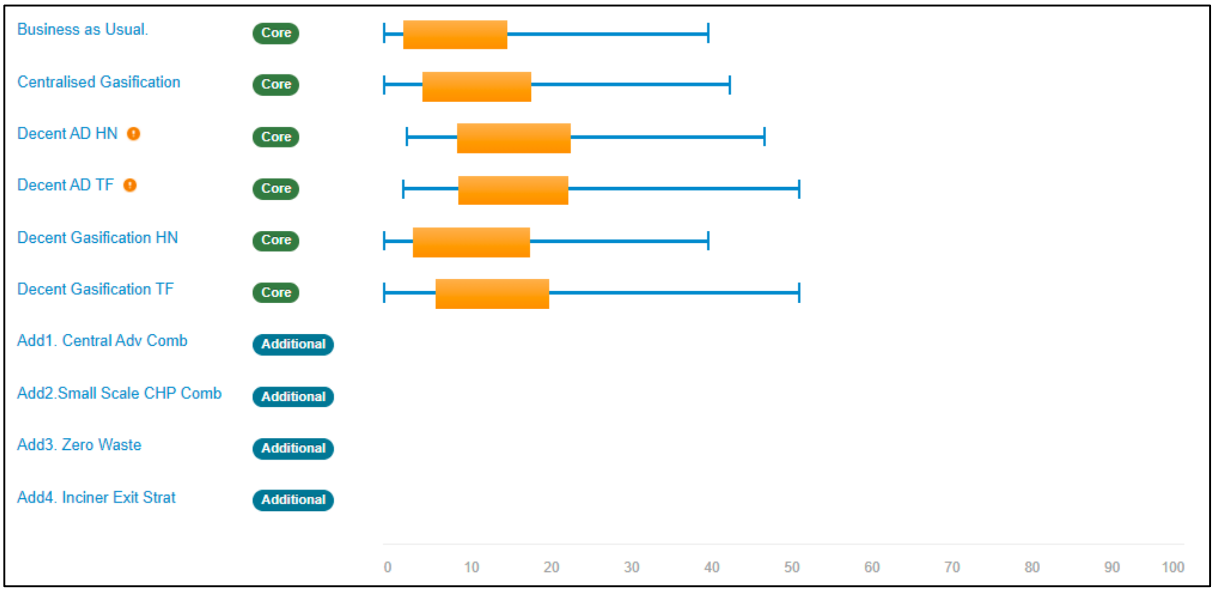

Figure 2.3.7. Pathways performance against Net Greenhouse Gas Emissions

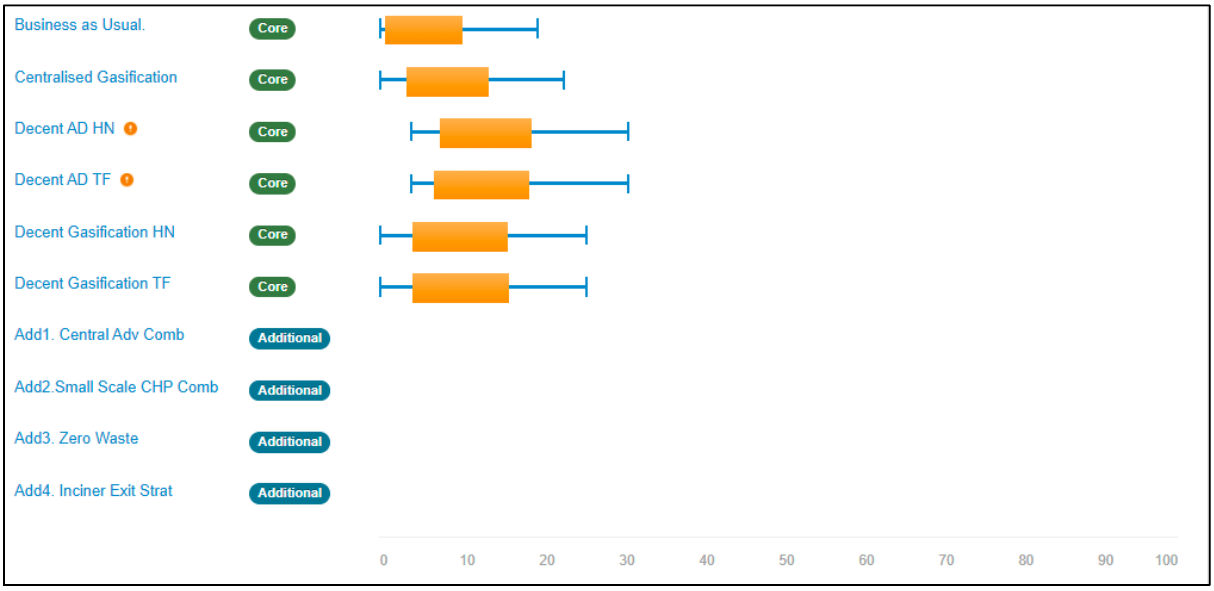

Figure 2.3.8. Pathways performance against Social Acceptance, Community Benefits and Air Quality impacts to Human Health, altogether.

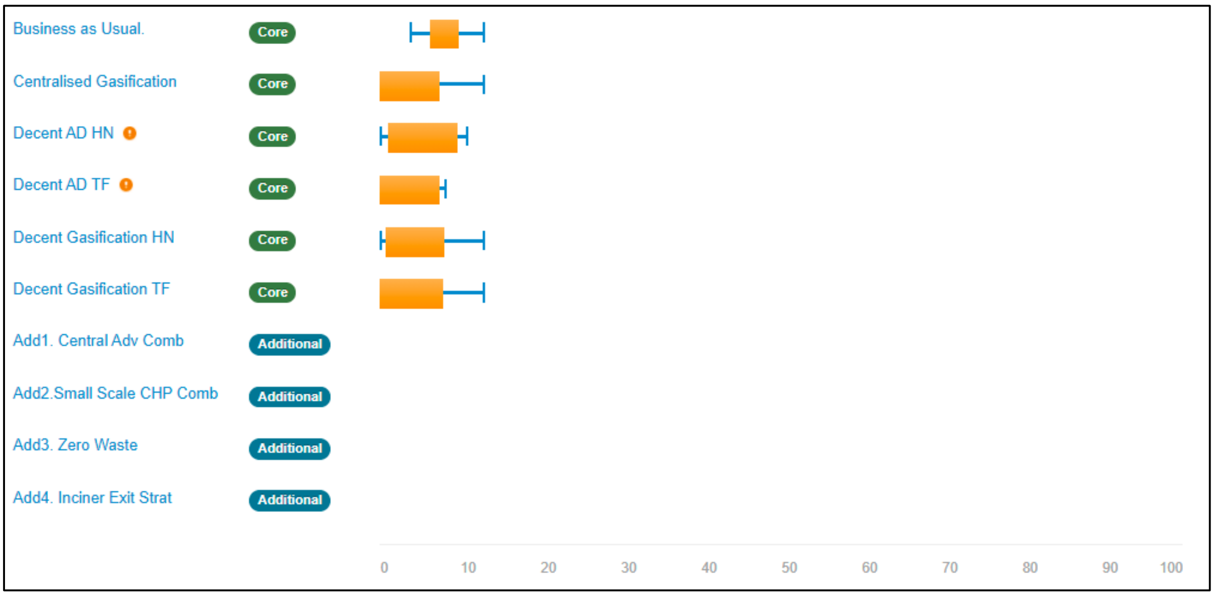

Figure 2.3.9. Pathways performance against Government Intervention