Economic evaluation of a hypothetical integrated energy recovery system for trommel fines

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Abstract

Trommel fines are a high-ash aggregate waste derived from material recycling facilities (MRFs) and are usually disposed in landfill. Increasing UK landfill tax and environmental concerns, however, calls for a flexible technology that can effectively process and extract valuable energy from trommel fines at high efficiencies. One possible technology is fast pyrolysis coupled to a combined heat and power (pyro-CHP) plant. To determine the feasibility of such technology, an understanding of its economic characteristics is required, in addition to the technical details. This study presents an economic evaluation of a pyro-CHP plant processing three pre-treated trommel fines feedstocks for energy recovery over a 20-year period. The three feedstocks were designated as DPT (from initial size reduction), AW (from ash reduction by washing DPT with water) and AWS (from ash reduction by washing DPT with aqueous surfactant solution). Under all processing capacities (200 kg/h to 2000 kg/h) total revenues from the pyro-CHP system were higher than landfill costs, but only became profitable at 2000 kg/h processing capacity for the DPT feedstock. Further analysis showed positive net present values (NPV) only for AW and AWS, e.g. at 2000 kg/h capacities, with payback periods of about 14 years compared to 35 years for DPT at a fixed CHP efficiency of 60% and 20% internal rate of return (IRR). Sensitivity analysis carried out using different values of IRR and CHP efficiencies, confirmed the superior economic performance of the washed feedstocks over DPT, with payback periods reducing to about 6 years in some cases.

Key words: *Trommel fines, landfill, energy from waste (EfW), fast pyrolysis, combined heat and power, economic evaluation*

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1.0 Introduction

The application of thermochemical processing for energy, chemicals and materials recovery from solid wastes fits perfectly with the global goals of Circular Economy and Zero Waste (EU CEAP, 2020) . In particular, pyrolysis can be applied as an adaptable thermochemical technology to a range of heterogeneous wastes with high organic fractions such as municipal solid wastes (MSW) (Ates et al., 2013), refuse-derived fuels (RDF) (Bosmans et al., 2013) and mixtures of plastic waste (Miskolczi et al., 2013). Depending on the type of pyrolysis process, valorisation of heterogenous waste streams can be in the form of liquid products (pyrolysis oils) (Khan et al., 2016), low - medium calorific value gas products (Zhou et al., 2015), and solid residues or char (Turan, 2020). For instance, fast pyrolysis is suitable for producing pyrolysis oils as the main product, which can be used as fuel or as feedstock for chemicals (Bridgwater, 2012). In the UK, the application of pyrolysis and gasification technologies for MSW treatment is relatively in the early stages of commercial operations, compared to the more established plants operating in North America, Europe and Japan (UK DEFRA, 2013).

The driving factors behind recent developments in thermochemical technologies in the UK are; increasing landfill costs (as a result of the Landfill Tax) and the implementation of the Waste (Circular Economy) (Amendment) Regulations 2020 (UK CEAR, 2020), which originated from the EU Landfill Directive (CEC, 1999). The UK Government is also promoting Circular Economy by encouraging diversion of wastes from landfill through increased recycling. A type of waste of growing interest to operators of material (waste) recycling facilities (MRF) is trommel fines. This highly heterogeneous waste results from the trommel screens used during waste processing in MRFs and were previously destined for landfill disposal in the UK. In 2016, the UK Government increased the associated landfill gate fees for trommel fines by a factor of 45 (from £2.5 per tonne to £115 per tonne), in a bid to encourage landfill disposal. This increased gate fees is applied on trommel fines with over 10% loss on ignition (LOI), following a standardised ashing test (UK HMRC, 2016). This has greatly increased the disposal costs for waste recyclers, who generate about 4.5 million tonnes of trommel fines each year and now seek alternative disposal routes. Trommel fines contain significant proportions of organic or combustible matter (>60 wt%, dry basis) as well as ash (Eke, Onwudili, & Bridgwater, 2017).

The increase in landfill tax rate for trommel fines would mean that an MRF operator producing 40 tonnes of trommel fines per day will see their landfill tax bill increase from £25,000 per year to about £1.1 million per year (UK HMRC, 2014; Watts, 2016). In the UK about 4.5 million tonnes of trommel fines are generated annually (UK HMRC, 2014), hence the disposal costs to MRF operators would be about £520 million per year. Therefore, extending fast pyrolysis technology to trommel fines may be a good valorisation route and results of such studies have been published recently (Eke, Bridgwater and Onwudili, 2020). These studies showed that significant pre-treatment was however, required to prepare trommel fines obtained from a UK-based MFR operator (Biffa Ltd) for fast pyrolysis in order to achieve high conversion efficiencies. The pre-treatment methods used in these studies included physical separation of visibly large stones, followed by grinding and sieving for size reduction (Eke, Onwudili, & Bridgwater, 2017). In addition, further wet treatment by washing with water and aqueous solution of surfactant was carried out on the dry pre-treated feedstock to reduce the ash contents (Onwudili, & Eke, 2020).

Following the results from the fast pyrolysis of the pre-treated trommel fines feedstocks (Eke, Bridgwater & Onwudili, 2020), it has become important to carry out a simple economic evaluation on the trommel fines-to-energy conversion process. This present study considered the economic aspects of a hypothetical integration of the trommel fines fast pyrolysis process with a combined heat and power (pro-CHP) generation system. The originality of this study was to present an economic performance model for the pre-treated trommel fines from the fast pyrolysis stage, based on the results from previously published experimental work (Eke, Bridgwater & Onwudili, 2020) to the hypothetical CHP system output.

This work was designed to identify the major technical and economic parameters that influence the economic performance of the Pyro-CHP system, such as system scale, feedstock pre-treatment choice, fast pyrolysis conversion efficiency, CHP efficiency and Internal Rate of Return (IRR. This present work therefore contributes new knowledge to the field of waste-to-energy (WtE) engineering on the subject of economic assessment of trommel fines valorisation based on a robust performance model. The results of this work can provide valuable data for solid waste processors and policy makers to consider pyro-CHP as an option for the handling of growing problem wastes such as trommel fines. The conclusions of this study would highlight some of the economic realities involved in waste-to-energy projects for trommel fines.

2.0 Methodology

2.1 Overall structure

In this section, the performance model formulation, the limits of the model scope and details of assumptions made relating to the technical aspects of the modelled system are presented. This model was based on the application of fast pyrolysis for energy (electrical and heat) recovery from the pre-treated trommel fines feedstocks. In this case, the feedstocks and products have been evaluated on the basis of their calorific values (extractable energy contents). Three different feedstocks were prepared and used for fast pyrolysis, namely; feedstock from dry physical pre-treatment via size reduction and separation (DPT), feedstock from aqueous washing of DPT for ash removal (AW) and feedstock from aqueous washing of DPT with added surfactant (AWS) (Onwudili, & Eke, 2020). Table 1 shows the yields and calorific values of fast pyrolysis products (liquid, gas and solid residue) from the different trommel fines feedstocks prepared for fast pyrolysis. This present study considered the pyrolysis oil and gas products as vapour-phase fuels for direct use in a hypothetical CHP plant.

Table 1: Pre-treated trommel fines feedstocks fast pyrolysis product yields and calorific values

	DPT		**AW**		**AWS**	
	Yield (wt.%)	HHV (MJ/kg)	Yield (wt.%)	HHV (MJ/kg)	Yield (wt.%)	HHV (MJ/kg)
Feedstock	-	13.6	-	15.7	-	16.1
Pyrolysis oil	19.6	26.9	36.5	26.3	34.8	27.7
Gas	12.9	2.10	16.7	2.70	15.8	2.25
Solid residues	52.1	4.10	31.7	4.31	33.5	3.43
Reaction water	13.0	-	8.30	-	8.69	-
^{a} Conversion efficiency (η, %)	-	41	-	64	-	62

DPT - Dry pre-treated Trommel Fines; AW – Agitated Washing; AWS – Agitated Washing with Surfactant (Decon Neutracon); ^{a} from pyrolysis oil and gas only

The model was constructed in three sections on an Excel spreadsheet and each section was represented by a tab (Patel, 2011). It enabled the estimation of the capital and operating costs of processing the feedstock using fast pyrolysis and the revenues that could be generated through the sale of electricity and heat at different system scales. The results were then compared to the cost of landfilling the waste based on current HMRC landfill tax rates. The cost and revenue values for the different plant capacities were utilised in an economic evaluation for calculating the total investment repayment period.

Delimitations: The starting point of the model was the upstream pre-treatment of the trommel fines feedstock. The end points of the model were: (1) the output of the electricity and heat from the engine CHP system and (2) the output of solid residue to the solid collection pot. The downstream use of the solid residues (ash and char) were not included in the scope of the model used.

Base-case scenario: In this model, a base-case scenario was defined on the basis of the experimentally derived conversion efficiency of the dry pre-treated feedstock (DPT) from the fast pyrolysis stage to the theoretical liquid product utilisation for power and heat production. The yields and calorific values of fast pyrolysis products obtained from DPT (Table 1), showed that the energy contents of the large amounts of solid residues (> 33 wt%) were relatively small compared to liquid products, and would require a separate solid handling combustor to extract its energy. Hence, economic use of the solid residue for energy was considered complicated and therefore ignored in this work. Although, the increasing acceptance and use of pyrolysis solid residues (char, biochar and ash) for soil remediation is interesting and indicate potential economic value. Such uses have been shown to give benefits of heavy metals removal, improving soil enzymatic activities and the impacts of these on plant nutritional quality and antioxidant defence system (Turan, 2020). While the gas products also had low calorific values, they would be combusted the same stream as the vapourised liquid products in the CHP plant, hence, the gas products were included. Therefore, in the present study, the liquid and gas products of fast pyrolysis were essentially hypothetically combusted in a CHP engine for energy production.

Calculation methodology: Figure 1 displays the schematic of calculations used in the economic evaluation model for energy production (TAB 1). The calculations were done on a one-year basis as the nominal accounting period. Firstly, the process conversion efficiencies from Table 1 were incorporated into TAB 1, where the total calorific values (CV), total capacities, CHP efficiency factor, total available energy, units produced, selling price per unit of heat and electricity were determined and calculated for a period of one year, according to equations 1-7.

$$Total\ energy\ content\ of\ feed\ pyrolysed\ \left(\frac{MJ}{year}\right) =$$

$$CV\ of\ feedstock\ \left(\frac{MJ}{kg}\right) x\ \ capacity\ \left(\frac{kg}{h}\right) x\ operating\ hours\ \left(\frac{h}{year}\right) ----(1)$$

$$Total\ energy\ in\ fast\ pyrolysis\ products\ \left(\frac{MJ}{year}\right) =$$

$$\sum CV\ of\ products\ \left(\frac{MJ}{kg}\right) x\ Yield\ \left(\frac{kg}{h}\right)\ x\ operating\ hours\ \left(\frac{h}{year}\right) ----- (2)$$

$$Fast\ pyrolysis\ conversion\ efficiency, \eta_p =$$

$$\frac{Total\ energy\ in\ fast\ pyrolysis\ products\ (liquid\ and\ gas)\ \left(\frac{MJ}{year}\right)}{Total\ energy\ in\ feed\ pyrolysed\ \left(\frac{MJ}{year}\right)} ----3$$

$$Total\ \ available\ energy\ from\ fast\ pyrolysis\ \left(\frac{MJ}{year}\right) =$$

$$Total\ energy\ in\ feed\ pyrolysed\ \left(\frac{MJ}{year}\right) \times\ \eta_p ----------------(4)$$

$$Total\ \ energy\ generated\ per\ year(MJ) =$$

$$Total\ avaiable\ energy\ from\ pyrolyis\ \left(\frac{MJ}{year}\right) \times CHP\ efficiency\ factor, \eta_{CHP} - (5)$$

$$Total\ \ units\ produced\ per\ year\ (kWh) =$$

$$\left(\frac{Total\ energy\ generated\ per\ year\ (MJ)}{3.6\,\frac{MJ}{kWh}}\right) - - - - - - - - - - - - - - - - - - (6)$$

$$Total\ \ revenue\ from\ energy\ produced\ per\ year (£)\ =$$

$$Total\ \ units\ produced\ per\ year\ (kWh)\ \times Unit\ selling\ price\ \left(\frac{£}{kWh}\right) - - - - - - (7)$$

TAB 2 was used to calculate annual gate fee revenue based on the different processing capacities for comparison. TAB 3 was used to estimate the capital and operating costs of running the fast pyrolysis plant at the different scales. The values obtained from TAB1, TAB2 and TAB3, were then fed into TAB4 to determine economic feasibility.

2.2 General assumptions and limitations

To carry out the above calculations, the following key assumptions were made;

a) The base year for this study is 2014 as this was the year this research commenced.

b) All data have been updated using an inflation rate of 3% to present costs in British Pound Sterling (Yang et al., 2017).

c) The assumed annual plant operating time is 8000 h (Sinnott, 2005) and the total project life is taken to be 20 years.

d) The fast pyrolysis process is incorporated in an existing MRF-type operation where energy-from-waste (EfW) is being added as an enhancement to the current capability. Thus, implying an assumption of zero feedstock transportation cost to the energy production facility since waste collection and delivery would be provided by the customer.

e) The DPT trommel fines fast pyrolysis systems are evaluated at four different capacities: 200, 600, 1000 and 2000 kg/h. For fast pyrolysis system exceeding this capacity, multiple reactor units are used (Yang et al. 2017)

f) All the pyrolysis oil and gas produced in the pyrolysis system are used to generate electrical power and heat in a hypothetical CHP plant, which will be sold through the grid and heating networks. The costs of setting up a network through which the electricity and heat could be distributed have not been considered because it is assumed that the end customer would be in the same area where energy production is taking place.

g) The trommel fines landfill cost was assumed to be £115/tonne while the gate fee cost was assumed to be £100/tonne (Letsrecycle.com, 2020). This gate fee is paid to the trommel fines processors within the plant to avoid landfill gate fees.

h) The cost of the Decon Nutracon Surfactant was £8/L and its usage in the work was at a rate of 7.5 ml/tonne of feedstock (i.e. £0.06/tonne).

i) The washing water is assumed to be 100% recycled using a dedicated equipment (Wet Separator MM S2000-300); so, cost of this utility is very small compared to the capital cost of the equipment.

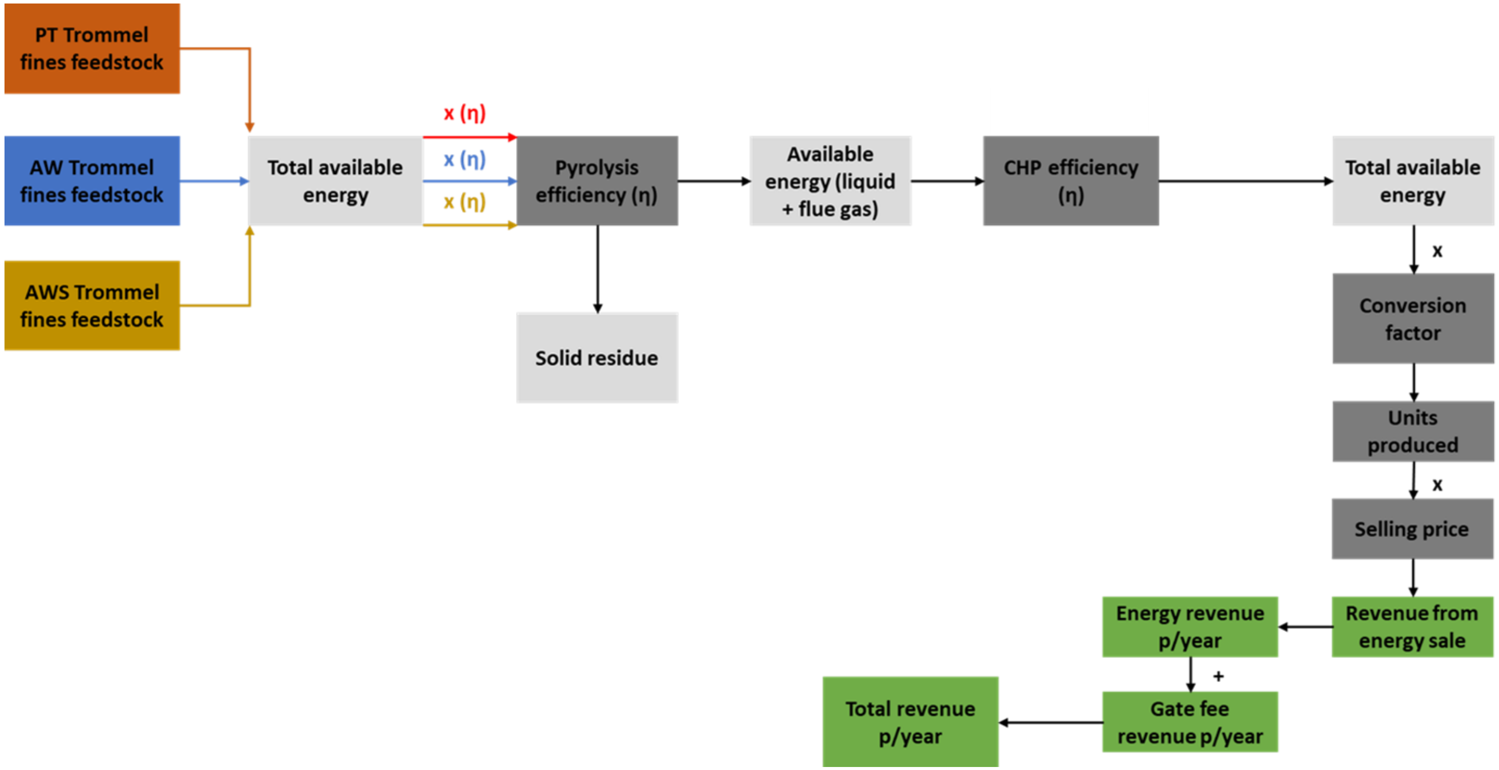

Figure 1: Structure of economic evaluation model indicating TAB1 created and used in Microsoft Excel Spreadsheet

To clarify, it is assumed in the economic evaluation model that the EfW facility would be integrated in the MRF and that the end customer, typically, a manufacturing process would consume the energy on a permanent basis (Lima, 2014).

2.3 Specific assumptions

a) The conversion efficiency of the fast pyrolysis process was calculated using Equation 3 and presented in Table 1.

b) The pyrolysis oils produced from the trommel fines feedstock are assumed to have consistent quality in terms of yield, calorific values and combustion characteristics at the different scales used in this economic analysis.

c) The efficiency of the CHP was assumed to be 60% (Carbontrust.com, 2018) for both heat and power, except for Section 3.3, where different CHP efficiencies were used for sensitivity analysis.

d) The electricity selling price (to the distribution grid) is taken as £0.055/kWh. The selling price for heat is taken to be £0.0349/kWh (UK DECC, 2015).

e) The total revenue per year is the sum of the revenue resulting from the sale of electricity and heat and the revenue resulting from gate fee charges.

f) Table SI1A shows the capital cost estimates used for the various pieces of equipment, with the different data sources indicated.

2.4 Capital investment

The capital investment was calculated as a total plant cost (TPC), which included both direct costs (installed equipment) and indirect costs (engineering, design, supervision, management, commissioning, contractor’s fees, interest accrued during construction, contingency) plus interest rate (Bridgwater et al., 2002). The baseline equipment costs of the fast pyrolysis system components used in this work were derived either from the cost estimates for the equipment available at the Aston University demonstration plant (i.e. the 1 kg/h fast pyrolysis reactor) or from the cost estimates provided by commercial suppliers or manufacturers (Yang, 2014; Anonymous, 2015). Traditionally, EfW projects attract high risk, which is then reflected in high interest rates (the technology is considered less proven and energy yield is very sensitive to fluctuations in chemical and physical properties of feedstock). Furthermore, there is a lack of pilot facilities that could assist with technical performance data. Therefore, based on work in literature for similar economic studies and the risk on capital investment, an interest rate of 20% has been used in this study (OECD/IEA/NEA, 2015).

In this study, the TPC was chosen to be 1.69 times the direct plant cost (DPC) to include increments for engineering design and management overheads costs a contingency element, commissioning costs, contractor’s fees and interest during construction (Rogers et al., 2012). The direct plant cost (DPC) was the sum of equipment costs (EC) of major components involved in the pre-treatment of the trommel fines, the fast pyrolysis process plant and the CHP plant, delivered to the plant gate. In addition, a number of multiplication factors to include increments for instrumentation, piping, erection and ducting, associated electrical equipment, structures and buildings, civil works and laggings. In this study, the DPC was chosen to be 3.5 times the equipment cost (EC) (Rogers et al., 2012).

Furthermore, the capital repayment produced a calculation of the Net Present Value (NPV) of the project. This is the sum of the present values of the annual net cash flows over the lifetime of the project (Equation 8). This value is used to establish the relationship between the process conversion efficiency and number of years necessary to repay the capital investment. These values will be varied in the scenario analysis and the results of this are presented in Section 3.3. The validity of this model can only be confirmed by comparison with actual cost data for installed plants, but there are few operational fast pyrolysis plants in the world which can be used as reference plants for model validation (Lima, 2014).

$$\mathrm{NPV} = \sum_0^n \frac{\mathrm{NCF}}{(1+r)^n} - (8)$$

Where: NPV = Net present value; NCF – Net cash flow; r = interest rate; n = number of years

2.5 Operating costs

In process plants, operating costs are typically split into maintenance, utility and labour costs, respectively. These are the ongoing costs incurred from plant operation and are represented as annual costs (Lima, 2014). These values will be varied in the scenario analysis and the results are presented subsequently in Section 3.

2.5.1 Estimation of maintenance and overhead costs

The annual maintenance costs and overheads costs (including insurance, rent, taxes etc.) are typically calculated as a percentage of TPC per annum. In this study, values corresponding to 2.5% of TPC and 2% of TPC for plant, were used for maintenance and overhead costs, respectively (Lima, 2014).

2.5.2 Estimation of utility costs

Utility costs in process plants, typically incorporates mainly electricity and total water usage. In this work, the electricity consumed by the fast pyrolysis and CHP system was imported from the grid, to ensure stable operation of the plant. According to Bridgwater et al. (2002), electricity consumption for a fast pyrolysis and engine plant was estimated to be 36.8 kWh/tonne of wood feedstock. The average electricity price for non-domestic consumers was assumed to be the 2014 rate of £0.1001/kWh (UK DECC, 2015).

The water utility cost included the cost of water usage (a fixed amount plus metre reading) and surcharges for sewerage and effluent treatment. In this study, the water consumption was based on mainly cooling requirements for the pyrolysis system and steam generation in the CHP plant. For the cooling requirements, it was estimated to be 17 m^3/tonne of DPT feedstock (Bridgwater et al., 2002) used in the fast pyrolysis process. For the washed feedstocks, an additional 0.1 m^3 of water per tonne was used, giving a total of 17.1 m^3 water usage for the fast pyrolysis of recovered wet physically pre-treated trommel fines (AW and AWS) feedstock. In line with industry standards, an approximate water cost of £2.80/m^3 is used here, based on an average value combining the costs of water utility and process wastewater disposal (Yang et al., 2017). A surfactant cost was of £0.06/tonne of feedstock added to the AWS trommel fines fast pyrolysis, based on an experimental usage of 0.001 m^3/tonne of recovered feedstock.

2.5.3 Labour cost

There is no established model for staffing levels on fast pyrolysis – CHP process. In this study, the staffing level was adapted from Yang et al., (2017) due to the similarities in system capacities. The staffing requirements of a day team and a shift team were considered. The day team included the plant manager and technician, and the number of staff required depended on the load of management work and any maintenance and support contracts in place. The shift team members included the plant operators and their supervisor, and the number of staff required also depended on the number of equipment items to be operated (Yang et al., 2017). The annual labour cost was assumed to be £46,680 per employee, based on the average wage for employees in the electricity industry (Rogers et al., 2012). Table SI1B in the Supplementary Information shows the estimated labour requirement for the process.

3.0 Results and discussion

The results of these situations were discussed based on their economic effects on capital cost repayment period for processing DPT using the hypothetical pyro-CHP system and used to determine the minimum processing capacity of the system. The fast pyrolysis system would require fabrication by contractors and when considering scale-up, account must be taken of the upper limit of reactor capacity for a single unit. For the reactor used in this study, this limit exists because in the current design, the reactor is externally heated at the reactor wall. Moreover, the heat demand for pyrolysis is proportional to the reactor volume due to the poor thermal conductivity of municipal solid waste, which ranges from 0.86 – 1.32 W/m°C (Nocko et al., 2020). When the reactor exceeds a certain scale, the reactor may be unable to transfer sufficient internal heat for the pyrolysis reaction. Therefore, 2000 kg/h was assumed as the upper processing limit of a single fast pyrolysis reactor.

The sensitivity analysis compared the use of dry and wet physically pre-treated trommel fines (DPT, AW and AWS) as feedstocks for the pyro-CHP system at the 2000 kg/h optimum processing capacity to examine the impact of ash reduction on economic performance. A plant life of 20 years was selected as the point at which the facility was most likely to breakdown. Commercial CHP plants can have lifespans of 20 - 30 years (Hammond, McManus and Kelly, 2014; Kumar, Ahmadi and Rajak, 2020). Therefore, a scenario that would result in a repayment period longer than 20 years would be unfeasible.

3.1 Energy revenue, capital and operating costs for DPT pyro-CHP energy system

In this study, energy production reflected the energy that could be theoretically generated as electricity and heat from the pyro-CHP system using the trommel fines feedstocks. The energy produced was used to calculate the revenue per year through a series of fixed factors as indicated in Figure 1. The calculations translated the energy produced into an economic context providing values for revenue per year which were then used to determine the feasibility of the scenarios analysed (Lima, 2014). The integrated Pyro-CHP system characteristics for DPT feedstock and the results of the calculated energy production potential and annual total revenue (combined electricity and heat output) at different waste processing capacities (200, 600, 1000, 2000 kg/h) are shown in the *Supplementary Information* (Table SI2), along with the calculated costs of landfilling the DPT trommel fines. In addition, the baseline data for capital and operating costs associated with running the facility at different processing capacities are provided in Table SI3 (*Supplementary Information*).

Figure 2a shows that the total energy revenue potential (combine electricity and heat output) per year was consistently greater than the yearly landfill cost for DPT trommel fines at all processing capacities evaluated (200, 600, 1000, 2000 kg/h). The potential energy revenues were higher than landfill costs by 16.7%, 18.2%, 20% and 22.2%, increasing steadily from 200 kg/h to 2000 kg/h processing capacities, respectively, indicating the pro-CHP could give cost savings, with potential economic benefits over landfills. The increasing percentage of energy revenues with increasing processing capacities may indicate that the project could benefit from economies of scale. In EfW plants, the cost per tonne of build and operate a large facility (up to about 300,000 tonnes per year) have been reported to be cheaper than a smaller facility (Warrell and Terrell, 2017). The maximum processing capacity of 2000 kg/h (16000 tonnes per year), used in this present study, is within the range recommended for medium-sized plants for the provision of local heat and power in industrial sites (Hornung, 2013).

However, the annual operating cost associated with running the facility at the different capacities evaluated was greater than the total energy revenue at 200, 600 and 1000 kg/h processing capacity as can be seen in Figure 2b. It can be observed from Figure 2b that the differences between the operating costs and revenues steadily became smaller with increasing process capacities, such that at the 2000 kg/h capacity, total revenues outstripped the operating costs by a margin of 28%. The main difference appeared to be the relative labour and utility costs for the different processing capacities (Table SI3). Indeed, at system scales less than 1000 kg/h of DPT processing capacities, the utility and labour cost combined were together greater than the total annual revenue generated. Even though the minimum labour requirements were estimated for each capacity, labour costs accounted for 75.3%, 65.2%, 55.7% and 41.8%, respectively, of the annual operating costs in order of increasing plant capacities. In contrast, utility costs expectedly increased with increasing process capacities from 12.6%, 24.6%, 33.8% and 47.4 % of the operating costs. However, these analyses showed the benefits of economies of scale including with respect to labour requirements and therefore, the potential impact this can have on economic performance of EfW plants (Warrell and Terrell, 2017).

Although, in small-scale EfW plants it is probable that the total labour costs could be reduced by sharing labour between the steps and between adjacent facilities (Lima, 2014). However, for this study, the current labour requirements have been left at their original values to align with expected higher labour requirements in early demonstration plants compared to established plants (Bridgwater et al., 2002). This was an early indication that the DPT trommel fines fast pyrolysis plants might not be feasible at processing capacities less than 1000 kg/h due to the high operating cost, mainly, the high utility and labour costs (Figure SI1).

The capital investment cost, operating costs and total revenue per year for the DPT trommel fines fast pyrolysis plant at different waste processing capacities were used to calculate the net present value (NPV) at 20% capital investment internal rate of return (IRR). This represented the sum of the present values of the annual net cash flows over the 20 years lifetime of the plan, i.e. the result of the total annual revenue excluding the total repayment . The NPV obtained were then applied to the repayment period calculation, which revealed that the processing of DPT was not feasible at scales up to 2000 kg/h processing capacity, as shown in Figure 2c. The non-feasibility of the DPT processing at these processing capacities was therefore, attributed to the high operating costs associated with running these smaller facilities as previously mentioned (Figure 2b). However, it would be interesting for future studies, to see whether NPV values would become more favourable at larger commercial scales (up to 300,000 tonnes per as a consequence of economies of scale, considering that other processing costs would also increase.

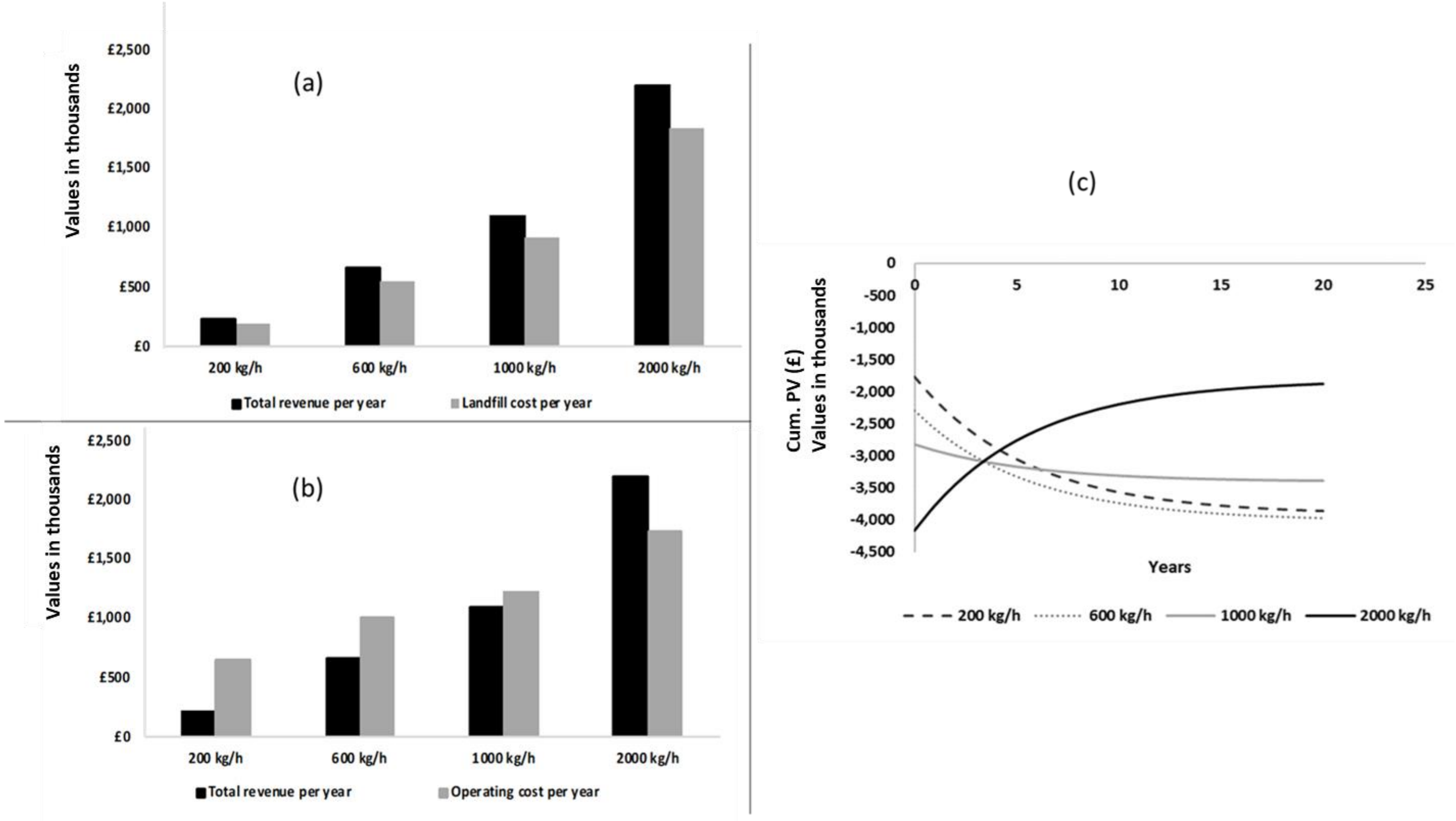

Figure 2: Comparison of economic data for DPT trommel fines at different capacities (a) total annual revenue from hypothetical pyro-CHP system and land fill cost ; (b) total annual revenue from fast pyrolysis and operating costs ; (c) cumulative present value (Cum. PV)

3.2 Effect of feedstock pre-treatment method on energy revenue, operating costs and economic evaluation

The results of the technical characteristics of the hypothetical Pyro-CHP system using the dry and wet physically pre-treated trommel fines feedstocks (DPT, AW and AWS) are provided in the *Supplementary Information* (Table SI4), along with calculated landfill costs. The results are based on the calculated energy production potential and total revenue per year (combined electricity and heat output) at 2000 kg/h processing capacities. In addition, baseline data for the capital and operating costs associated with running the facility for each pre-treatment process are given Table SI5.

Figure 3a below shows that the total annual revenues (combine electricity and heat output) for all the pre-treated trommel fines feedstocks were greater than their potential landfill costs at 2000 kg/h processing capacity. The results indicate the influence of the ash reduction operation prior to the fast pyrolysis of the feedstocks. Table 1 shows that the highest process conversion efficiency was obtained with the AW trommel fines sample (64%), closely followed by the AWS sample obtained by washing the PT with 1% Decon Neutracon at 62% (Table 1). Hence, similar total annual revenues were obtained when AW and AWS were processed, with each being at least 25% higher than revenues from DPT.

The annual operating costs associated with running the 2000 kg/h Pyro-CHP facilities for all three pre-treated trommel fines feedstocks were found to be lower than their total annual energy revenues as can be seen in Figure 3a. However, the operating cost increased slightly with the wet physically pre-treated feedstocks with AWS having the highest operating costs due to the use of surfactant in the ash reduction operation

(Table SI5). The increasing operating costs associated with AW and AWS energy recovery systems were related to the slight increase in process water cost items of the total utility costs as can be seen in the Supplementary Information (Figure SI2). However, for all three feedstocks, utility costs could further be reduced via system integration as being proposed in this study. For instance, a significant amount of utility have been accounted for from the cooling of the pyrolysis vapours to condense the liquid products during the experimental fast pyrolysis carried out in this research, in order to have a complete picture of the present situation. Whereas, in an integrated pyro-CHP plant, the pyrolysis vapours would be directly combusted without the quench-condensation stage that requires cooling duty (cooling water, in this case), thereby avoiding the associated utility costs. However, it is important to note that such integrated systems will require additional operations such as hot vapour filtration and aerosol precipitation (Hornung, 2013) to condition the pyrolysis vapours for the CHP engine. . It is therefore suggested that the influence of the afore-mentioned reduced utility costs as well as the additional costs of pyrolysis vapour conditioning be considered for incorporation into future economic studies of this type of EfW system as more data become available..

It has already been established in Section 3.1 that processing the DPT feedstock using the hypothetical Pyro-CHP system was not economically viable even up to 2000 kg/h processing capacity. However, the effect of ash reduction on pre-treated trommel fines fast pyrolysis process can be seen in Figure 3b, which shows that the NPV increased with the AW and AWS feedstocks, such that AW gave the highest NPV over the 20-year lifetime of the project.

The slightly positive NPVs NPV for AW and AWS feedstocks resulted in a reduced capital investment repayment period with AW having the shortest repayment period of 14 years (Figure 3b). In contrast, the repayment period for the pyro-CHP system powered by DPT would take 35 years, which is 2.5 times longer compared to AW and AWS. Therefore, processing DPT at 2000 kg/h, 60% CHP efficiency and 20% IRR on capital investment resulted in a negative NPV and remained unviable within the 20-year project lifetime. These results suggest that wet pre-treatment of the trommel fines was an effective method to improve the feasibility of the energy recovery process by enhancing calorific values and making the feedstock more suitable for fast pyrolysis (Eke, Onwudili and Bridgwater, 2020; Onwudili and Eke, 2020). However, the results work also suggest that washing the feedstock with water alone for ash reduction, was as effective as washing it with a 1% aqueous solution of a surfactant (Decon Neutracon), since both washing methods gave similar total capital repayment periods of around 14 years (Figure 3b). The use of the surfactant during feedstock washing actually increased the operating cost associated with the AWS processing (Table SI4).

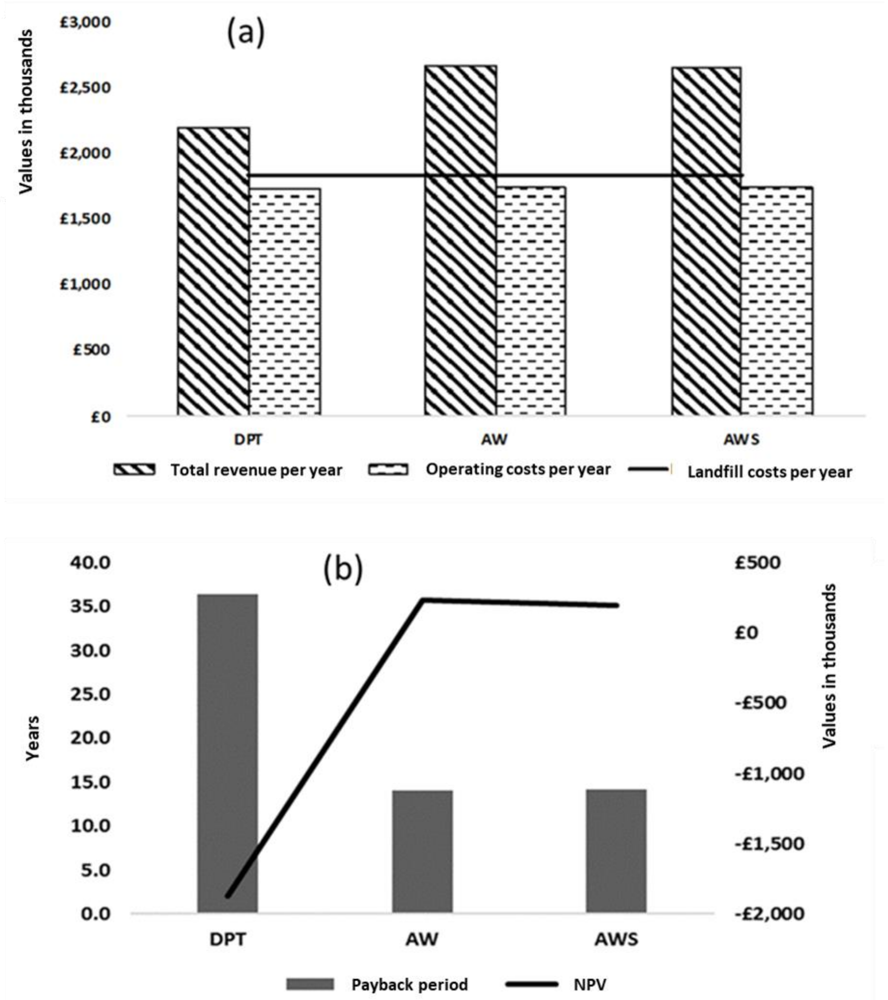

Figure 3: Comparison of (a) total annual revenue , operating cost and annual landfill costs; (b) calculated capital investment repayment period, for dry and wet physically pre-treated trommel fines 2000 kg/h fast pyrolysis energy system. (DPT - dry pre-treated Trommel Fines; AW – Agitated Washing; AWS – Agitated Washing with Surfactant (Decon Neutracon)

3.2.2 Effect of internal rate of return (IRR) on economic evaluation the hypothetical integrated energy recovery system

The NPVs at 10%, 15% and 20% capital investment internal rate of return (IRR) were calculated for the processing of all three pre-treated trommel fines feedstocks, using the total revenue per year (Table SI2), capital investment cost and operating costs (Table SI5) at 2000 kg/h processing capacity over the 20 years lifetime of the project. The results of these analyses on the economic performance of the pyro-CHP system powered by each of the three feedstocks can be seen in Figure 4. The analyses show that the NPVs increased with decreasing IRR for all three feedstocks, with AW and AWS having consistently higher NPVs than DPT over the life of the project. For both AWS and AW, payback periods increased from about 6.4 years at 10% IRR to around 8 years at 15% IRR, but there was an exponential increased to about 14 years at 20% IRR, which shows the sensitivity of EfW plants to IRR.

However, the DPT was still not viable even at 10% IRR, with its negative NPV resulting in a capital repayment period of 20.8 years, which was still greater than the 20 years plant life (Figure 4). AW and AWS both had the earliest repayment period of 6.4 years at 10% IRR (Figure 4). The reduced capital repayment period observed a low IRR for the three feedstocks suggested that this is an important parameter to help improve the feasibility of the trommel fines Pyro-CHP system. EfW plants, such as those based on incineration have been reported to be profitable with IRR of 11% and pay back times of just under 13 years (Xin-gang et al., 2016). This present work indicates a potentially better economic performance for pyro-CHP plants powered by trommel fines after ash reduction compared to incineration. Therefore, working at IRR of between 10-15% would be advisable.

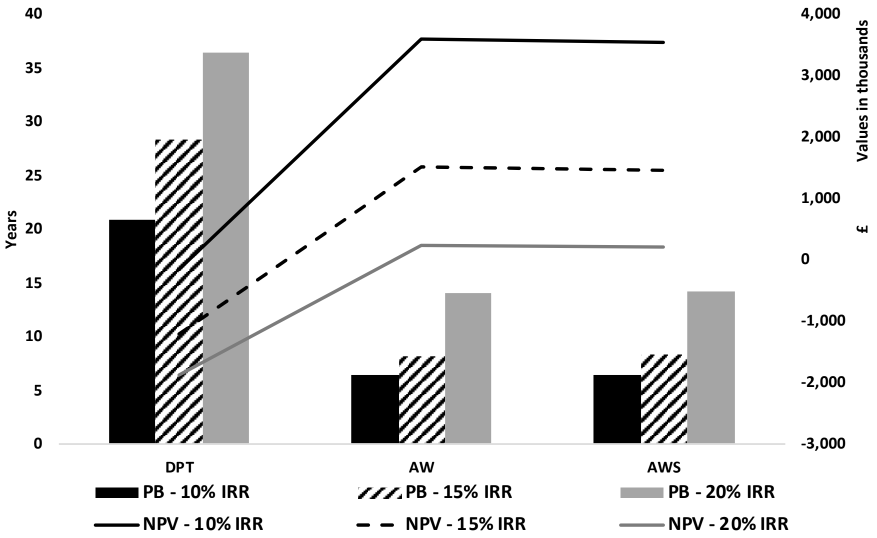

Figure 4: Comparison of calculated capital investment repayment period for dry and wet physically pre-treated trommel fines 2000 kg/h fast pyrolysis system at varying interest rates. (DPT - dry pre-treated Trommel Fines; AW – Agitated Washing; AWS – Agitated Washing with Surfactant (Decon Neutracon); PB – Payback; IRR – internal rate of return; NPV – Net Present Value)

3.3 Effect of CHP efficiencies on energy revenue and operating costs.

In this section, CHP efficiencies ranging from 40 – 80 % have been used to determine the impact on the annual revenues and operating costs of the hypothetical Pyro-CHP plant. The range of CHP efficiencies selected was in line with those reported for commercial CHP plants, with some plants approaching 90% depending on the fuel type and plant type and size as well the characteristic of the heat demand (Balli and Aras, 2007; Gambini and Venilli, 2015). The results of the calculated energy production potential and total annual revenue at 2000 kg/h processing capacity for all three feedstocks at 40% and 80% CHP efficiencies, respectively, compared with the base scenario data for 60% CHP efficiency are given in the *Supplementary Information* (Table SI6 and Table SI7), and used as baseline data for the economic analysis.

Figure 5 below shows that the total annual revenue potential for all the pre-treated trommel fines feedstock increased with increasing CHP efficiency and they were all greater than their respective landfill costs when operating the Pyro-CHP system at a capacity of 16000 tonnes per year. As previously established in section 3.2 (Figure 3), similar determinations were made at at 60% CHP efficiency.. These results showed the robustness of the integrated system in handling wastes of different compositions and calorific values, which influence both the pyrolysis conversion efficiency (de Marco et al., 2002; and CHP efficiencies (Burnes and Camuo, 2019). However, these results need further analyses to determine whether they translated into economic viability of the systems at the scale being considered.

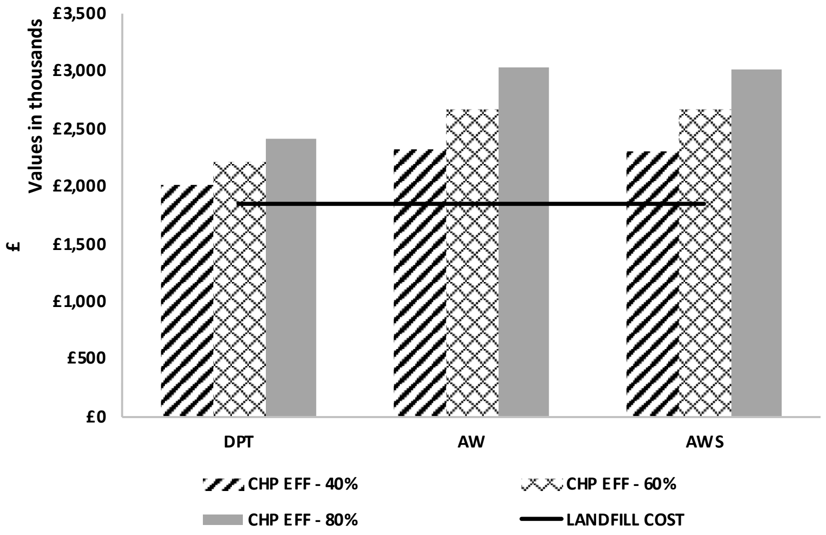

Figure 5: Comparison between of total revenue per year 2000 kg/h fast pyrolysis system (dry and wet pre-treated trommel fines) at varying CHP efficiencies and annual landfill costs. (DPT - dry pre-treated Trommel Fines; AW – Agitated Washing; AWS – Agitated Washing with Surfactant (Decon Neutracon); EFF – Efficiency)

3.3.1 Effect of CHP efficiencies on economic viability of Pyro-CHP system for pre-treated trommel fines

The net present values (NPV) at 20% capital investment internal rate of return (IRR) were calculated for all three pre-treated trommel fines feedstocks, using the calculated total annual revenues given in the *Supplementary Information* (Table SI2, SI6, and SI7) at varying CHP efficiencies and capital investment cost and operating costs (Table SI5) at 2000 kg/h feedstock processing capacity over the 20 years lifetime of the project. The effect of CHP efficiencies on pre-treated trommel fines fast pyrolysis process can be seen in Figure 6, which shows that the NPV increased with increasing CHP efficiencies for all three pre-treated trommel fines feedstocks. For instance, processing the three feedstocks at 80% CHP efficiency, resulted in their highest NPVs over the 20-year lifetime of the project. Overall, increasing CHP efficiencies led to reduced capital repayment periods for all three feedstocks, suggesting that the CHP efficiency is an important parameter to consider in order to improve the viability of energy recovery from trommel fines.

However, processing DPT for energy recovery was still not viable even at 80% CHP efficiency as shown in Figure 6, due to its repayment period being around 24 years, which is still higher that the project’s life time. In contrast, both AW and AWS both gave the short repayment periods of 6 years each at 80% CHP efficiency (Figure 6), which are lower by 3 to 4 years compared to conventional waste to energy plants (Chen et al., 2020; Kumar, Ahmadi and Rajak, 2020). As established in Section 3.2, the strong influence of IRR on economic performance EfW systems may make DPT processing more favourable at lower IRR and high CHP efficiency. A rough calculation using 10% IRR and 80% CHP efficiency, resulted in a positive NPV and a repayment period of 18.2 years, which is too close to the end of the project and so, does not hold much economic prospect, in the opinion of the authors.

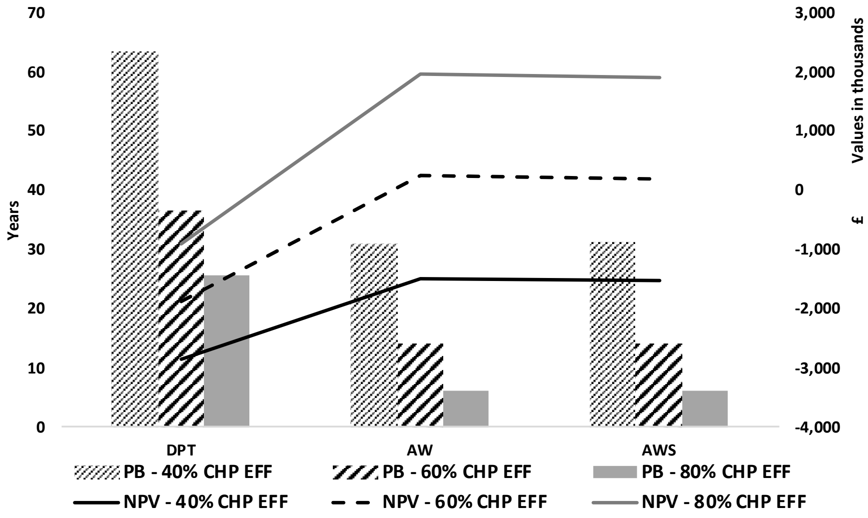

Figure 6: Comparison of calculated capital investment repayment period for dry and wet physically pre-treated trommel fines 2000 kg/h fast pyrolysis system at varying CHP efficiencies. (DPT - dry pre-treated Trommel Fines; AW – Agitated Washing; AWS – Agitated Washing with Surfactant (Decon Neutracon); PB – Payback; EFF – Efficiency; NPV – Net Present Value)

3.4 Effect of capital investment on economic evaluation of integrated Pyro-CHP system for pre-treated trommel fines

Capital cost is a significant item with overarching influence on the profitability of capital projects such as EfW plants. Therefore, any credible savings that can be obtained by eliminating capital costs e.g. by sharing of facilities, could have significant impact on the economic performance the present hypothetical Pyro-CHP system. For instance, the base scenario used in this study included the cost of purchasing industrial grinding and sieving equipment inevitably required but significantly expensive for size reduction of the trommel fines prior for fast pyrolysis . It was assumed in Section 2.2 that the EfW facility would be integrated as part of an MRF facility as the energy end-user (Hornung, 2013). It can therefore be further assumed that the Pyro-CHP facility would already have access to equipment for the dry pre-treatment process, hence no additional industrial grinder and sieving machine will be required.

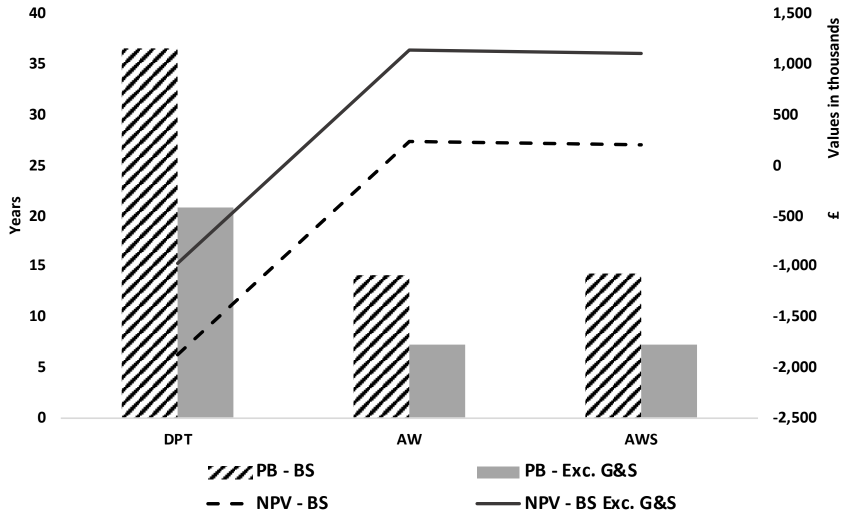

Figure 7: Comparison of calculated capital investment repayment period for dry and wet physically pre-treated trommel fines 2000 kg/h fast pyrolysis system for base scenario and without a grinder and sieving machine. (DPT - dry pre-treated Trommel Fines; AW – Agitated Washing; AWS – Agitated Washing with Surfactant (Decon Neutracon); PB – Payback; NPV – Net Present Value; BS – Base Scenario; BS Exc. G&S – Base Scenario Excluding Grinder & Sieving)

Hence, eliminating the capital costs of these pre-treatment operations by using an existing systems would reduce the TPC by about 17%. It would also reduce the operating costs associated with running the facility as seen in the *Supplementary Information* (Figure SI3). Hence, a revised capital and operating cost (excluding

Commented [MOU1]: Correct reduction value grinder and sieving machine) associated with running the facility at 2000 kg/h processing capacity have been computed and displayed in the *Supplementary Information* (Table SI8).

The net present values (NPV) at 20% capital investment internal rate of return (IRR) were then recalculated for the processing of pre-treated trommel fines feedstocks in the described EfW system, using the total annual revenue (Table SI4), the reduced capital investment and operating costs (Table SI8)) at 2000 kg/h processing capacity over the 20 years lifetime of the project. Figure 7 shows that the NPV increased with the reduced capital investment cost when compared to the base scenario for all three feedstocks, with DPT still having a negative NPV over the 20-year lifetime of the project, with a 20.7 years repayment period. In a more optimistic scenario, a rough calculation using the combination of the reduced capital and operating costs, a lower IRR of 10% and an enhanced CHP efficiency of 80%, gave a positive NPV for DPT processing, with a viable payback period of 11.5 years. This appeared to hold commercial relevance to potential investors, however, the combination of 10% IRR and 80% CHP efficiency may be impossible to achieve in rela life scenarios. In contrast, the hypothetical Pyro-CHP system powered by AW and AWS returned positive NPVS, with their repayment periods both reduced by half (7.2 years), compared to the base case scenario (14 years). The values obtained for AW and AWS were still lower than payback periods (9 – 10 years) reported for conventional bioenergy plants (Chen et al., 2020; Kumar, Ahmadi and Rajak, 2020), indicating their potentially better economic performance.

4.0 Conclusions

This present work has investigated the economic performance of a hypothetical integrated Pyro-CHP energy production system powered by pre-treated trommel fines, up to a processing capacity of 16000 tonnes per year. The analyses showed that a reasonable combination of technical (feedstock pre-treatment, fast pyrolysis efficiency, system scale and CHP efficiency) and economic (IRR, capital costs and operating costs) factors was needed to ensure the economic viability of the proposed EfW system. Results showed that, although the hypothetical Pyro-CHP system would be economically preferred to landfill disposal, extensive pre-treatment (in this case, ash reduction) of the feedstock prior to fast pyrolysis was required. This was main technical factor that influenced the economic performance, which improved in line with increase in the conversion efficiency of fast pyrolysis system 41% to 64%, after ash reduction. Sensitivity analyses based on IRR (three scenarios), CHP efficiencies (three scenarios) and reduced capital and operating costs (one scenario), confirmed the superior economic performance of the Pyro-CHP system powered by the ash-reduced feedstocks (AW and AWS) compared to DPT.

Potentially, a Pyro-CHP system for pre-treated trommel fines can offer environmental to society and economic benefits to MRF operators, especially with the potential to reduce landfill costs. However, realistic implementation of such combination of economic and technical factors will need further rigorous economic tests. In addition, even for the ash-reduced feedstocks, challenges remain in terms of adopting a cost-effective and technically operable commercial-scale feedstock ash reduction process, the conditioning/upgrading of liquid and gas pyrolysis products to make them suitable for real-life CHP plants and handling of residual solids.

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