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

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Abstract

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

KEYWORDS:

Municipal Solid Waste (MSW); Energy from Waste (EfW); Combined Heat and Power (CHP); Intermediate Pyrolysis; Techno-economic Analysis

ABBREVIATIONS

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

1. Introduction

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

With over 130 year’s history, direct combustion/incineration has been the most widely employed technology in waste management and the energy recovery industry. A modern incineration system can process kilo tonnes per day that combust all the organic fraction in the MSW feedstock to raise steam for large-scale steam turbine generators; however, the overall electrical efficiency of the plant is typically around 20% [3,4]. Following increasing concerns over environmental issues and strong growth in the future EfW market, it is increasingly important that more efficient and flexible technologies with high standards of emission control are developed.

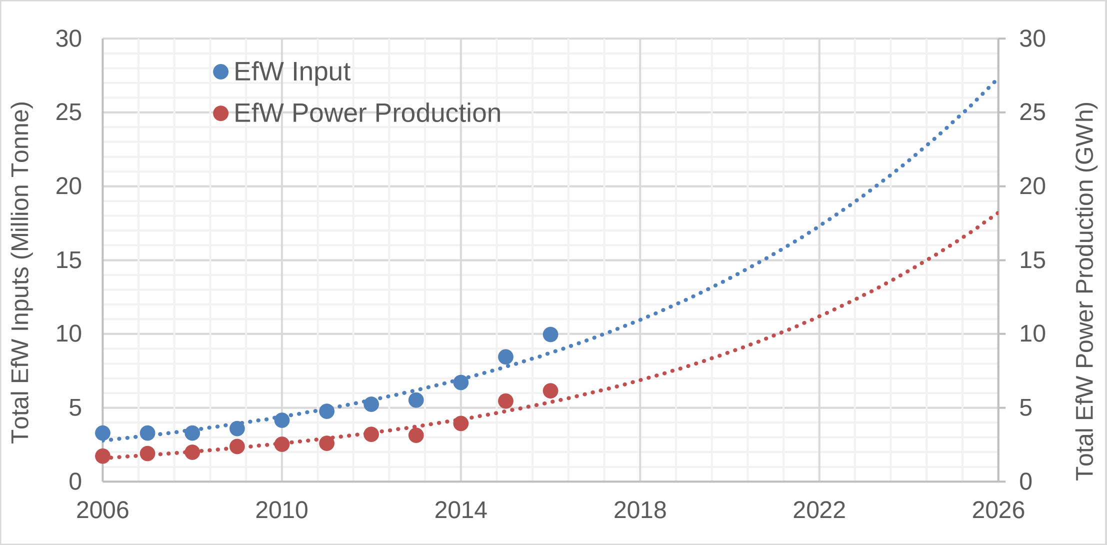


Figure 1. Industrial development of Energy from Waste in the UK

Alternative thermal EfW processes proposed by researchers frequently involve advanced conversion technology (ACT), namely pyrolysis [4] and gasification [5]. Pyrolysis is the thermal decomposition of organic materials in the absence of oxygen at elevated temperatures of around 500 °C. The feedstock is converted to liquid, gaseous and solid products in varying proportions with potential in biofuel applications. Gasification involves a partial combustion process at over 800 °C with the controlled presence of air/oxygen, and it converts solid organics into a fuel gas containing mainly CO, CH_4, H_2 and CO_2. Industrial development and commercialisation of ACT in waste energy recovery began in the 1960s. For example, the Norwegian company ENERGOS has established over 10 EfW plants based on gasification and steam turbine generator across Europe [6], including the Isle of Wight gasification plant, which was operational from 2009 to 2017 with a processing capacity of 30,000 tonne MSW per year and an electrical power output of 1.8 MW [7]. The company claims the plant availability can reach as high as 8000 hours per year. Nevertheless, a recent report from

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

Along with industrial EfW development, there have been a number of research studies that have addressed technical novelties in different aspects of the thermochemical conversion of different waste materials for EfW. These include co-processing of different types of feedstock, for example, co-gasification of waste with coal [9], co-pyrolysis of waste with biomass and other wastes [10,11] and application and integration of advanced technologies, for example study of thermal catalytic reforming [12] and integrations of advanced pre-treatment system [13] and plasma gasification reactors [14]. For any novel energy system, a sound understanding of the technical and economic performance at industrial scale is essential, as it provides key information about the project and helps the project developer to identify the direction that can ensure the effort and investment are targeted at the areas of most significant impact. However, not much work has been carried out in this respect. Ledon et al. [15] carried out an exergo-economic analysis of a hypothetical MSW gasification system integrated with a combined cycle power system in Chile. It was found that the energy loss in the gasifier accounted for nearly 60% of the total energy loss. Use of a higher gasification temperature and/or lower equivalence ratio could result in better overall system performance. The author claimed that the power production through the proposed process could be economically viable, comparing performance to the current Chilean energy market. Salman et al. [16] performed a techno-economic analysis on a new process with coupled anaerobic digestion of MSW and pyrolysis of digestate that gave high-efficiency bio-methane production. In this process, char obtained from pyrolysis was added to the digester as a medium for toxic chemical/micro-organism adsorption and development of a stable microbial community. The pyrolysis liquid and gas produced in the pyrolysis process were steam reformed into syngas and converted to bio-methane through the methanation process. The economic analysis on a 23,000 tonne per year plant indicated a positive result with a payback period of about six years. Sensitivity analysis on the project indicated the change in product price is the major influencing factor for the project profitability. Luz et al. [17] carried out a techno-economic analysis on MSW gasification for power generation in Brazilian municipalities. Net present value (NPV) and the internal rate of return (IRR) were selected as economic indicators for the evaluation. The technical analysis indicated that the gasification and engine plant would have electricity production of between 794 and 1065kWe per tonne MSW input. The authors concluded that large plants with high installed power tend to be more economically viable, but without incentives from governments, such plants are unlikely to be built. Arena et al. [18] evaluated the techno-economic performance of a fluidised bed gasification and steam turbine system for processing mixed plastic waste (MPW) for power generation at 2-6 MW capacity. Based on the results from a pilot-scale system, the plant would have a total energy conversion efficiency of 23.7% for electricity. With a total plant investment at €4.79 million per megawatt capacity, the plant would generate an internal rate of return of 8.3%. The authors recommended that further governmental incentives for renewable energy are required to enable the project to be economically attractive to investors. Rezaei et al. [19] conducted an economic assessment for power generation from MSW under different scenarios in Iran. They found that gasification based EfW systems would be economically viable when the MSW feedstock could attract a gate fee of US$126 per tonne and the power was sold under a purchase agreement of US$0.276/kWh. In the 2016 Arup/DECC’s publication on UK electricity generation cost [20], it was stated that the 2016 LCOE of ACT-based EfW system with CHP was between £89 and £189 per MWh, and the capital cost of such systems was up to 16.53 million per MW. The capital cost of EfW with CHP in 2016 was 6.2 million per MW, as indicated in Parsons Brinckerhoff’s report on electricity generation costs model [21].

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

2. The Process Model

2.1. Feedstock

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

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

Table 1. Characterisation of the organic fraction of MSW feedstock (on a dry basis) evaluated 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

* calculated by difference;

2.2. The integrated Pyro-CHP system

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

The system boundary of the process model includes all processing steps from feedstock reception to the energy production and waste disposal. The starting point of the model is the entry of the received feedstock into the feedstock storage units. The two endpoints of the model are: (1) the output of the electrical power and heat from the CHP system and (2) the output of ash and pyrolysis water for disposal.

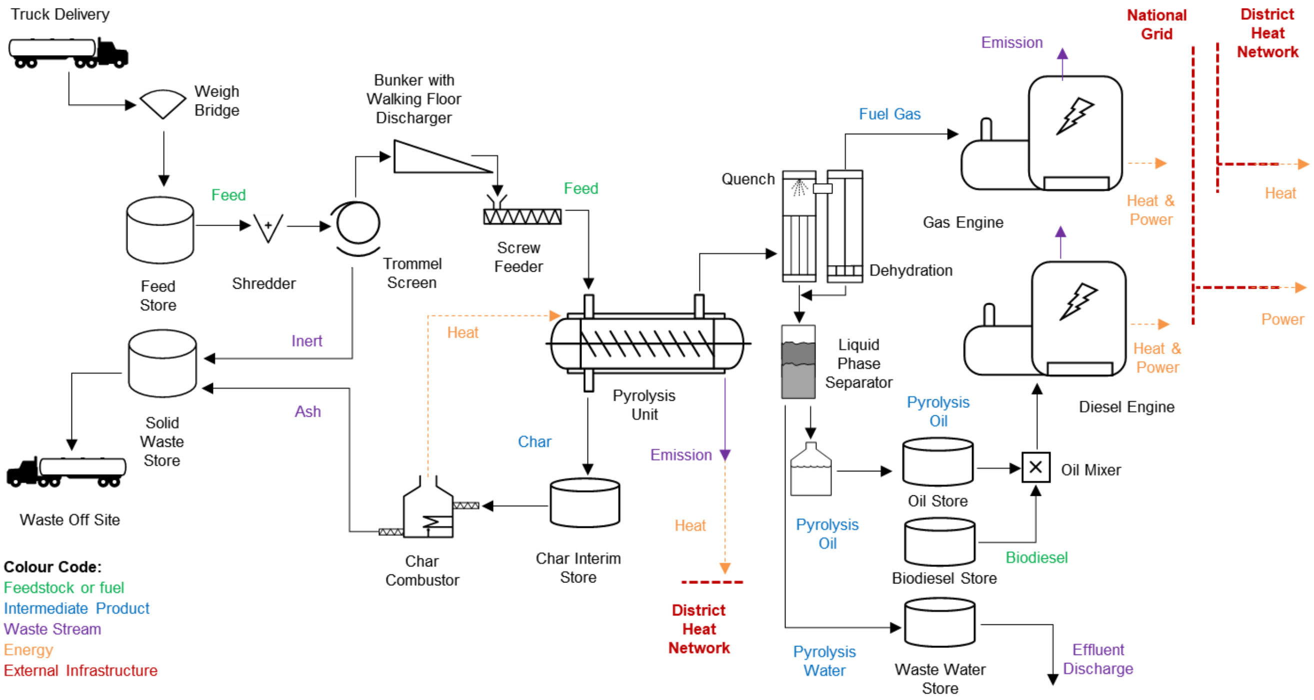


Figure 2. Schematic diagram of the overall EfW process based on pyrolysis and CHP

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

2.2.1. Feedstock handling and pre-treatment

A series of handling and pre-treatment steps are required to process the received feedstock to ensure the characteristics of the feedstock for the feeder and pyrolysis reactor Upon delivery, all the received waste is weighed on a 50-tonne weighbridge and then stored in an 18,000 m^3 concrete storage unit, which is capable of storing four weeks feedstock supply. Before feeding to the pyrolyser, the received MSW is shredded in a ball mill to reduce particle size to no larger than 20 mm. The shredded material undergoes trommel screening to ensure material particle sizes fall within appropriate limits. This step is also used to eliminate about 5% of feedstock moisture and 20% of the solid inert material in the feed such as metal, stones, glass etc. The oversize organic fraction is recycled to the shredder, and the separated inert material is sent offsite for disposal or recycling. The pre-treated feed is temporarily stored in bunker storage and then sent to the pyrolysis reactor's feeding screws by a discharge floor. A feed rate of 5 tonnes (wet) per hour was selected for this work.

2.2.2. The intermediate pyrolysis system

The intermediate pyrolysis reactor is an auger screw reactor, comprising a horizontal carbon steel vessel containing two co-axial rotating screws, which transports the feed and recycle the char inside of the reactor. The reactor has one inlet for the feed, one outlet for the solid product (char) and one outlet for pyrolysis vapours. The heating is provided externally through a heating jacket, and the pyrolysis temperature can be maintained up to 600°C. The novel feature of this reactor is the use of co-axial screws for internal char recycling. The hot recycled char acts both as heat transfer medium and as a catalytic cracking medium, thereby maintaining the desired temperature inside of the reactor and enhancing the secondary cracking reactions for pyrolysis vapours, so as to produce a higher fraction of permanent fuel gases (H_2 and CO) and lower molecular weight condensable organics and less heavy tars. The pyrolysis liquid is usually produced with clear phase separation under gravity. The liquid will be separated under gravity in the collection tank into two phases, i.e. an organic fraction (pyrolysis oil) and an aqueous fraction (pyrolysis water). The pyrolysis oil has a lower density than water, whilst the pyrolysis water remains in the bottom phase and can, therefore, be drained and pumped to a different storage tank. In this work, a heating temperature of 500 °C and a solid residence time of 10 minutes was selected for the reactor operating conditions. The detailed process mass balance is presented in Section 2.3 and the characteristics of the liquid, solid and gaseous products can be found in the previous related works [24,25].

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

2.2.3. Char combustion

The solid char product is collected in a char vessel as interim storage and then directly burnt in a char combustor at 1000 °C to generate hot gases to meet the heat requirement of the pyrolysis reactor. A controlled stream of hot combustion flue gas (at around 700°C) is pumped into the heating jacket located within the reactor skin to maintain the pyrolysis temperature at approximately 550 °C, which is slightly higher than the demanded heating temperature. The waste-derived char may be unsaleable in the market, as it usually has a high ash content and can contain contaminants. Therefore, all the char product is combusted onsite to minimise the solid waste for disposal. The high-temperature flue gas with (at around 300 °C) from the pyrolysis heating jacket will enter a heat exchanger for further heat recovery before being emitted to atmosphere.

2.2.4. Energy generation

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

2.2.5. Waste disposal

A significant waste stream generated in the plant is pyrolysis water, which is obtained as the aqueous fraction of the pyrolysis liquid separated from the pyrolysis oil. The aqueous liquid from pyrolysis typically contains various water-miscible chemicals produced during pyrolysis, such as alcohols, organic acids and ketones. This liquid is disposed of to industrial sewage works at a high cost due to the high chemical oxygen demand (COD) value. The ash from the char combustor is another waste stream, which is sent offsite and disposed of by landfill.

2.3. Process mass and energy balances

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

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

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

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

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

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

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

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

3. Economic Evaluation

3.1. General assumptions

The base year of this study was selected to be 2016. All cost data was updated by using an inflation rate of 3% to the present cost in 2016 Great British Pound Sterling (GBP) [26]. All the equipment cost values collected before 2016 have been adjusted to 2016 values by using the Chemical Engineering Plant Cost Index (CEPCI) [29]. These Chemical Engineering Economic Indicators (EI) 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 EI_{2016}= 541.7. Some cost data was collected in the currencies of EUR and USD. They were converted at the rates of EUR: GBP=1: 0.8187 and USD: GBP= 1: 0.7402 (average exchange rates in 2016) [30].

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

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

3.2. Capital cost

In this work, the total capital requirement for the Pyro-CHP plant was calculated by using the economic analysis model developed by Bridgwater et al. in the early 2000s [26]. The total plant cost (TPC) was used as the measurement of the project capital cost, which is the total amount of capital required to finance the whole system to the point at which it is ready to operate. This includes the costs incurred in pre-development and during the construction stage. The calculation of TPC starts with the summation of the equipment cost (EC), which is the cost of purchasing brand new equipment for all the components in the subsystems and delivered to the plant gate. The ECs used in this work were collected from quotations provided by suppliers when available, otherwise were taken from published data in the literature. Incremental factors were included for erection, instrumentation, piping and ducting, associated electrical equipment, structures and buildings, civil works and lagging, to give a direct plant cost (DPC). Costs of engineering design and management overheads are then added to give an installed plant cost (IPC), and finally commissioning costs, contractor's fees, interest during construction and a contingency element are added to give the TPC. These increments are less specific to system modules, being usually approximated as fixed percentages of direct plant cost. According to a study for a similar system, the TPC was chosen to be 1.69 times the DPC, which was the production of the EC and a number of multiplication factors [26,35]. The breakdown of the ECs and calculated TPC are presented in Table 3.

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**
Pre-treatment Section				
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	*
Pyrolysis				
Pyrolysis system with liquid collection	5 t/h	1	3,995,224	[22]
Gas dehydration column	2,000 m3/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	*
Generation				
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	

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

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

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

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

3.3. Operational cost

3.3.1. Feedstock and gate fee

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

3.3.2. Fuel

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

3.3.3. Utility

Utility costs include electricity and water usage in the plant. In this work, electricity is consumed within the general plant site, office/laboratory usage and the parasitic load of the plant. The electricity is imported from the grid to ensure stable operation of the plant The majority of the water usage is for pyrolysis process cooling.

The electricity consumption rate was estimated to be 28 kWh per tonne of wet MSW treated. This was converted from the data quoted by Bridgwater et al. [26] and Diebold et al. [41] based on processing dried biomass in a pyrolysis plant. The average 2016 electricity price for UK medium industrial consumer was taken to be £0.1084 per kWh [42]. The water usage was estimated to be 13 m^3 per tonne of wet MSW treated. The water utility cost includes the cost of water usage and sewerage surcharges. According to a UK water supplier, the water cost for a plant at the proposed scale in 2016 should consist of a fixed annual charge of £1724 and a unit price of £0.2609/m^3. The sewerage charge should consist of a fixed annual charge of £5,673 and a unit price of £1.2347/m^3 [43].

3.3.4. Waste disposal

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

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

Where R is reception and conveyance at a fee of £0.1813/m^3; VB is volumetric and primary treatment for £0.3305/m^3; O_t is the chemical oxygen demand (COD) of the trade effluent after one-hour quiescent settlement, determined by milligram of COD per litre liquid; O_s is the mean strength of settled sewage at a wastewater plant taken to be 489 COD mg /l; B is a biological treatment for

£0.2698/m^3; S_t is total suspended solids of the trade effluent, determined by milligram of solid content per litre liquid; S_s: the mean suspended solids content at a wastewater plant, taken to be 415mg/l; S is the sludge treatment and disposal for £0.2032/m^3. In this work, the COD of the untreated aqueous liquid is 94g/L, and total suspended solid content is less than 5mg/l. This gives a calculated cost of trade effluent of £52.38 per tonne of aqueous liquid discharged.

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

3.3.5. Labour

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

3.3.6. Plant maintenance and overheads

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

3.4. Energy product sales

3.4.1. Electricity and heat sales

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

3.4.2. Renewable energy incentives

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

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

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

3.5. Levelised cost of electricity (LCOE)

The LCOE is the minimum selling price of the product, which covers the costs of energy production [32]. It is often cited as an effective measure of the overall competitiveness of different energy generating technologies by the authorities [53]. In this work, the proposed system produces combined electricity and heat. The calculation of LCOE assumes the customers can purchase the heat at its market price and the associated government incentive subsidies have been paid.

The LCOE is calculated as:

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

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

3.6. Internal rate of return (IRR)

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

The following formula is used to calculate the NPV:

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

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

When the NPV equals zero, the value of discount rate r is the IRR of the project. The IRR can be used as an indicator of the potential probability of the project, by comparing with the target IRR. For a novel technology with a high risk associated, the target IRR may be up to 25% [54]. The Corporation Tax rate for the company profits was taken to be 20%, as the actual 2016 rate in the UK [21].

4. Results and Discussion

4.1. Overall process efficiencies

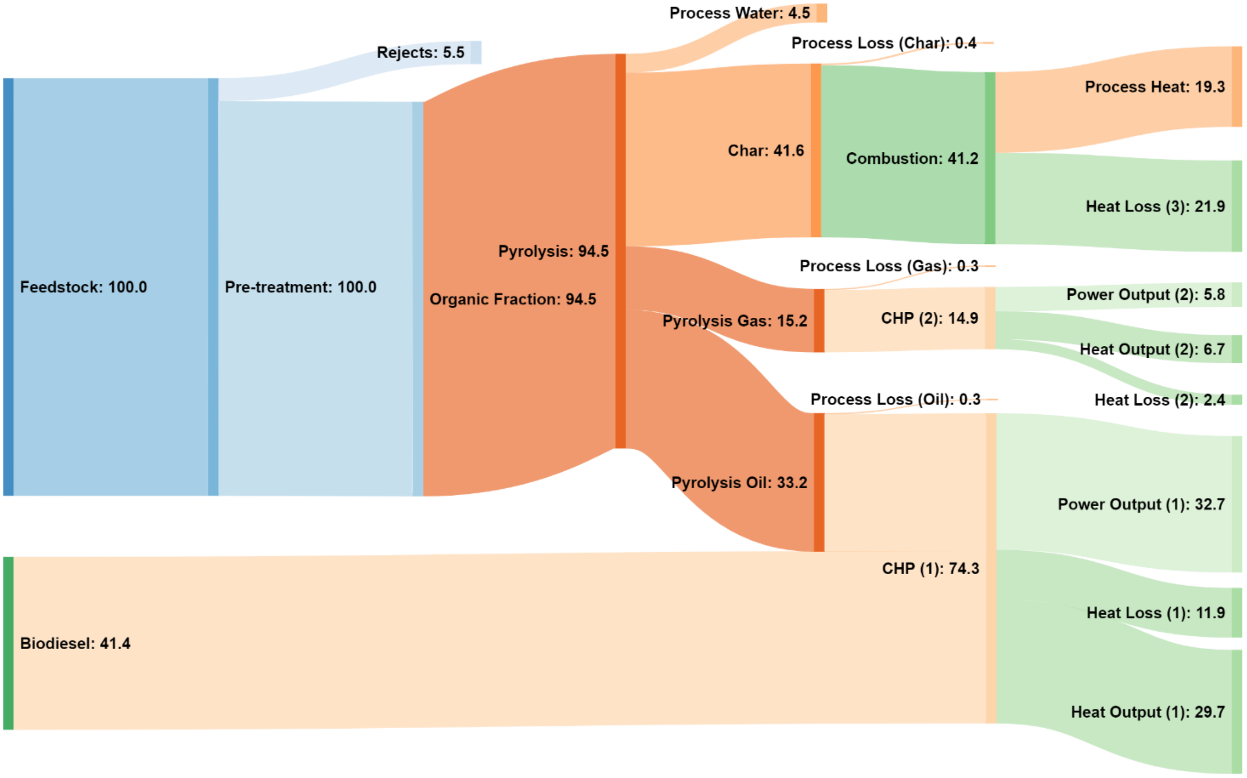
Table 4 presents the process mass and energy balances of the overall EfW plant and the overall system efficiencies calculated by the model as described in Section 2.3 [22,55]. Further illustration of the process energy conversion is presented in Figure 3.

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

	Description	**Mass (kg/h)**	**Energy (kW)**
Feedstock Pre-treatment			
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
Pyrolysis			
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
Energy Generation			

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
Total Plant Output			
Power	Output as a final product		4,436.03
Heat	Output as a final product		5,296.55
Process Waste			
Solid Rejects and Waste	Waste to offsite	1,383.9	
Aqueous Liquid	Waste to disposal	1,350.5	
Process Efficiency			
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%

During the pre-treatment stage (shredding and screening), approximately 20% of the inert components and 5% of organic components in the feed was screened out, along with 25% of the moisture in the MSW. The solid rejects are sent out of the plant as solid waste at a rate of 782.5 kg/h. Therefore, 4217.5 kg of a pre-treated organic fraction of MSW was fed into the pyrolysis reactor per hour, which is equivalent to 94.5% of feedstock energy input (11,527.8 kW). As described in Section 2.3, the intermediate pyrolysis system converts the wet solid feed into 11.6% organic liquid (pyrolysis oil), 32.0% aqueous liquid (pyrolysis water), 17.4% fuel gas and 39.0% char. After separation from the aqueous fraction/ pyrolysis water, the pyrolysis oil (491.2 kg/h and 3,825.6 kW) was stored in the oil tank for engine use. The total energy content of the pyrolysis oil accounted for 33.2% of the feedstock energy input. The char production rate was 1,643.8 kg/h, accounting for 41.6% of the feedstock energy. All the char was combusted on site, and this was used to generate 4,794.7 kW heat to meet the minimum heat requirement of the pyrolyser, which was 2,222.5 kW. The fuel gas consisted of nearly 40 vol. % combustible fraction with a production rate of 732.0 kg/h giving an energy input of 1,713.9 kW to the gas CHP engine. The pyrolysis oil was blended with biodiesel at 50/50 to fuel the liquid CHP engine. This, in total, was able to generate 4,436 kW electrical power and 5,297 kW heat in the form of hot water. The system can achieve an electrical efficiency of 27.2%, a CHP efficiency of 84% and an overall heat and power efficiency of 59.7%.



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

Figure 3. Process energy flow

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

4.2. Levelised cost of electricity

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

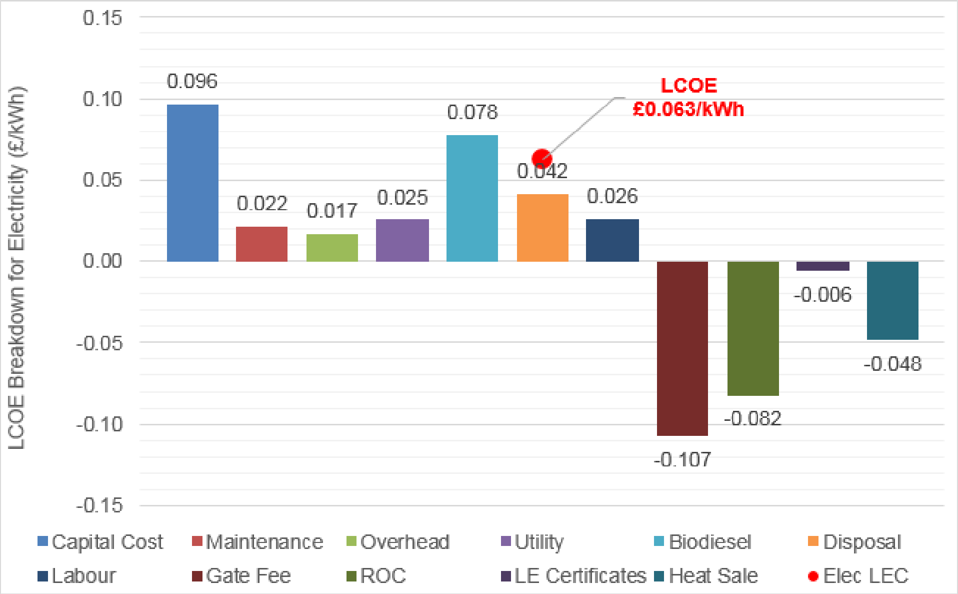


Figure 4. Levelised Energy Cost (LCOE) and its Breakdown

The capital investment of the proposed project was calculated as £6.23 million per megawatt. This is close to the lower end of the range (£5.33-£16.41/MW) of the UK bioenergy capital requirement according to the Arup's recent estimation (the range was derived after deduction of general infrastructure cost from the original data quoted in the report, which accounts for 20% of the total cost but was not considered in this work) [20]. As shown in Figure 4, this is the most significant contributing factor in the LCOE. Following this is the cost of using biodiesel to blend with the pyrolysis oil for energy production, which is the highest cost in the operating cost category. Disposal costs incurred, the char/ash to landfill (62% of the total) and wastewater disposal (38% of the total), is the second highest cost during the plant operation. However, it is worth noting that this work did not consider the opportunity in selling ash to cement businesses, which otherwise may avoid a cost but attract an additional revenue stream. There is also a possibility of investing in additional wastewater treatment facilities, which can reduce the COD of the pyrolysis water and consequently reduce the cost of trade effluent. The labour and plant utility costs are at a similar level. The cost of plant maintenance and overheads are insignificant compared to the other factors.

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

4.3. Sensitivity analysis

Figure 5 presents the effects of input parameter variation on the LCOE, which takes into account the uncertainties in these single variables. Fourteen key input parameters related to the project capital cost, operating costs and productivities are analysed in turn with ± 20% changes to their baseline data. This can be used to determine how variation in key variables can impact the LCOE and consequently help the project developer to identify strategies for reducing production cost.

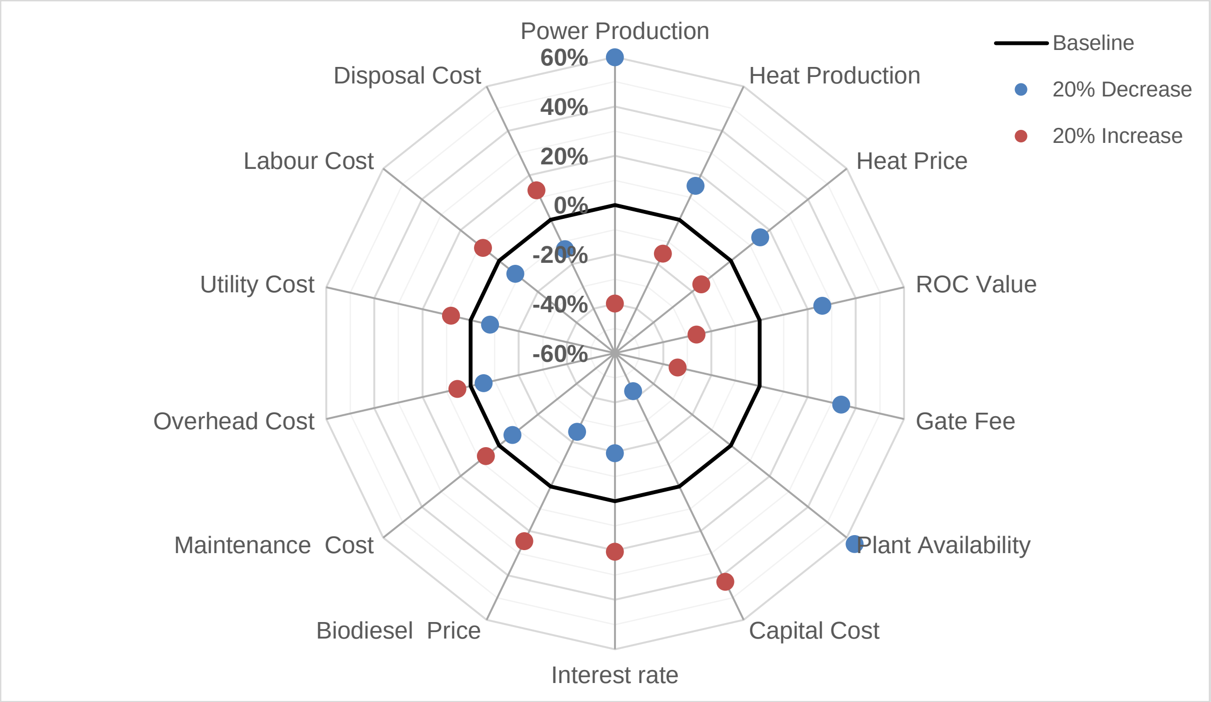


Figure 5 Sensitivity analysis for calculated LCOE

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

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

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

4.4. Internal rate of return

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

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

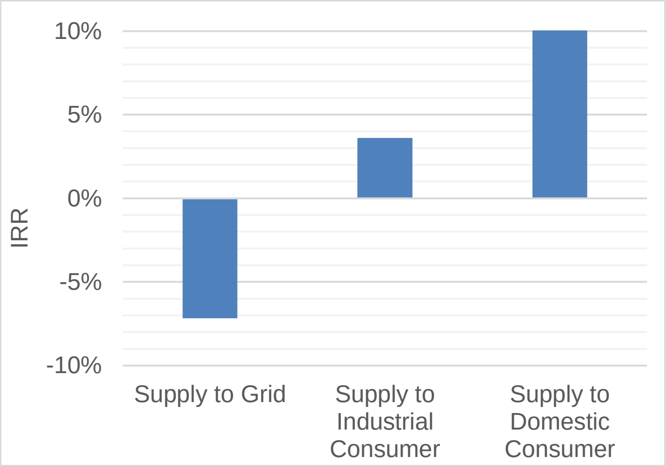


Figure 6. Internal rate of return

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

5. Conclusions

This work has presented the results of a techno-economic analysis on a conceptual proposed Pyro-CHP plant based on an intermediate pyrolysis system and CHP generator in the UK context. According to the result of mass balances from pilot scale tests and literature data, a plant having 5 t/h feedstock processing capacity could produce and supply 4.4 MW electrical power and 5.3 MW thermal energy with an overall electrical efficiency of 27.2% and overall CHP efficiency of 59.7%. The most significant heat loss occurred in the pyrolysis process, where a considerable heat was required to maintain the reaction temperature of the pyrolyser.

The economic analysis indicated that the levelised electricity cost of the plant was £0.063/kWh, which agree the range of UK EfW cost as evaluated by the UK government. The capital investment was calculated to be £6.23 million per megawatt for the specific plant evaluated. The breakdown analysis of the production cost showed that the capital cost was the largest part of the LCOE. Following that were the costs of biodiesel fuel, waste disposal, labour, utility and plant maintenance and overheads. Compared to the product sales, the income from feedstock gate fee and the renewable incentive payment played a more significant role in offsetting the production cost. This implied the importance of the government's and policymakers' role in the economic viability of such projects. To maximise the feasibility of a project, the technology developer should endeavour to seek the routes to reduce electricity production cost and identify the target customers that can pay electricity at a high rate. Special attention should be given to the most influential factors as indicated in the sensitivity analysis, such as feedstock cost (or gate fee for waste), enhancing the plant availability, increasing the productivities of the fuels and electric power, reducing equipment costs and ensuring the heat sales can meet the target level.

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