

1 **A techno-economic analysis on the integration of intermediate pyrolysis and**
2 **combined heat and power (CHP) for efficient energy recovery from organic**
3 **fraction of municipal solid waste (MSW)**

4

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9

10 **Abstract**

11 The increasing environmental concerns and the significant growth of the waste to energy market
12 calls for innovative and flexible technology that can effectively process and convert municipal solid
13 waste into fuels and power at high efficiencies. To ensure the technical and economic feasibility of
14 new technology, a sound understanding of the characteristics of the integrated energy system is
15 essential. In this work, a comprehensive techno-economic analysis of a waste to power and heat plant
16 based on integrated intermediate pyrolysis and CHP (Pyro-CHP) system was performed. The overall
17 plant CHP efficiency was found to be nearly 60% defined as heat and power output compared to
18 feedstock fuel input. By using an established economic evaluation model, the capital investment of a
19 5 tonne per hour plant was calculated to be £27.64 million and the Levelised Cost of Electricity was
20 £0.063/kWh. This agrees the range of cost given by the UK government. To maximise project
21 viability, technology developers should endeavour to seek ways to reduce the energy production
22 cost. Particular attention should be given to the factors with the greatest influence on the
23 profitability, such as feedstock cost (or gate fee for waste), maintaining plant availability, improving
24 energy productivity and reducing capital cost.

25

26

27 **KEYWORDS:**

28 *Municipal Solid Waste (MSW); Energy from Waste (EfW); Combined Heat and Power (CHP);*

29 *Intermediate Pyrolysis; Techno-economic Analysis*

30

31 **ABBREVIATIONS**

32

ACC	Annual Cost of Capital	ACT	Advanced Conversion Technology
CCL	Climate Change Levy	CHP	Combined Heat and Power
COD	Chemical Oxygen Demand	DPC	Direct Plant Cost
EC	Equipment Cost	EfW	Energy from Waste
IPC	Installed Plant Cost	IRR	Internal Rate of Return
LCOE	Levelised Cost of Electricity	MSW	Municipal Solid Waste
NPV	Net Present Value	OP	Operating Cost
RDF	Refused Derived Fuel	RO	Renewables Obligation
ROC	Renewables Obligation Certificate	TPC	Total Plant Cost

33

34 **1. Introduction**

35

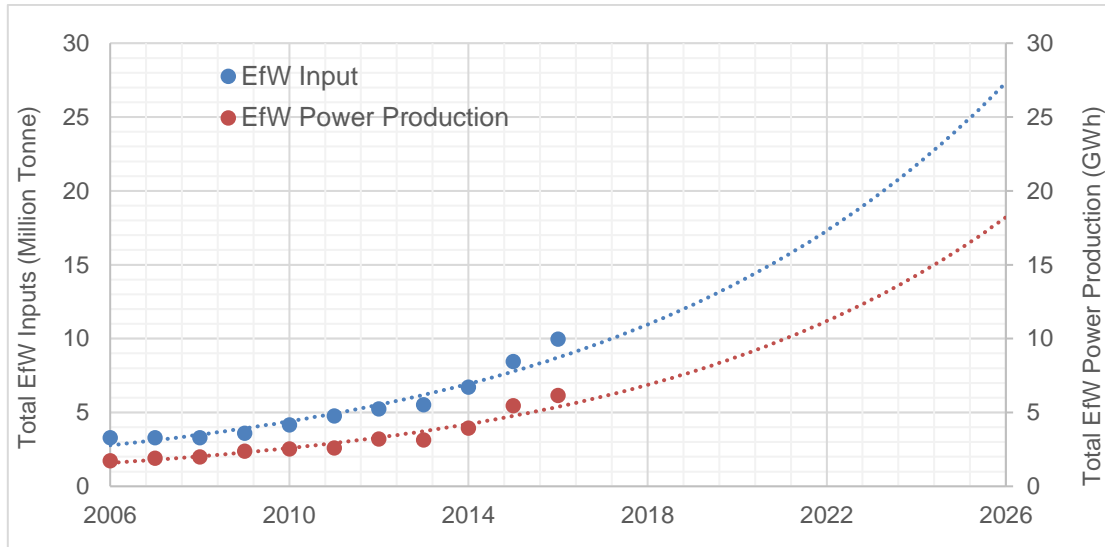
36 Municipal solid waste (MSW) consists mainly of household black bin waste, which is typically
37 treated or disposed of by waste treatment plants on behalf of local authorities in various ways. Over
38 the past twenty years, the focal point of UK waste management has shifted from disposal to
39 recycling or recovery, which has led to a significant reduction in the quantity of MSW sent to
40 landfill. In 2016, a total of 9.96 million tonnes of the organic fraction of solid waste and refuse
41 derived fuel (RDF) was processed at UK Energy-from-Waste (EfW) facilities, which generated a
42 total of 6.15 GWh electrical power but the amount of heat was not reported [1]. As shown in Figure
43 1, the input to EfW plants increased by 18% in 2016 compared to the previous year and nearly twice
44 the amount as a decade ago. Meanwhile, in 2016 total EfW power production increased by 2.5 times
45 the equivalent number in 2006. This is due to the increase in generation efficiency over the past ten
46 years. A forecast based on analysis of past data indicates that the levels of EfW input and power
47 production in 2026 could increase by 1.7 and 1.9 times respectively compared to 2016 values,
48 suggesting further improvements in efficiency. According to the statistics from WasteDataFlow (a
49 web-based system for municipal waste data reporting by UK local authorities to the government),
50 over 85% of the UK EfW inputs are derived from local authority collected waste with up to 15% is
51 from commercial and industrial waste [1,2].

52

53 With over 130 year's history, direct combustion/incineration has been the most widely employed
54 technology in waste management and the energy recovery industry. A modern incineration system
55 can process kilo tonnes per day that combust all the organic fraction in the MSW feedstock to raise
56 steam for large-scale steam turbine generators; however, the overall electrical efficiency of the plant
57 is typically around 20% [3,4]. Following increasing concerns over environmental issues and strong

58 growth in the future EfW market, it is increasingly important that more efficient and flexible
59 technologies with high standards of emission control are developed.

60



61

62 **Figure 1. Industrial development of Energy from Waste in the UK**

63

64 Alternative thermal EfW processes proposed by researchers frequently involve advanced conversion
65 technology (ACT), namely pyrolysis [4] and gasification [5]. Pyrolysis is the thermal decomposition
66 of organic materials in the absence of oxygen at elevated temperatures of around 500 °C. The
67 feedstock is converted to liquid, gaseous and solid products in varying proportions with potential in
68 biofuel applications. Gasification involves a partial combustion process at over 800 °C with the
69 controlled presence of air/oxygen, and it converts solid organics into a fuel gas containing mainly
70 CO, CH₄, H₂ and CO₂. Industrial development and commercialisation of ACT in waste energy
71 recovery began in the 1960s. For example, the Norwegian company ENERGOS has established over
72 10 EfW plants based on gasification and steam turbine generator across Europe [6], including the Isle
73 of Wight gasification plant, which was operational from 2009 to 2017 with a processing capacity of
74 30,000 tonne MSW per year and an electrical power output of 1.8 MW [7]. The company claims the
75 plant availability can reach as high as 8000 hours per year. Nevertheless, a recent report from

76 UKWIN described that there has been a series of failures in the ACT based EfW projects or
77 companies due to different technical and economic issues in the plant operation [8].
78

79 Along with industrial EfW development, there have been a number of research studies that have
80 addressed technical novelties in different aspects of the thermochemical conversion of different
81 waste materials for EfW. These include co-processing of different types of feedstock, for example,
82 co-gasification of waste with coal [9], co-pyrolysis of waste with biomass and other wastes [10,11]
83 and application and integration of advanced technologies, for example study of thermal catalytic
84 reforming [12] and integrations of advanced pre-treatment system [13] and plasma gasification
85 reactors [14]. For any novel energy system, a sound understanding of the technical and economic
86 performance at industrial scale is essential, as it provides key information about the project and helps
87 the project developer to identify the direction that can ensure the effort and investment are targeted at
88 the areas of most significant impact. However, not much work has been carried out in this respect.

89 Ledon et al. [15] carried out an exergo-economic analysis of a hypothetical MSW gasification
90 system integrated with a combined cycle power system in Chile. It was found that the energy loss in
91 the gasifier accounted for nearly 60% of the total energy loss. Use of a higher gasification
92 temperature and/or lower equivalence ratio could result in better overall system performance. The
93 author claimed that the power production through the proposed process could be economically
94 viable, comparing performance to the current Chilean energy market. Salman et al. [16] performed a
95 techno-economic analysis on a new process with coupled anaerobic digestion of MSW and pyrolysis
96 of digestate that gave high-efficiency bio-methane production. In this process, char obtained from
97 pyrolysis was added to the digester as a medium for toxic chemical/micro-organism adsorption and
98 development of a stable microbial community. The pyrolysis liquid and gas produced in the
99 pyrolysis process were steam reformed into syngas and converted to bio-methane through the
100 methanation process. The economic analysis on a 23,000 tonne per year plant indicated a positive

101 result with a payback period of about six years. Sensitivity analysis on the project indicated the
102 change in product price is the major influencing factor for the project profitability. Luz et al. [17]
103 carried out a techno-economic analysis on MSW gasification for power generation in Brazilian
104 municipalities. Net present value (NPV) and the internal rate of return (IRR) were selected as
105 economic indicators for the evaluation. The technical analysis indicated that the gasification and
106 engine plant would have electricity production of between 794 and 1065kWe per tonne MSW input.
107 The authors concluded that large plants with high installed power tend to be more economically
108 viable, but without incentives from governments, such plants are unlikely to be built. Arena et al.
109 [18] evaluated the techno-economic performance of a fluidised bed gasification and steam turbine
110 system for processing mixed plastic waste (MPW) for power generation at 2-6 MW capacity. Based
111 on the results from a pilot-scale system, the plant would have a total energy conversion efficiency of
112 23.7% for electricity. With a total plant investment at €4.79 million per megawatt capacity, the plant
113 would generate an internal rate of return of 8.3%. The authors recommended that further
114 governmental incentives for renewable energy are required to enable the project to be economically
115 attractive to investors. Rezaei et al. [19] conducted an economic assessment for power generation
116 from MSW under different scenarios in Iran. They found that gasification based EfW systems would
117 be economically viable when the MSW feedstock could attract a gate fee of US\$126 per tonne and
118 the power was sold under a purchase agreement of US\$0.276/kWh. In the 2016 Arup/DECC's
119 publication on UK electricity generation cost [20], it was stated that the 2016 LCOE of ACT-based
120 EfW system with CHP was between £89 and £189 per MWh, and the capital cost of such systems
121 was up to 16.53 million per MW. The capital cost of EfW with CHP in 2016 was 6.2 million per
122 MW, as indicated in Parsons Brinckerhoff's report on electricity generation costs model [21].
123
124 While several references have addressed the techno-economic performance of various EfW
125 processes based on gasification and pyrolysis technology, less focus has been given to the integration

126 of ACT and CHP systems for energy recovery from municipal waste. This aim of this work is to
127 study the technical aspects of a MSW energy recovery plant (therein referenced as the **Pyro-CHP**
128 system) consisting of an intermediate pyrolysis reactor and engine system for combined heat and
129 power generation and presents the economic feasibility and the parameters that affect the plant's
130 performance and viability (Comprehensive information about the intermediate pyrolysis system can
131 be found in previously published work [22–24]). The overall mass and energy balances of the
132 pyrolysis process were developed from real experimental data obtained in pilot scale tests, and the
133 data for the engine system was carefully selected from the literature (details can be found in Section
134 2.3). All of the process streams ranging from feedstock delivery to waste disposal have been
135 considered. The results of system performance and efficiency were used in an economic evaluation
136 model to study the Levelised Cost of Electricity (LCOE) and its sensitivity to the variation of a range
137 of factors. Finally, the Internal Rate of Return (IRR) was analysed to understand the potential return
138 on investing in such a Pyro-CHP system.

139

140 **2. The Process Model**

141

142 **2.1. Feedstock**

143 The feedstock evaluated in this work was the organic fraction of MSW material provided by a local
144 municipal waste treatment plant in Leicester UK in winter. The original waste was collected from
145 local households. After mechanical removal of the majority of metals, paper/cardboard, glass and
146 plastics, the raw material mainly consisted of the organic fraction of MSW, which comprised small
147 pieces of biomass (wood and grass), plastics, decomposed materials (such as from food waste and
148 paper) and inorganics including metal, ceramics, sand etc. This material usually has high moisture
149 content due to the presence of biologically degraded food waste, and a high ash content due to the
150 presence of small inorganic material pieces that were unable to be removed in the sorting stage.

151 Table 1 presents the characteristics of the organic fraction of MSW feedstock evaluated in this work.
 152 The methods used for the proximate and ultimate analyses are presented in the previous work
 153 [24,25].

154
 155 **Table 1. Characterisation of the organic fraction of MSW feedstock (on a dry basis) evaluated**
 156 **in this work**

Proximate Analysis	Unit	Content (wt.%)
Moisture	wt.%	42.9
Volatiles	wt.%	51.6
Fixed Carbon	wt.%	4.1
Ash	wt.%	44.3
Ultimate Analysis		
Carbon	wt.%	34.5
Hydrogen	wt.%	4.7
Nitrogen	wt.%	1.6
Sulphur	wt.%	0.4
Oxygen *	wt.%	14.4
Composition		
Biodegraded material (paper/food etc.)	wt.%	57.6
Coated paper	wt.%	0.2
Plastics	wt.%	6.5
Glass	wt.%	5.9
Green waste	wt.%	1.9
Metal	wt.%	4.2
Textiles	wt.%	1.0
Stones/sand/ceramic	wt.%	5.2
Other (unidentified)	wt.%	17.5

157 * calculated by difference;

158

159 2.2. The integrated Pyro-CHP system

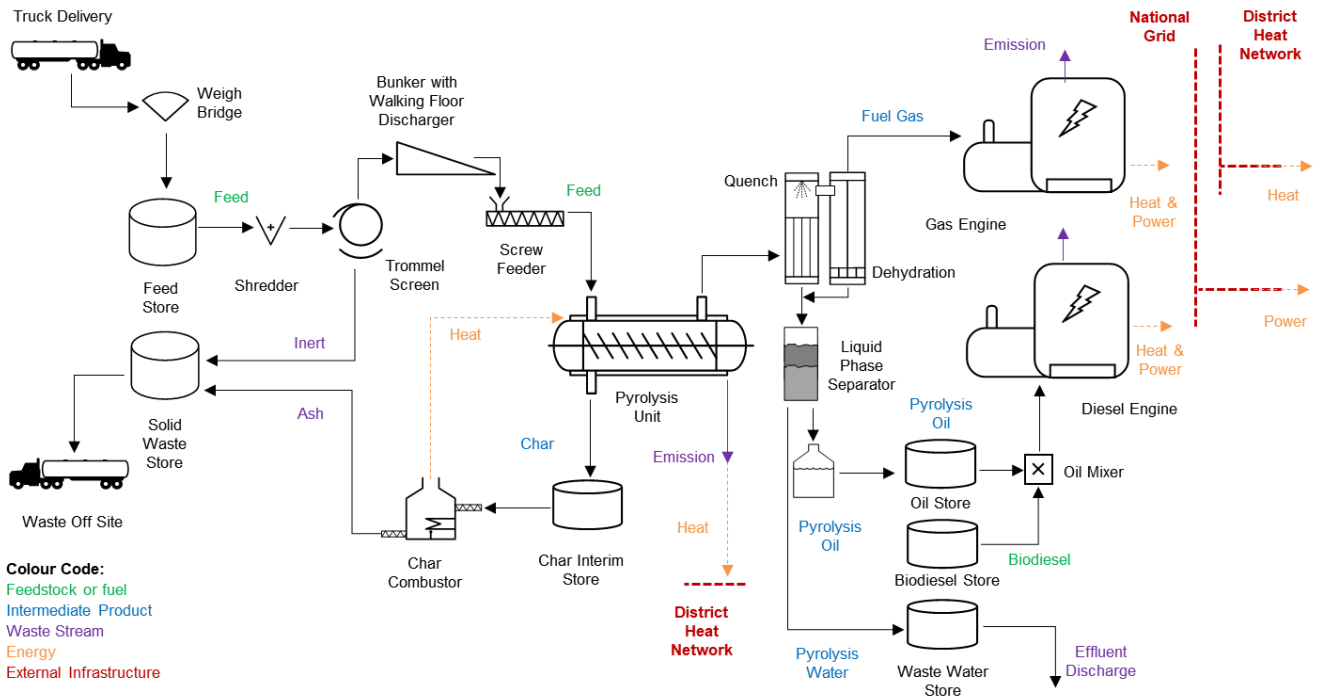
160 The Pyro-CHP system comprises five major subsystems, namely feedstock handling and pre-
 161 treatment, pyrolysis processing and product separation, char combustion, engine generators and
 162 waste treatment and disposal. Figure 2 illustrates the schematic of the proposed process.

163

164 The system boundary of the process model includes all processing steps from feedstock reception to
 165 the energy production and waste disposal. The starting point of the model is the entry of the received

166 feedstock into the feedstock storage units. The two endpoints of the model are: (1) the output of the
 167 electrical power and heat from the CHP system and (2) the output of ash and pyrolysis water for
 168 disposal.

169



170

171 **Figure 2. Schematic diagram of the overall EfW process based on pyrolysis and CHP**

172

173 As shown in Figure 2: upon reception, the feedstock is weighed and then stored in the feedstock
 174 storage units until sent for pre-treatment. After pre-treatment, the processed feed is sent to the
 175 intermediate pyrolysis reactor to produce pyrolysis liquid, gas and char products. The organic liquid
 176 (pyrolysis oil) is separated from the aqueous product and stored in liquid storage units. After
 177 blending with biodiesel, the liquid fuel blend will be burnt in a diesel engine based CHP system for
 178 energy production. The fuel gas from pyrolysis is cleaned and directly combusted in a gas engine
 179 CHP system. The pyrolysis char is burned in a combustor to provide the process heat for the
 180 pyrolysis reactor. The ash from char combustion is the process waste for disposal. The detailed
 181 processing in the five subsystems is described in the following sections.

182

183 *2.2.1. Feedstock handling and pre-treatment*

184 A series of handling and pre-treatment steps are required to process the received feedstock to ensure
185 the characteristics of the feedstock for the feeder and pyrolysis reactor Upon delivery, all the
186 received waste is weighed on a 50-tonne weighbridge and then stored in an 18,000 m³ concrete
187 storage unit, which is capable of storing four weeks feedstock supply. Before feeding to the
188 pyrolyser, the received MSW is shredded in a ball mill to reduce particle size to no larger than 20
189 mm. The shredded material undergoes trommel screening to ensure material particle sizes fall within
190 appropriate limits. This step is also used to eliminate about 5% of feedstock moisture and 20% of the
191 solid inert material in the feed such as metal, stones, glass etc. The oversize organic fraction is
192 recycled to the shredder, and the separated inert material is sent offsite for disposal or recycling. The
193 pre-treated feed is temporarily stored in bunker storage and then sent to the pyrolysis reactor's
194 feeding screws by a discharge floor. A feed rate of 5 tonnes (wet) per hour was selected for this
195 work.

196

197 *2.2.2. The intermediate pyrolysis system*

198 The intermediate pyrolysis reactor is an auger screw reactor, comprising a horizontal carbon steel
199 vessel containing two co-axial rotating screws, which transports the feed and recycle the char inside
200 of the reactor. The reactor has one inlet for the feed, one outlet for the solid product (char) and one
201 outlet for pyrolysis vapours. The heating is provided externally through a heating jacket, and the
202 pyrolysis temperature can be maintained up to 600°C. The novel feature of this reactor is the use of
203 co-axial screws for internal char recycling. The hot recycled char acts both as heat transfer medium
204 and as a catalytic cracking medium, thereby maintaining the desired temperature inside of the reactor
205 and enhancing the secondary cracking reactions for pyrolysis vapours, so as to produce a higher
206 fraction of permanent fuel gases (H₂ and CO) and lower molecular weight condensable organics and

207 less heavy tars. The pyrolysis liquid is usually produced with clear phase separation under gravity.
208 The liquid will be separated under gravity in the collection tank into two phases, i.e. an organic
209 fraction (pyrolysis oil) and an aqueous fraction (pyrolysis water). The pyrolysis oil has a lower
210 density than water, whilst the pyrolysis water remains in the bottom phase and can, therefore, be
211 drained and pumped to a different storage tank. In this work, a heating temperature of 500 °C and a
212 solid residence time of 10 minutes was selected for the reactor operating conditions. The detailed
213 process mass balance is presented in Section 2.3 and the characteristics of the liquid, solid and
214 gaseous products can be found in the previous related works [24,25].

215

216 The industrial intermediate pyrolysis reactor is coupled to a quench column for scrubbing and
217 condensing the pyrolysis vapour at room temperature to form the whole pyrolysis liquid. After the
218 separation of the organic fraction and aqueous fraction, the organic fraction (pyrolysis oil) is sent to
219 fuel storage. A stream of the aqueous fraction is recirculated back to the quench column for
220 condensing and scrubbing the hot pyrolysis vapour. The permanent gas then passes through a
221 dehydration column for moisture removal before it is sent to the gas engine. Both pyrolysis oil and
222 biodiesel are stored in oil tanks prior to being utilised downstream. In the industrial scale system, it
223 was estimated that process losses for liquid, gaseous and char products were 2%, 2% and 1%,
224 respectively. These values were provided by an experienced technician based on experience in the
225 long-term operation of a fast pyrolysis plant. After the scrubbing column, the pyrolysis gas (fuel gas)
226 passes through a dehydration column for gas moisture removal.

227

228 2.2.3. *Char combustion*

229 The solid char product is collected in a char vessel as interim storage and then directly burnt in a char
230 combustor at 1000 °C to generate hot gases to meet the heat requirement of the pyrolysis reactor. A
231 controlled stream of hot combustion flue gas (at around 700°C) is pumped into the heating jacket

232 located within the reactor skin to maintain the pyrolysis temperature at approximately 550 °C, which
233 is slightly higher than the demanded heating temperature. The waste-derived char may be unsaleable
234 in the market, as it usually has a high ash content and can contain contaminants. Therefore, all the
235 char product is combusted onsite to minimise the solid waste for disposal. The high-temperature flue
236 gas with (at around 300 °C) from the pyrolysis heating jacket will enter a heat exchanger for further
237 heat recovery before being emitted to atmosphere.

238

239 *2.2.4. Energy generation*

240 The proposed plant contains two CHP engine generator sets: a diesel engine based generator fuelled
241 by pyrolysis oil and biodiesel blends, and a gas engine based generator fuelled by fuel gas (pyrolysis
242 gas). Both engine generators produce heat and power that is sold to generate plant revenue. A dual
243 fuel engine was not considered in this work for two reasons. Firstly, typical dual fuel engines require
244 a fixed ratio of gaseous and liquid fuels, which may be different from the ratio of the pyrolysis gas
245 and oil produced from the reactor; secondly, the compatibility of a dual fuel engine operating with
246 both pyrolysis oil and gas is not proven. Pyrolysis oil and gas produced in the pyrolysis system are
247 used to generate electrical power and heat in the form of hot water. The electricity will be sold
248 through the grid to a utility company for further distribution. All the hot streams pass through a set of
249 heat exchanges which will heat water up from 40 to 70 °C for supplying to a local district heating
250 network. It was assumed that all the infrastructure is in place and can be connected when the plant is
251 ready to output power and heat.

252

253 *2.2.5. Waste disposal*

254 A significant waste stream generated in the plant is pyrolysis water, which is obtained as the aqueous
255 fraction of the pyrolysis liquid separated from the pyrolysis oil. The aqueous liquid from pyrolysis
256 typically contains various water-miscible chemicals produced during pyrolysis, such as alcohols,

257 organic acids and ketones. This liquid is disposed of to industrial sewage works at a high cost due to
258 the high chemical oxygen demand (COD) value. The ash from the char combustor is another waste
259 stream, which is sent offsite and disposed of by landfill.

260

261 **2.3. Process mass and energy balances**

262 A spreadsheet-based technical process model was created to represent the complete process flow as
263 presented in Figure 2. The overall model was developed with individual linked worksheets
264 containing sub-models of the system components described in Section 2.2. The primary input data of
265 the pyrolysis system was based on real experimental data from a pilot scale reactor as shown in
266 Table 2. The methods used for obtaining the process mass balance and determining the product
267 composition and characteristics were presented in the previous related work [25].

268

269 The energy consumption of the pyrolysis system is critical since it plays a significant role in the
270 efficiency and economics of the whole process. The pyrolysis reactor is a major energy consumer
271 within the plant, as the reactor needs to be maintained at 500 °C in the continuous processing of the
272 wet MSW raw material. The continuous heat supply is achieved by burning the by-product char,
273 which is a conventional approach used in most industrial pyrolysis systems [26]. It is estimated that
274 the heat requirement of the reactor to process the chosen feedstock is 2168 kJ per kilogram of as
275 received MSW feedstock. This value is calculated based on the heat required for raising the
276 temperature of the moisture/vapour and thermal decomposition of the organic fraction of the
277 feedstock [27].

278

279

280

281

Table 2. The process mass balance and product information for model input source

Process Mass Balance (dry feed basis)	Unit	Mass Balance
Pyrolysis Oil	%	11.3
Pyrolysis Water (reaction water)	%	8.2
Pyrolysis Water (feedstock moisture)	%	42.9
Fuel Gas (Pyrolysis Gas)	%	24.9
Char	%	55.5
Pyrolysis Gas Composition	Unit	Volume Distribution
H ₂	%	17.4
CH ₄	%	8.9
CO	%	14.8
CO ₂	%	58.9
Energy Content	Unit	Heating Value
Feedstock (dry)	MJ/kg	15.4
Pyrolysis Oil	MJ/kg	28.0
Pyrolysis Water	MJ/kg	1.4
Pyrolysis Gas	MJ/kg	10.5
Char	MJ/kg	5.4
Biodiesel	MJ/kg	35.0

283

284 The efficiencies of the CHP generators used in this work were obtained from the modern engine
 285 efficiency chart developed by Lantz [28]. For the diesel engine generator, the electrical and heat
 286 efficiencies were taken to be 44% and 40% respectively. For the gas engine generator, the electrical
 287 and heat efficiencies were taken to be 39% and 45% respectively.

288

289 The process efficiencies were calculated based on the relation of the total energy input from the
 290 feedstock plus fuel, and the output of heat and power from the engine systems. The overall electrical
 291 efficiency and overall heat efficiency were calculated as:

292

$$293 \quad \eta_{elec} = \frac{P_1 + P_2}{E_{feed} + E_{BD}} \times 100\% \quad (1)$$

294

$$295 \quad \eta_{heat} = \frac{Q_1 + Q_2 + Q_3 - Q_R}{E_{feed} + E_{BD}} \times 100\% \quad (2)$$

296

297 Where E_{feed} and E_{BD} are the energy contents of feedstock and biodiesel fuel (shown in Table 2); P_1
298 and P_2 are the net power outputs from the diesel engine and gas engine systems, respectively; Q_1 and
299 Q_2 are the net heat outputs from the diesel engine and gas engine systems, respectively; Q_3 is the net
300 heat output from the char combustor and Q_R is the heat required by the pyrolysis reactor. The CHP
301 efficiency is the energy output divided by the energy content of the fuels. The overall Pyro-CHP
302 system efficiency is the sum of equations (1) and (2).

303

304 **3. Economic Evaluation**

305

306 **3.1. General assumptions**

307 The base year of this study was selected to be 2016. All cost data was updated by using an inflation
308 rate of 3% to the present cost in 2016 Great British Pound Sterling (GBP) [26]. All the equipment
309 cost values collected before 2016 have been adjusted to 2016 values by using the Chemical
310 Engineering Plant Cost Index (CEPCI) [29]. These Chemical Engineering Economic Indicators (EI)
311 are $EI_{2010}= 550.8$; $EI_{2011}= 585.7$; $EI_{2012}= 584.6$; $EI_{2013}= 567.3$; $EI_{2014}= 567.1$; $EI_{2015}= 556.8$ and
312 $EI_{2016}= 541.7$. Some cost data was collected in the currencies of EUR and USD. They were
313 converted at the rates of EUR: GBP=1: 0.8187 and USD: GBP= 1: 0.7402 (average exchange rates in
314 2016) [30].

315

316 The interest rate for the capital loan was taken to be 9.3%, which was an average interest rate taken
317 from some relevant economic studies about MSW treatment facilities or EfW projects [16,22,31–33].
318 It was assumed that the plant technology meets the criteria of the UK's Renewable Obligations
319 Certificates (ROC) at the ACT band with CHP and is eligible to an incentive at 1.9 ROC per
320 megawatt hour of renewable electricity generated (the rate in early 2016) [34].

321

322 The processing plant operates 335 days per year and will be shut down for 30 days for plant
323 maintenance. During the operational time, it is assumed that the plant availability is 95% giving 7638
324 hours per annum. The large-scale intermediate pyrolysis process is evaluated as a first of a kind
325 technology, since there is no commercial experience in the UK, excluding demonstration projects.
326 The plant life was taken to be 20 years. At the end of plant life, all the equipment will have a salvage
327 value of 10%. It is assumed that the plant was located close to an established industrial area where
328 the electricity and district heating infrastructure were in place and can be connected to the plant
329 directly. It is also assumed that the consumers were willing and able to purchase all of the products
330 (including all the electricity and heat produced) when they are available in the market. The engine
331 fuels used satisfy the criteria of the UK Renewable Obligation (RO).

332

333 **3.2. Capital cost**

334 In this work, the total capital requirement for the Pyro-CHP plant was calculated by using the
335 economic analysis model developed by Bridgwater et al. in the early 2000s [26]. The total plant cost
336 (TPC) was used as the measurement of the project capital cost, which is the total amount of capital
337 required to finance the whole system to the point at which it is ready to operate. This includes the
338 costs incurred in pre-development and during the construction stage. The calculation of TPC starts
339 with the summation of the equipment cost (EC), which is the cost of purchasing brand new
340 equipment for all the components in the subsystems and delivered to the plant gate. The ECs used in
341 this work were collected from quotations provided by suppliers when available, otherwise were taken
342 from published data in the literature. Incremental factors were included for erection, instrumentation,
343 piping and ducting, associated electrical equipment, structures and buildings, civil works and
344 lagging, to give a direct plant cost (DPC). Costs of engineering design and management overheads
345 are then added to give an installed plant cost (IPC), and finally commissioning costs, contractor's

346 fees, interest during construction and a contingency element are added to give the TPC. These
 347 increments are less specific to system modules, being usually approximated as fixed percentages of
 348 direct plant cost. According to a study for a similar system, the TPC was chosen to be 1.69 times the
 349 DPC, which was the production of the EC and a number of multiplication factors [26,35]. The
 350 breakdown of the ECs and calculated TPC are presented in Table 3.

351
 352 **Table 3. List of equipment and associated costs for a 5 t/h plant**

Equipment or type of cost	Capacity	No.	Cost	Source of reference
<i>Pre-treatment Section</i>				
Weighbridge	50 t	1	£19,432	*
Feedstock store	3,500 t	2	26,509	[36,37]
Belt conveyers	60 m	2	20,000	*
Mill/shredder	5 t/h	2	38,412	[38]
Trommel screen with conveyers	5 t/h	1	90,000	*
Bunker	5 t/h	1	50,000	Estimation
Waste store	1,500 t	1	10,604	[36]
Loading shovels	2 t	1	45,000	*
Excavator	2 t	1	45,000	*
<i>Pyrolysis</i>				
Pyrolysis system with liquid collection	5 t/h	1	3,995,224	[22]
Gas dehydration column	2,000 m ³ /h	1	15,000	[39]
Liquid storage organic	672 t	2	69,000	*
Liquid storage aqueous	672 t	2	69,000	*
Biodiesel store	1,400 t	1	138,000	*
Screw conveyers	30 m	2	10,000	*
<i>Generation</i>				
Fuel Gas CHP Engine	3,800 kW _e	1	3,062,818	*
Diesel CHP Engine	660 kW _e	1	835,275	*
Char combustion with heat recovery	4,800 kW _h	1	1,165,969	[38]
DPC			16,206,912	
IPC			20,258,640	
TPC			27,641,751	

353 * denote the data was obtained by the quotations from equipment suppliers
 354

355 The Annual Cost of Capital (ACC) is the annual levelised repayment over the lifetime of the project
 356 and assumes that the full capital amount (or TPC) is loaned at the start of the project at a specified
 357 real interest rate. The ACC is calculated as follows:

358

$$359 \quad ACC = TPC \frac{i(1+i)^n}{i(1+i)^n - 1} \quad (3)$$

360

361 Where n is the project lifetime in years, and i is the interest rate for the capital loan.

362

363 **3.3. Operational cost**

364 *3.3.1. Feedstock and gate fee*

365 Treating and disposing of waste can attract a gate fee from the local authorities. This fee is levied on
366 each tonne of waste taken into the treatment plant for offsetting the plant's capital and operation
367 costs [31], hence receiving feedstock is considered as a revenue stream. The gate fee is generally
368 specific to site, process and scale. The WRAP UK reported the median value of gate fee paid to the
369 EfW facilities in 2015/16 as £95 per tonne, and this was used in this work [40].

370

371 *3.3.2. Fuel*

372 A blend of biodiesel and pyrolysis oil on 50/50 volumetric ratio is required to ensure smooth
373 operation of a CHP engine running pyrolysis oil. The biodiesel price used here was £0.65/l (or
374 £0.73/kg), as agreed by local a supplier. The biodiesel is considered as a consumable of the plant,
375 and hence the cost and energy required for the biodiesel production are not considered in this work.
376 It is worth noting that value-added tax and road fuel duty is not applicable to UK commercial
377 stationary generators.

378

379 *3.3.3. Utility*

380 Utility costs include electricity and water usage in the plant. In this work, electricity is consumed
381 within the general plant site, office/laboratory usage and the parasitic load of the plant. The

382 electricity is imported from the grid to ensure stable operation of the plant The majority of the water
383 usage is for pyrolysis process cooling.

384

385 The electricity consumption rate was estimated to be 28 kWh per tonne of wet MSW treated. This
386 was converted from the data quoted by Bridgwater et al. [26] and Diebold et al. [41] based on
387 processing dried biomass in a pyrolysis plant. The average 2016 electricity price for UK medium
388 industrial consumer was taken to be £0.1084 per kWh [42]. The water usage was estimated to be 13
389 m³ per tonne of wet MSW treated. The water utility cost includes the cost of water usage and
390 sewerage surcharges. According to a UK water supplier, the water cost for a plant at the proposed
391 scale in 2016 should consist of a fixed annual charge of £1724 and a unit price of £0.2609/m³. The
392 sewerage charge should consist of a fixed annual charge of £5,673 and a unit price of £1.2347/m³
393 [43].

394

395 3.3.4. Waste disposal

396 Waste disposal includes the disposal of aqueous liquid along with pyrolysis oils and ash from the
397 combustion of pyrolysis char. UK water companies charge a “trade effluent” when industrial
398 wastewater is disposed of in the sewers. The following equation calculated the cost of trade effluent
399 based on the characteristics of the liquid discharged to the sewage [43]:

400

$$401 \quad C = R + VB + \left(\frac{O_t}{O_s} \times B\right) + \left(\frac{S_t}{S_s} \times S\right) \quad (4)$$

402

403 Where R is reception and conveyance at a fee of £0.1813/m³; VB is volumetric and primary
404 treatment for £0.3305/m³; O_t is the chemical oxygen demand (COD) of the trade effluent after one-
405 hour quiescent settlement, determined by milligram of COD per litre liquid; O_s is the mean strength
406 of settled sewage at a wastewater plant taken to be 489 COD mg /l; B is a biological treatment for

407 £0.2698/m³; S_t is total suspended solids of the trade effluent, determined by milligram of solid
408 content per litre liquid; S_s: the mean suspended solids content at a wastewater plant, taken to be
409 415mg/l; S is the sludge treatment and disposal for £0.2032/m³. In this work, the COD of the
410 untreated aqueous liquid is 94g/L, and total suspended solid content is less than 5mg/l. This gives a
411 calculated cost of trade effluent of £52.38 per tonne of aqueous liquid discharged.

412
413 Ash produced in the char combustion unit is sent to landfill. The cost of ash landfill includes a
414 landfill fee and a landfill tax, at rates of £19/t and £80/t in 2016 [40].

415 416 *3.3.5. Labour*

417 The staffing levels of the plant were estimated to be 18 working staff per day. This includes a day
418 team formed of one plant manager, one administrator and one technical manager and a shift team
419 formed of one supervisor and four operators in three rotations. The annual average cost of
420 employment per staff was estimated to be £47,004 per year. This was calculated from the 2013 UK
421 average weekly labour wage in energy sector- £715 [44], the ratio of 2016 and 2013 UK Labour
422 Costs Index Points - 1.022 [45] and an increment (123.7%) to staff wage that covers the employer's
423 national insurance (11%), pension contribution (5%), and training (2.7%) and administration charges
424 (5%) [35].

425 426 *3.3.6. Plant maintenance and overheads*

427 Annual maintenance costs and overhead costs (including insurance, rent, taxes etc.) were calculated
428 as a percentage of TPC per annum. The present study used 2.5% of TPC for plant maintenance and
429 2.0% of TPC for plant overheads costs, in line with previous comparable work [26].

430

431 **3.4. Energy product sales**

432 *3.4.1. Electricity and heat sales*

433 In this work, three different electricity selling scenarios with different target customers were
434 considered to measure the profitability of the CHP plant. These included exporting the electricity
435 directly to the national grid at a rate of £0.055/kWh and selling to domestic consumers at a rate of
436 £0.1541/kWh or industrial customers at a rate of £0.1054/kWh [22,42]. The heat price was taken to
437 be £0.0403/kWh, in line with previous research [22], which allows for an assumed 10% transmission
438 loss. It is worth noting that there are always electrical power losses of approximately 2% in the
439 distribution and transmission and heat transmission losses of approximately 10% [46,47]. However,
440 within the economic evaluations, these losses were not taken from the total saleable energy units,
441 since costs like these are typically passed on to the consumers through the selling price. It was also
442 assumed that the customers were willing and able to purchase all of the heat and power products
443 when they were available in the market.

444

445 *3.4.2. Renewable energy incentives*

446 Renewable Obligation (RO) was introduced by the UK government in 2002 to support the national
447 renewable energy deployment. The Renewable Obligation Certificates (ROCs) generated by the
448 licenced renewable generators can be traded under the RO scheme and hence produce revenue for
449 the plant (detailed policy can be found in the official document [48]). It was assumed that the current
450 CHP scheme satisfies the quality assessment defined by the UK authority, which was recognised as
451 Good Quality CHP) [49]. The pyrolysis oil used satisfied the criteria of the UK Renewable
452 Obligation and fully qualified for the incentive payments. The renewable generator accredited in
453 early 2016 can receive 1.9 ROCs per kWh electrical power generated. The average trade value was
454 £44.33/ROC in 2016 [50].

455

456 It is important to note that the ROC payment will only be issued to the proportion of energy
457 generated from the renewable sources with an accredited renewable system. The pyrolysis oil is
458 produced from MSW, which is recognised as a renewable feedstock. However, the biodiesel used is
459 generally produced via transesterification process of vegetable oil (or used cooking oil) with
460 methanol, which is primarily produced from natural gas by steam reforming and associated reactions.
461 It is, therefore, highly likely that the liquid fuel used in the liquid CHP engine will contain a fossil
462 part that is ineligible for claiming the ROC payment. The Fuel Measurement and Sampling (FMS)
463 method [51] issued by the UK Ofgem has clearly explained the method to calculate the mass and
464 energy shares of the different types of biodiesel. Assuming the biodiesel assessed in this work was
465 derived from used (soybean) cooking oil. It is reported that this type of biodiesel contains an average
466 mass share of 10.64% methoxy group (fossil-derived part), which is equivalent to an energy share of
467 3.92% of the total biodiesel energy content. This means 96.08% of the fuel energy in the biodiesel
468 eligible for ROC claim. Considering the blending ratio of the pyrolysis oil and biodiesel and their
469 heating values, a total of 97.80% of the energy in the fuel blend is eligible for ROC credit.

470

471 The Climate Change Levy (CCL) is a tax introduced by the UK government on energy delivered to
472 non-domestic users. It aims to provide an incentive to increase energy efficiency and to reduce
473 carbon emissions. The renewable or CHP generators are exempt from paying CCL, which was
474 £5.59/MWh in 2016 [52].

475

476 **3.5. Levelised cost of electricity (LCOE)**

477 The LCOE is the minimum selling price of the product, which covers the costs of energy production
478 [32]. It is often cited as an effective measure of the overall competitiveness of different energy
479 generating technologies by the authorities [53]. In this work, the proposed system produces

480 combined electricity and heat. The calculation of LCOE assumes the customers can purchase the
481 heat at its market price and the associated government incentive subsidies have been paid.

482

483 The LCOE is calculated as:

484

$$485 \quad LCOE = \frac{(ACC+OP)-S_{heat}}{Q_{elec.}} - Q_{elec.} \times R_{elec.} \quad (5)$$

486

487 Where, ACC is the annual cost of capital, in £/a; OP is the annual operating cost, in £/a; Q is the
488 quantity of energy product produced, in kWh/a; S is the annual sale of the product, in £/a; R is the
489 rate of incentive subsidy, in £/kWh, i.e. ROC trade value for electricity.

490

491 **3.6. Internal rate of return (IRR)**

492 In this work, the internal rate of return (IRR) is employed to measure and evaluate the profitability of
493 the proposed project investments. The IRR is a discounted cash flow rate of return that makes the net
494 present value (NPV) of cash flows equal to zero. The NPV is the summation of the present values
495 (PVs) of the individual annual net cash flows. The PV is the cash flow in future that has been
496 discounted to reflect its present value as if it existed today. It is a characteristic of money referred to
497 as its time value. The present value of money is always less than its future value as it has interest-
498 earning potential.

499

500 The following formula is used to calculate the NPV:

501

$$502 \quad NPV = -C_0 + \sum_{t=1}^T \frac{C_t}{(1+r)^t} + C_{SV} \quad (6)$$

503

504 Where C_0 is the initial investment; C is the cash flow; r is the discount rate; t is the year; T is the
 505 project lifetime, and C_{SV} is the PV of the salvage value of the equipment at the end of plant life.

506

507 When the NPV equals zero, the value of discount rate r is the IRR of the project. The IRR can be
 508 used as an indicator of the potential probability of the project, by comparing with the target IRR. For

509 a novel technology with a high risk associated, the target IRR may be up to 25% [54]. The

510 Corporation Tax rate for the company profits was taken to be 20%, as the actual 2016 rate in the UK
 511 [21].

512

513 4. Results and Discussion

514

515 4.1. Overall process efficiencies

516 Table 4 presents the process mass and energy balances of the overall EfW plant and the overall
 517 system efficiencies calculated by the model as described in Section 2.3 [22,55]. Further illustration
 518 of the process energy conversion is presented in Figure 3.

519

520 **Table 4. Process Mass and Energy Balances and System Efficiencies (base case)**

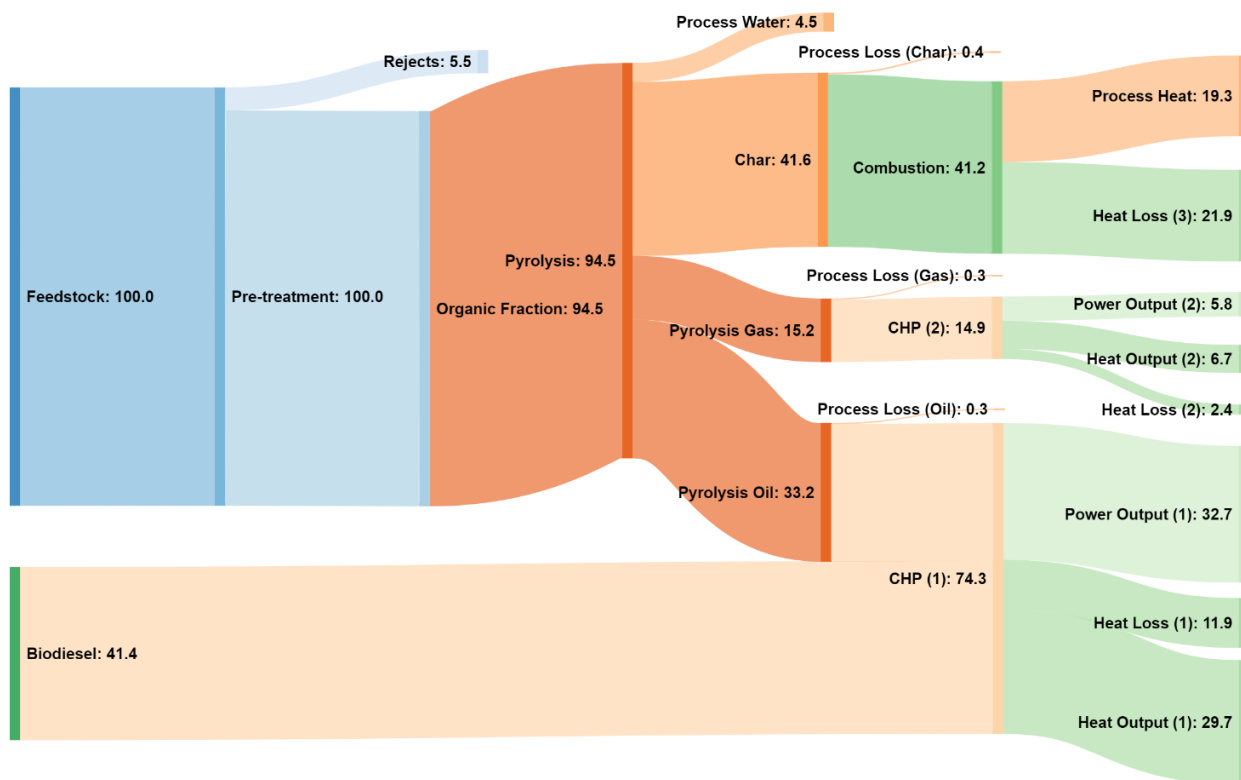
	Description	Mass (kg/h)	Energy (kW)
<i>Feedstock Pre-treatment</i>			
Raw Feed (wet)	Input to pre-treatment	5,000.0	11,527.8
Processed Feed	Pre-treatment product and feed to pyrolysis	4,217.5	10,895.2
Pre-treatment Reject	Waste to offsite	782.5	632.6
<i>Pyrolysis</i>			
Feed	Feed for pyrolysis	4,217.5	10,895.2
Pyrolysis Oil	Pyrolysis product and fuel for engine	491.2	3,825.6
Aqueous Liquid	Pyrolysis product for Energy Recovery or disposal	1,350.5	526.1
Char	Pyrolysis product and fuel for char combustor	1,643.8	4,794.7
Fuel Gas	Pyrolysis product and fuel for engine	732.0	1,748.9
<i>Energy Generation</i>			

Biodiesel	Engine fuel	491.2	4,775.5
Biodiesel + Pyrolysis oil	Fuel blend to engine	977.5	8,562.8
Power	Energy product from diesel engine		3,767.6
Heat	Energy product from diesel engine		3,425.1
Fuel Gas	Input to gas engine	717.3	1,713.9
Power	Energy product from gas engine		668.4
Heat	Energy product from gas engine		771.2
Char to Combustor	Input to combustor	1,627.4	4,746.7
Heat	Energy product from char combustor		3,322.7
<i>Total Plant Output</i>			
Power	Output as a final product		4,436.03
Heat	Output as a final product		5,296.55
<i>Process Waste</i>			
Solid Rejects and Waste	Waste to offsite	1,383.9	
Aqueous Liquid	Waste to disposal	1,350.5	
<i>Process Efficiency</i>			
Electrical Efficiency	Efficiency of the overall electrical output		27.2%
Heat Efficiency	Efficiency of the overall heat output		32.5%
The Pyro-CHP System	Efficiency of the overall energy output		59.7%

521

522 During the pre-treatment stage (shredding and screening), approximately 20% of the inert
523 components and 5% of organic components in the feed was screened out, along with 25% of the
524 moisture in the MSW. The solid rejects are sent out of the plant as solid waste at a rate of 782.5 kg/h.
525 Therefore, 4217.5 kg of a pre-treated organic fraction of MSW was fed into the pyrolysis reactor per
526 hour, which is equivalent to 94.5% of feedstock energy input (11,527.8 kW). As described in Section
527 2.3, the intermediate pyrolysis system converts the wet solid feed into 11.6% organic liquid
528 (pyrolysis oil), 32.0% aqueous liquid (pyrolysis water), 17.4% fuel gas and 39.0% char. After
529 separation from the aqueous fraction/ pyrolysis water, the pyrolysis oil (491.2 kg/h and 3,825.6 kW)
530 was stored in the oil tank for engine use. The total energy content of the pyrolysis oil accounted for
531 33.2% of the feedstock energy input. The char production rate was 1,643.8 kg/h, accounting for
532 41.6% of the feedstock energy. All the char was combusted on site, and this was used to generate
533 4,794.7 kW heat to meet the minimum heat requirement of the pyrolyser, which was 2,222.5 kW.
534 The fuel gas consisted of nearly 40 vol. % combustible fraction with a production rate of 732.0 kg/h

535 giving an energy input of 1,713.9 kW to the gas CHP engine. The pyrolysis oil was blended with
 536 biodiesel at 50/50 to fuel the liquid CHP engine. This, in total, was able to generate 4,436 kW
 537 electrical power and 5,297 kW heat in the form of hot water. The system can achieve an electrical
 538 efficiency of 27.2%, a CHP efficiency of 84% and an overall heat and power efficiency of 59.7%.



539
 540 (Footnote: The colours presented in the Sankey diagram are only for distinguishing different energy streams. All values
 541 given are the proportion of energy contained in each stream, referencing to the base value of 100 for the MSW feedstock)

542 Figure 3. Process energy flow

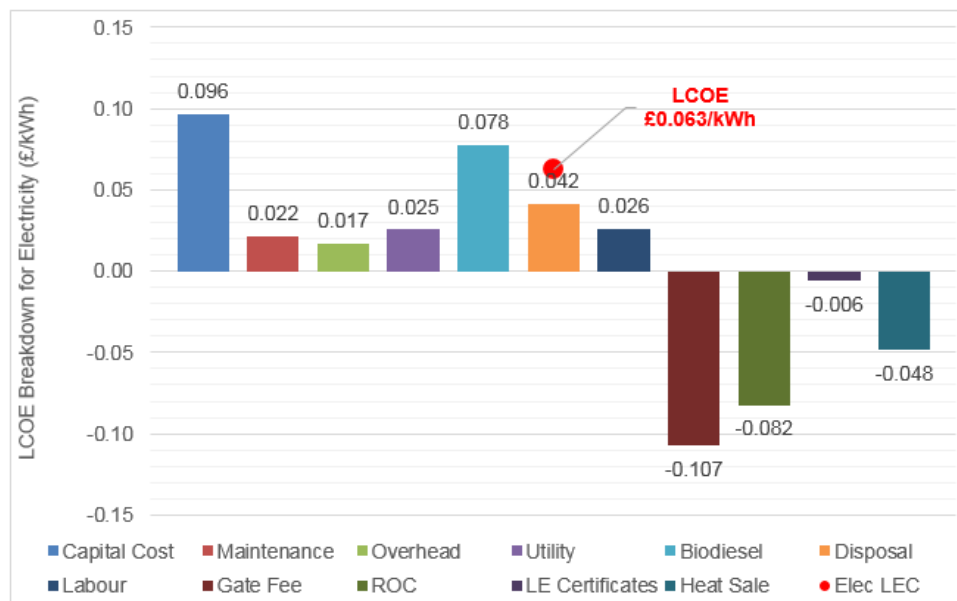
543
 544 It can be observed that most of the energy losses occurred during the pyrolysis stage, where all the
 545 char product was burnt to meet the heat demand of the pyrolysis reactor. In addition, hot pyrolysis
 546 vapour was condensed to form liquid products, and char was cooled in the collecting vessel before
 547 being sent to the burner. Heat was therefore transferred into the cooling water and air and eventually
 548 ended up in the environment and became system heat losses. In real industrial applications, these
 549 parts should be designed and integrated carefully to gain an optimised overall system efficiency.

550

551 4.2. Levelised cost of electricity

552 Figure 4 illustrates the calculated LCOE and its breakdown of contributions including the project
 553 costs and incomes from incentive payment and product sales. Bars with positive values indicate the
 554 direct cost incurred in the project investment and the plant operation, while the bar with negative
 555 values represents the sales revenues from the heat, as well as the government incentive payments for
 556 the electricity and heat. Combining all the contributing values, the LCOE value for the proposed
 557 plant is £0.063 per kilowatt-hour. This value fits well in the range of the UK EfW generation cost as
 558 evaluated by the BEIS, which is £0.045-0.083/kWh [56].

559



560

561 Figure 4. Levelised Energy Cost (LCOE) and its Breakdown

562

563 The capital investment of the proposed project was calculated as £6.23 million per megawatt. This is
 564 close to the lower end of the range (£5.33-£16.41/MW) of the UK bioenergy capital requirement
 565 according to the Arup's recent estimation (the range was derived after deduction of general
 566 infrastructure cost from the original data quoted in the report, which accounts for 20% of the total

567 cost but was not considered in this work) [20]. As shown in Figure 4, this is the most significant
568 contributing factor in the LCOE. Following this is the cost of using biodiesel to blend with the
569 pyrolysis oil for energy production, which is the highest cost in the operating cost category. Disposal
570 costs incurred, the char/ash to landfill (62% of the total) and wastewater disposal (38% of the total),
571 is the second highest cost during the plant operation. However, it is worth noting that this work did
572 not consider the opportunity in selling ash to cement businesses, which otherwise may avoid a cost
573 but attract an additional revenue stream. There is also a possibility of investing in additional
574 wastewater treatment facilities, which can reduce the COD of the pyrolysis water and consequently
575 reduce the cost of trade effluent. The labour and plant utility costs are at a similar level. The cost of
576 plant maintenance and overheads are insignificant compared to the other factors.

577

578 In the revenue stream, the waste gate-fee has become the most significant factor, which can
579 completely offset the sum of labour and biodiesel fuel costs. The renewable energy and
580 environmental incentive payments are also critical in offsetting the plant costs, and the total value is
581 almost twice the income attracted by the sales of heat. Both of the revenues from gate fees and
582 incentive payments reflect the importance of the government's role in the deployment of sustainable
583 waste treatment and renewable energy. From the analysis, it can be understood that the sustainability
584 policies largely determine the probability of these technologies being developed at an industrial
585 scale.

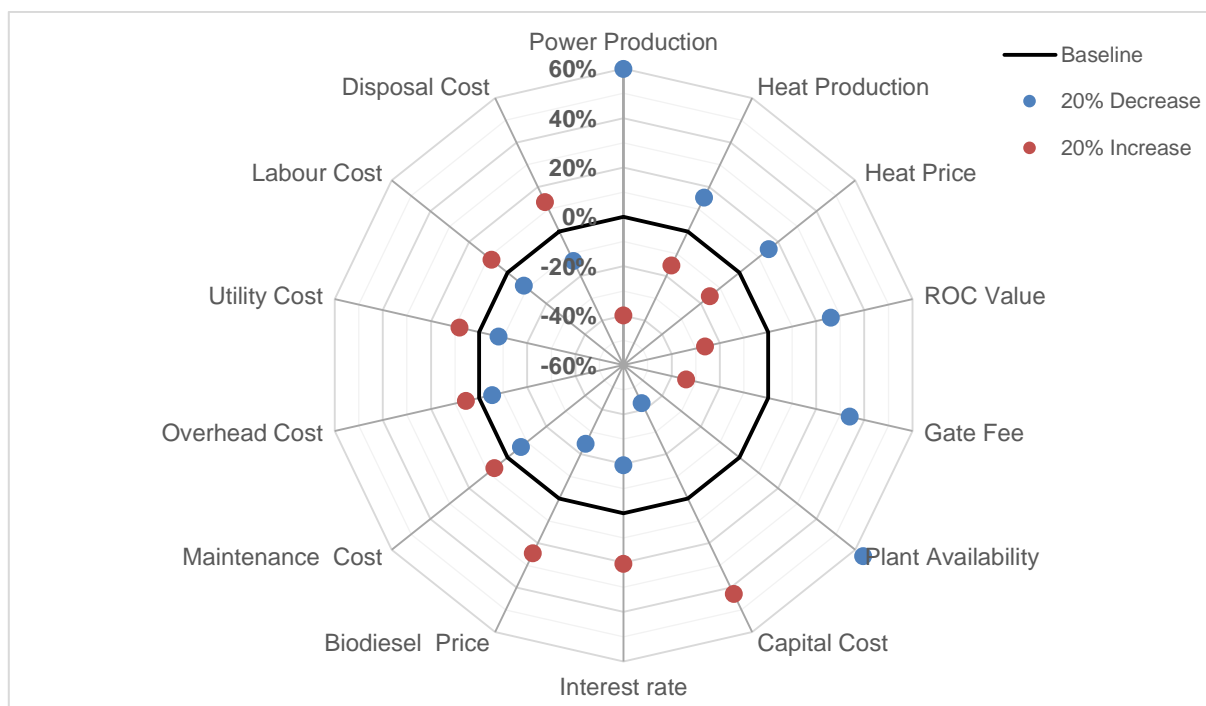
586

587 **4.3. Sensitivity analysis**

588 Figure 5 presents the effects of input parameter variation on the LCOE, which takes into account the
589 uncertainties in these single variables. Fourteen key input parameters related to the project capital
590 cost, operating costs and productivities are analysed in turn with $\pm 20\%$ changes to their baseline

591 data. This can be used to determine how variation in key variables can impact the LCOE and
592 consequently help the project developer to identify strategies for reducing production cost.

593



594

595 Figure 5 Sensitivity analysis for calculated LCOE

596

597 It can be observed from the chart that the plant availability has the highest impact on the LCOE. A
598 20% decrease of the current plant availability can increase the production cost by 64.2%, indicating
599 the importance of maintaining the highest possible plant availability. The power production rate of
600 the Pyro-CHP system has the second highest impact on the LCOE. A 20% increase can reduce the
601 LCOE by nearly 40%, and a 20% decrease can increase the LCOE by nearly 60%. Since the thermal
602 efficiencies of modern engine systems are relatively fixed, it is important to consider any
603 improvement that could increase the pyrolysis oil yield or the energy content (heating value) of
604 pyrolysis oil.

605

606 The capital cost of the project, along with the interest rate charged to the capital loan, is the next
607 important influencing factor. Decreasing capital cost and interest rate by 20% can result in a
608 reduction in the production cost by 42.9% and 19.5% respectively. In real industrial development, it
609 is widely accepted that the costs of a novel process reduce as more units are built, and experience
610 accumulates. The learning effect is a factor that can be applied to the plant construction cost and
611 national electric grid and heat network connection [20]. In novel thermal energy system deployment,
612 a learning factor of 20% has frequently been applied, which can correspond to a resulted 50%
613 reduction in capital costs after ten installations of a novel process [22,26].

614

615 The changes in feedstock gate fee and ROC values earned from the electricity sales also contribute to
616 the variation of production cost considerably. Increasing the feedstock gate fee and ROC value by
617 20% can decrease the LCOE by 34.0% and 26.2% respectively. The gate fee for municipal waste is
618 expected to continually increase in the long-term, along with the increase of landfill tax and cost of
619 waste treatment due to the growing concerns over the environment and sustainability issues. A
620 similar tendency is expected in the future ROC prices, but it is important to note that the ROC can be
621 only issued for a maximum of 20 years and cannot be issued beyond 31 March 2037 [48]. The
622 effects of heat production and price and costs of labour, waste disposal, utility, maintenance and
623 overhead are relatively insignificant compared to other factors, which have been discussed.

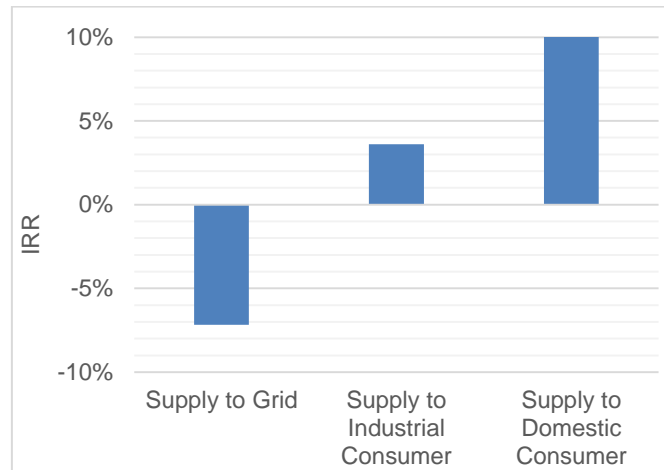
624

625 **4.4. Internal rate of return**

626 Figure 6 shows the IRR of the proposed project, which was calculated based on the cost of
627 generation, products sales (at purchase rates as described in Section 3.4.1) and gross and net profits
628 of the plant over a 20-year project lifetime. It is worth noting that this calculation did not include the
629 costs on the use of grid network for transmission and balancing service which is covered by the
630 network operator [57]. It can clearly be seen that selling the electrical power to the grid

631 (£0.055/kWh) can result in an IRR of -7.2%. This means that the net annual profit rates during the
632 project lifetime are eventually unable to cover the initial capital investment, even if the capital were
633 obtained at a zero interest rate.

634



635

Figure 6. Internal rate of return

636

637

638 In the cases of selling electricity to industrial and domestic customers, the project can generate
639 positive IRR and consequently make the project profitable. However, this requires the generator to
640 arrange additional retail contracts with relevant customers and play a role as a network distributor.
641 Selling electricity at a domestic rate (£0.1541/kWh) can allow the project to have an IRR of 10.1%,
642 which is 7.5% higher than selling at an industrial rate (£0.1054/kWh). Nevertheless, it is also
643 important to notice the significant differences in managing the bulk business contracts and individual
644 domestic contracts. Achieving an IRR of just over 10% is considered barely satisfactory in general
645 investment. As discussed in Section 3.6, for a novel technology with a high risk associated, a target
646 IRR up to 25% can be expected. Therefore, the economic performance of the baseline case seems
647 relatively unattractive for investors in terms of investment return.

648

649 **5. Conclusions**

650

651 This work has presented the results of a techno-economic analysis on a conceptual proposed Pyro-
652 CHP plant based on an intermediate pyrolysis system and CHP generator in the UK context.

653 According to the result of mass balances from pilot scale tests and literature data, a plant having 5 t/h
654 feedstock processing capacity could produce and supply 4.4 MW electrical power and 5.3 MW
655 thermal energy with an overall electrical efficiency of 27.2% and overall CHP efficiency of 59.7%.

656 The most significant heat loss occurred in the pyrolysis process, where a considerable heat was
657 required to maintain the reaction temperature of the pyrolyser.

658

659 The economic analysis indicated that the levelised electricity cost of the plant was £0.063/kWh,
660 which agree the range of UK EfW cost as evaluated by the UK government. The capital investment
661 was calculated to be £6.23 million per megawatt for the specific plant evaluated. The breakdown
662 analysis of the production cost showed that the capital cost was the largest part of the LCOE.

663 Following that were the costs of biodiesel fuel, waste disposal, labour, utility and plant maintenance
664 and overheads. Compared to the product sales, the income from feedstock gate fee and the renewable
665 incentive payment played a more significant role in offsetting the production cost. This implied the
666 importance of the government's and policymakers' role in the economic viability of such projects.

667 To maximise the feasibility of a project, the technology developer should endeavour to seek the
668 routes to reduce electricity production cost and identify the target customers that can pay electricity
669 at a high rate. Special attention should be given to the most influential factors as indicated in the
670 sensitivity analysis, such as feedstock cost (or gate fee for waste), enhancing the plant availability,
671 increasing the productivities of the fuels and electric power, reducing equipment costs and ensuring
672 the heat sales can meet the target level.

673

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679

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