Techno-economic assessment of a novel integrated system of mechanical-biological treatment and valorisation of residual municipal solid waste into hydrogen: A case study in the UK

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Abstract

Resources embedded in the waste streams are often not properly recovered and are mostly ended up in landfills or only recovered as energy via energy-from-waste (EfW) facilities. Innovative resource recovery from waste strategies are urgently needed to maximise resource efficiency, divert waste from landfills and reduce reliance on EfW. This study proposes a novel mechanical-biological treatment with valorisation concept (MBT-v) that combines material recovery and fuel production, as alternatives to EfW for residual municipal solid waste (MSW) treatment. The polygeneration feature exhibited by the MBT-v system enhances resource efficiency and product diversification. The proposed MBT-v system involves valorisation of rejected materials from MBT into hydrogen by incorporating an additional gasification system. A comprehensive techno-economic assessment is conducted for the proposed MBT-v system and compared against a conventional MBT. The results reveal that the conventional MBT strongly relies on gate fees to be economically viable while it is heavily impacted by the rejects disposal cost. The analysis also shows that higher economic potential (36.4 M£/y) for MBT-v can be obtained compared to that of conventional MBT (3.4 M£/y) for a 100 kt/y residual MSW system. The minimum hydrogen selling price (MHSP) from the Gasification-H_2 system is estimated to be at 3.4 £/kg (28.3 £/GJ), with potential for further reduction through upscaling the facility. This study concludes that producing high value product such as hydrogen (with the current assumed market price of hydrogen of 10 £/kg) can significantly improve the economic performance and minimise financial instability of the facilities. It is recommended that the scale and optimal configuration of MBT-v to be designed based on local conditions.

Keywords: Resource recovery; waste-to-hydrogen; polygeneration; mechanical-biological treatment; sustainable waste management; gasification.

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1. Introduction

The UK has generated 26.4 Mt of household waste in 2018 (DEFRA, 2020). A recycling rate of 45% has been reportedly achieved in the recent years, but it has reached a plateau (Smith and Bolton, 2018). Poor segregation of waste at source, inefficient collection of recyclable materials, increased multi-occupancy dwellings and ineffective policy levers are among the barriers to achieving a higher recycling rate (Smith and Bolton, 2018). The lack of appreciation of resource recovery from waste concept at the household level has led to significant loss of value and resources (Ng and To, 2020). Hence, there is a pressing need for government intervention through regulations and financial support to achieve further improvements on the UK recycling rates (Rhodes and Thair, 2017). If the recycling rates remain unchanged, there might be a residual MSW treatment capacity gap of 13 Mt by 2030 (Environmental Services Association and Tolvik Consulting Ltd., 2017). Residual MSW, in the present context, is defined as the fraction of household waste from regular collections (i.e. black bag or black bin waste), bulky waste, residual waste from civic amenity centres and rejects from recycling (DEFRA, 2019). Residual MSW is considered to be unsuitable for reuse, recycling or composting, and is normally sent to incineration with or without energy recovery, or may end up in landfills.

Driven by significant concerns over insufficient capacity of landfills in the UK and ability to cope with the rising amount of residual MSW, investments in energy-from-waste (EfW) facilities, have gained traction. This is owing to EfW's ability to serve as a supporting treatment method for eliminating residual MSW and reducing the burden on landfills, while generating heat and electricity that supplies nearby communities (Rhodes and Thair, 2017). Waste management is a devolved matter in the UK, and each Administration (England, Wales, Scotland and Northern Ireland) is responsible for the development of its own waste strategy. The UK waste management legislation and policies are strongly influenced by the EU Waste Framework Directive (Directive 2008/98/EC) (European Commission, 2008). Waste hierarchy has been emphasised where prevention of waste and preparing for reuse and recycling are placed as top priorities, followed by recovery, and finally, disposal (European Commission, 2008). Diversion of waste from the landfills through recycling is the key objective of the waste management policies in the UK and the government has imposed strict regulations through the *Waste (England and Wales) Regulations 2011* (The National Archives, 2011), the *Landfill (Scotland) Regulations 2003* (The National Archives, 2003a) and the *Landfill Regulations (Northern Ireland) 2003* (The National Archives, 2003b) to control the amount and type of waste disposed of to landfills. The Private Finance Initiative (PFI) scheme (HM Treasury, 2006), a mechanism to support large waste infrastructure projects underpinned by long-term contracts (typically 25-30 years), has stimulated the development of a number of large-scale recycling facilities. EfW facilities have also been financed by the PFI scheme to enable the UK to meet the landfill diversion targets. The investment in EfW facilities via this scheme has created a technological lock-in into long-term contracts and has hindered optimum resource recovery (Hall, 2014).

Although EfW can reduce burdens on landfills and generate heat and electricity, they also contribute to negative environmental externalities, e.g. every tonne of MSW processed in EfW releases 0.7 - 1.7 tonne of CO_2 (Zero Waste Europe, 2019). Realisation of the UK government's rhetoric of achieving a low-carbon and circular economy, demands a reconsideration of using EfW for the management of residual MSW. A more sustainable solution needs to be brought forward to valorise residual MSW into value-added products (Ng et al., 2019). Advanced thermal treatment technologies such as gasification and pyrolysis have been increasingly proposed as alternatives to EfW (DEFRA, 2013a). This is because the syngas generated from gasification and bio-oil from pyrolysis can be further upgraded into higher value products such as fuels and chemicals (Sadhukhan et al., 2014). Direct upgrading of residual MSW into these value-added products, without prior extraction of recyclable materials is not sustainable. It is thus timely and exigent to redesign an approach to dealing with residual MSW and accelerate innovation and progress towards sustainable and circular waste management.

Mechanical-biological treatment (MBT) has commonly been regarded as an alternative option for residual MSW treatment, and often been used as pre-treatment to incineration, EfW or landfill. MBT can be configured to meet different purposes and address various issues (DEFRA, 2013b). The advantages of MBT include diversion of biodegradable solid waste from landfill, extraction of recyclable materials through mechanical sorting, stabilisation of compost-like output (CLO), or production of biogas and digestate (depending on the biological treatment method used), and generation of refuse derived fuel (RDF) / solid recovered fuel (SRF) for energy recovery (DEFRA, 2013b). RDF and SRF can be used as an alternative fuel in cement industry to replace fossil fuel (Chatziaras et al, 2016). There are some concerns over the application of RDF/SRF for energy recovery purposes. The exploitation and market of RDF/SRF as a combustible fuel has been restricted and has varying cost of production depending on its application (Nizami et al., 2017). The energy recovery route has been placed at a lower priority in the waste hierarchy, underscoring the benefits of RDF/SRF generation from waste (Rada et al, 2017). Previous studies have explored the role of MBT and its efficiency in enhancing resource recovery (Połomka and Jędrczak, 2019); the effect of different selective collection strategies on the residual MSW characteristics and bio-drying performance (Rada and Ragazzi, 2015); the variability of the MBT output characteristics attributed to the heterogeneity of feedstock and different configurations of MBT processing units (Di Lonardo et al., 2012); characterisation of MBT input and output materials (Tintner et al., 2010); the effects of temperature, water content and inoculum on biogas production from MBT waste (Pantini et al., 2015); and treatment of volatile organic compounds (VOCs) emitted from MBT (Ragazzi et al., 2014). These studies have highlighted the limitations of conventional MBT in coping with the high variability of MSW and the generation of low-value products, and these technological barriers need to be overcome. Innovative technologies for resource recovery from waste are of paramount importance to achieve maximum value extraction from MSW, which is underexplored.

A residual MSW management strategy that focuses largely on the use of EfW and landfill, shown in Fig. 1(a), is not a sustainable option. Adopting MBT, illustrated in Fig. 1(b), could form part of an integrated sustainable waste management strategy, but its application can be limited as the materials and by-products recovered are of inferior quality, and additional processes may be needed for optimal disposal and treatment. In this study, anaerobic digestion (AD) is considered as the biological treatment option. This is because the biogas generated from AD can be used in combined heat and power (CHP) facility which can supply energy to the MBT system and reduce external energy requirement (Fan et al., 2018). Alternative biogas upgrading routes such as biomethane (Martín-Hernández et al., 2020) and methanol (Furtado Amaral et al., 2020) production show promising potential of AD. Bong et al. (2018) provide a comprehensive review on the biogas production potential with variation in food waste characteristics, followed by strategies to improve the performance of both mono- and co-digestion routes. The co-digestion of organic feedstock in AD is highly relevant to the MBT context used in the present study, as the organic fraction of MSW mainly consists of a mixture of food and garden waste. Combining the strengths of MBT and advanced thermal treatment processes in an integrated MBT and valorisation approach (MBT-v), as shown in Fig. 1(c), enables the maximisation of resource efficiency. The residual stream from MBT can be converted into value-added products through an advanced polygeneration system, i.e. an integrated system for simultaneous generation of energy/fuels/chemicals/materials (Ng et al., 2013). Adopting polygeneration strategies in process design enables efficient sharing of materials and energy, enhanced diversity in product generation, and higher flexibility, optimality and circularity in resource utilisation (Ng and Martinez-Hernandez, 2016), as demonstrated in previous case studies for CO_2 reuse (Ng et al., 2012) and waste-to-hydrogen system (Ng and Phan, 2021).

Producing hydrogen from waste stream can potentially reduce reliance on fossil fuels and contribute to a low-carbon economy (RenewableUK, 2020). Hydrogen has been selected as the target valorised product because it serves as an important energy carrier and clean fuel for the future (IEA, 2019). The proposed waste-to-hydrogen concept enables rejected materials from mechanical sorting processes to be fully utilised, thereby enhancing resource efficiency and economic performance of the system. Hydrogen can be generated from gasification of biomass and MSW. The cost of production of hydrogen ranges from 2.3-5.2 $/kg for biomass feedstock and 1.4-4.8 $/kg for residual waste (Shahabuddin et al., 2020). Most of the existing studies related to hydrogen production from MSW gasification has been focused on enriching hydrogen content in the product gas while reducing tar formation. These improvements include addition of a catalyst or CO_2 sorbent in the gasifier such as waste marble powder (Irfan et al., 2019) or calcium oxide powder (Hu et al., 2015); and adjustment of process parameters such as increasing temperature (Chen et al., 2020), CO_2-to-steam ratio (Zheng et al., 2018) and steam-to-MSW ratio (He et al., 2009) in the gasifier. The utilisation of rejected materials from MBT for hydrogen production has not been demonstrated. The future potential and economic viability of deploying an integrated MBT and gasification system for hydrogen production using residual MSW as the feedstock remains unclear. This study, for the first time, aims to address the knowledge gaps by examining the future potential of realising an advanced material recycling, energy recovery and valorisation system through a polygeneration strategy. This research is highly relevant to addressing global agenda in ensuring sustainable production and consumption patterns (United Nations Sustainable Development Goal 12) (United Nations, 2015); meeting the net zero emission target by 2050 (Committee on Climate Change, 2019) and national ambitions in minimising waste and promoting resource efficiency, cleaner technologies and circular economy as set out in the *Resources and Waste Strategy for England* (HM Government, 2018), which together forms the basis for *Circular Economy Package* introduced in 2020 (Department for Environment, Food & Rural Affairs, Welsh Government, The Scottish Government, and Department of Agriculture, Environment and Rural Affairs (Northern Ireland), 2020).

The aim of this study is to explore the techno-economic potential of the proposed novel MBT-v system in creating value-added products, which can promote clean growth and low carbon economy in the UK. The novelty of this research lies in the development of an integrated residual MSW treatment system using polygeneration strategy, where MBT is integrated with a gasification system for hydrogen production ("Gasification-H_2"), realising a robust resource recovery and cleaner energy production model. The objective of this study is to compare MBT and MBT-v systems by examining (i) technical performance of the systems through establishing material and energy balances; and (ii) economic performance of the systems through evaluating the capital and operating costs and revenues. It should be noted that despite EfW and landfills have been considered as final recovery and disposal methods for rejected materials from MBT, it is not the intention of this study to compare MBT and MBT-v against EfW and landfill approach for residual MSW treatment. This paper is structured as follows. Section 2 describes the methodology for process modelling, energy integration and economic assessment. Detailed process description as well as material and energy balances for conventional MBT and proposed MBT-v systems are presented in Section 3. A comprehensive techno-economic assessment of the systems is presented Section 4. Key findings and recommendations of the study are concluded in Section 5.

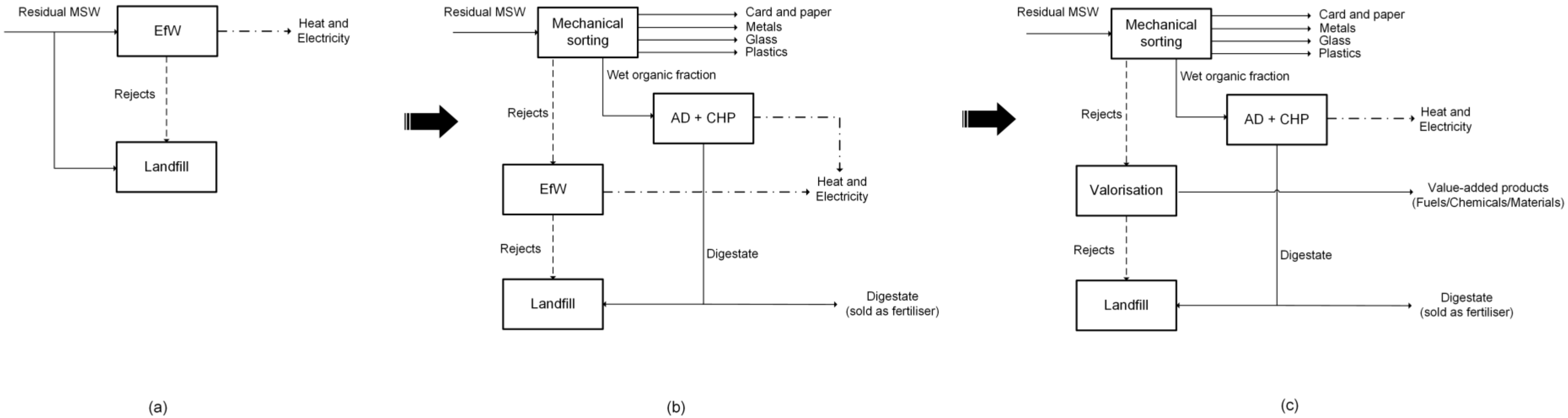

Fig. 1. Advancement in residual municipal solid waste (MSW) management. (a) Energy-from-waste (EfW) and landfill approach; (b) Mechanical-biological treatment (MBT) approach; (c) Mechanical-biological treatment and valorisation (MBT-v) approach. AD: Anaerobic digestion; CHP: Combined heat and power.

2. Methodology

A methodical approach to conceptual process design and techno-economic analysis (Ng and Martinez-Hernandez, 2020) was adopted to develop system models and analyse technical and economic performances of MBT and MBT-v systems, presented in Fig. 2.

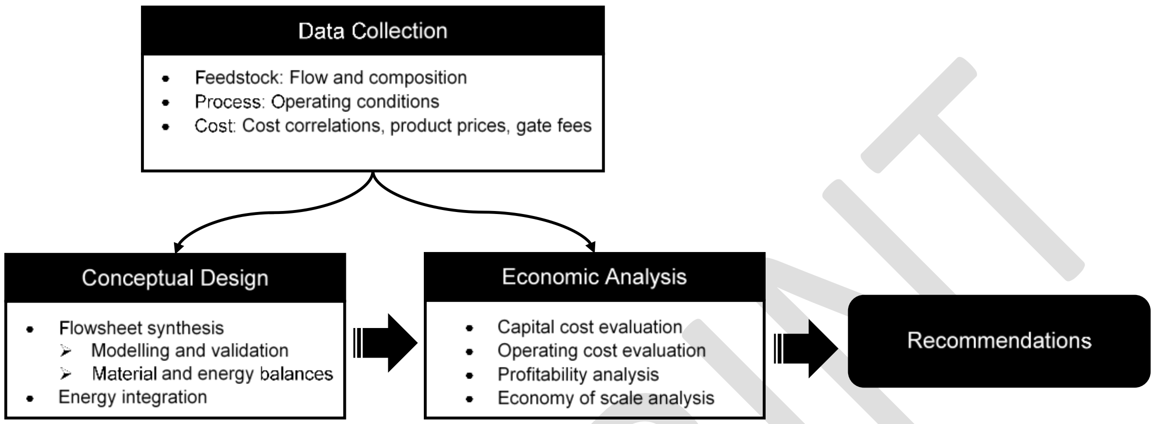

Fig. 2. Overview of methodology for conceptual design and techno-economic analysis.

Data collection: Secondary data were collected from a range of published sources. The data required in this study include: (a) feedstock mass flow and compositional data; (b) process operational parameters; and (c) cost data. The mass flow and compositional data were adopted from the WRAP *National Household Waste Composition 2017* report (WRAP, 2020) and included kerbside household residual, Household Waste Recycling Centres (HWRC) household residual, bulky waste collection and street sweepings, cleansing and litter. Process operational parameters such as separation efficiencies of mechanical sorting equipment were collected from Pressley et al. (2015) (see Supplementary Materials, Table A.1); and operating conditions of process units in AD and Gasification-H_2 facilities were obtained from the BALKWASTE (Inglezakis et al., 2011) and National Renewable Energy Laboratory (NREL) reports (Spath et al., 2005). The equipment and operating cost data for mechanical sorting were obtained from Pressley et al. (2015) and WRAP (2009); and data for Gasification-H_2 facility were adopted from Sadhukhan et al. (2014) and Spath et al. (2005). An estimation of AD equipment cost was obtained from Weddle (2014). Factors for capital cost and fixed operating cost estimation were obtained from Sadhukhan et al. (2014). The most recent market prices of recyclable products (i.e. metals, glass, plastics, paper and card) and gate fees for MBT, landfill and EfW were obtained from LetsRecycle.com.

Conceptual design: Flowsheet models of the MBT and MBT-v systems were developed in Excel spreadsheet environment and included three distinct parts: mechanical sorting; AD; and Gasification-H_2 (only for MBT-v) facilities. A generic structure of the mechanical sorting system was constructed based on the flowsheets presented in Pressley et al. (2015) and WRAP (2009). The AD and Gasification-H_2 facilities were modelled using the Aspen Plus software since sophisticated reaction-separation processes were involved. The flowsheets were constructed by adopting an evolutionary approach or commonly referred to an "onion" model for process design (Martinez-Hernandez and Ng, 2018) where modelling starts from reaction, and progresses towards separation, and energy systems (i.e. heat exchangers and utility systems). A simplified steady-state simulation modelling approach was adopted by considering only the final products from AD (i.e. mainly CH_4 and CO_2) and gasification (i.e. mainly CO, H_2, CO_2 and H_2O) reactions. This approach eliminates intermediate species and reaction pathways and has the advantage of reducing computational complexity. In this study, AD was modelled using a stoichiometric reactor model while gasification was modelled using Gibbs free energy minimisation method in Aspen Plus, using non-random two-liquid (NRTL) physical property method. AD and gasification models were validated against the published results in Archinas and Euverink (2016) and He et al. (2009).

Systematic energy integration was performed in view of achieving maximum energy recovery within the system and thereby reducing the reliance on external source of energy. The methodology (Ng et al., 2017) follows the sequence of steps as below:

(i) Temperature and heat duty information of heat exchangers and process units (i.e. process streams that experience temperature/enthalpy changes) were extracted from the flowsheet;

(ii) Energy integration tasks were classified based on level of temperatures and heat duties of the extracted streams. High level tasks refer to steam generation and consumption at different pressures, while low level tasks refer to boiler feed water generation. The stream classification procedure ensures appropriate placement of utilities and avoid missed opportunities for energy recovery;

(iii) Steam and power generation and distribution within the system are incorporated in the CHP network design. All energy supply and demand in the system must be satisfied.

Economic analysis: The capital and operating costs of the MBT and MBT-v systems were evaluated, and a profitability analysis was carried out to examine the economic performance of the systems (Ng and Martinez-Hernandez, 2020).

The total purchased equipment cost was estimated using Equations (1)-(2) (Ng and Martinez-Hernandez, 2020). This cost was then multiplied by Lang factors to determine the total capital cost (*TCC*) of the system which includes the direct costs (e.g. installation, instrumentation and control, piping, electrical systems), indirect costs (e.g. engineering and supervision, contractors' fees and contingency) and working capital.

The purchased equipment cost for the current system was estimated using Equation (1) by exploiting the capacity and cost data of the base system reported in the literature.

$$\frac{\mathrm{COST}_{\mathrm{size}2}}{\mathrm{COST}_{\mathrm{size}1}} = \left(\frac{\mathrm{SIZE}_2}{\mathrm{SIZE}_1}\right)^R \tag{1}$$

where

$SIZE_1$ is the capacity of the base system,

$SIZE_2$ is the capacity of the system after scaling up/down,

$COST_{size1}$ is the cost of the base system,

$COST_{size2}$ is the cost of the system after scaling up/down,

R is the scaling factor.

Chemical Engineering Plant Cost Index (CEPCI) was applied in Equation (2) to levelise the purchased equipment costs (Equation (1)) to the present year.

$$C_p = C_o \left(\frac{I_p}{I_o}\right) \quad (2)$$

where

C_p is the present cost of equipment,

C_o is the original cost of equipment,

I_p is the present index value,

I_o is the original index value.

Annualised capital cost (C_{cap}) of the system was determined using Equation (3). The capital recovery factor (CRF) converts present value of TCC into annual payment over n years (i.e. plant life) at a specified discount rate of r using Equation (4) (Ng and Martinez-Hernandez, 2020).

$$C_{cap} = TCC \times CRF \quad (3)$$

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (4)$$

Operating costs (C_{op}) consist of (i) fixed costs (e.g. maintenance, capital charges, insurance, local taxes) which were estimated based on percentage of indirect capital cost or personnel costs; and (ii) variable costs (e.g. fuel, electricity, baling wire and catalyst) costs which were estimated using the latest available price data.

The economic performance of the systems was indicated by economic potential (EP) using Equation (5) and minimum hydrogen selling price (MHSP) using Equation (6) (Sadhukhan et al., 2014). EP indicates the margins between the revenues generated from sales of products and associated costs of production. The cost of feed (i.e. residual MSW) was assumed to be zero in this analysis. MHSP is particularly useful for evaluating the minimum value of hydrogen from the MBT-v system. MHSP must be lower than the market price of hydrogen for an economically competitive scenario.

$$\text{EP} = \text{Value of products} - (\text{Cost of feed} + \text{Annualised capital cost} + \text{Operating cost}) \quad (5)$$

$$\text{MHSP} = \frac{(\text{Cost of feed} + \text{Annualised capital cost} + \text{Operating cost})}{\text{Production rate of hydrogen}} \quad (6)$$

Economies of scale analysis was conducted to investigate the effect of increasing capacity of the Gasification-H_2 within the MBT-v system (i.e. throughput of MBT rejected materials) on MHSP. Regression analysis was performed to predict the scale of Gasification-H_2 facility for which the MHSP could be competitive with existing hydrogen production technologies.

Recommendations on the design of MBT and MBT-v were drawn based on the techno-economic performance of the systems.

3. Conceptual design of sustainable residual MSW treatment and valorisation systems

3.1 Basis for feedstock

Residual MSW: In this study, the throughput of residual MSW into the MBT and MBT-v systems was assumed to be 100,000 t/y (equivalent to 18.52 t/h considering 5400 h/y operational period). The composition of the residual MSW was refined based on the UK data from WRAP *National Household Waste Composition 2017* report (WRAP, 2020). The waste components were categorised into recyclable and non-recyclable fractions, and the corresponding mass flow and composition (as received) are presented in Table 1. The recyclable and non-recyclable fractions for each waste category (except for plastics) were deduced using the same ratio as in the study conducted by Pressley et al. (2015). Polyethylene terephthalate (PET) bottles, high-density polyethylene (HDPE) bottles and mixed rigid plastics (i.e. dense plastics non-bottles) and plastic films and bags were considered as recyclable plastics in this study, while other types of plastic materials were regarded as non-recyclables. "Other materials" consist mainly of textile waste as well as other unclassified organic and inorganic wastes. Waste Electrical and Electronic Equipment (WEEE) waste, hazardous waste, wood, miscellaneous combustibles and non-combustibles, fines were considered as non-MBT compliant waste and so these wastes were excluded from the analysis.

Table 1: Residual MSW flow and composition (as received) for a 100,000 t/y MBT/MBT-v system.

Waste category	Waste component	Composition (wt%)	Mass Flow (t/h)	Mass Flow (t/y)
Organics	Food waste	36.68	6.79	36685.0
	Garden waste	10.91	2.02	10909.1
Paper and card	Paper and card	11.53	2.13	11525.2
	Non-recyclable	4.84	0.90	4840.6
Metals	Ferrous metals	2.32	0.43	2317.5
	Aluminium metals	1.51	0.28	1507.9
	Non-recyclable	0.17	0.03	173.9

Glass	Glass	4.16	0.77	4155.1
	Non-recyclable	0.00	0.00	0.0
Plastics	PET bottles	0.92	0.17	917.7
	HDPE bottles	0.57	0.11	567.1
	Mixed rigid plastics	7.92	1.47	7918.0
	Plastic films and bags	7.74	1.43	7738.6
	Non-recyclable	0.25	0.05	254.9
Other materials	Organics and inorganics	10.49	1.94	10489.6
	Total	**100.00**	**18.52**	**100000.0**

MBT wet organic fraction: The organic fraction of residual MSW was assumed to contain 65 wt% moisture (Inglezakis et al., 2011) with a molecular formula of $C_6H_{10}O_4$ (Madigan et al., 2018).

MBT rejected materials: In the proposed MBT-v system, rejects from MBT were processed in gasification to generate hydrogen. It was assumed that (i) non-combustible materials such as metals and glass were completely eliminated from the rejected streams prior to processing in the gasifier, and (ii) 1% loss of rejected materials in the MRF processing stage due to inefficiency of equipment. The proximate and ultimate analyses of the rejected materials from MBT (i.e. input materials into gasification) which were adapted from the original laboratory analysis (Nasrullah et al., 2015) are presented in Table 2.

Table 2: Proximate and ultimate analyses of rejected materials from MBT (Adapted from Nasrullah et al. (2015)).

Component	Value	Unit
Proximate analysis (as received)		
Volatile matter (i)	47.59	wt%
Fixed carbon (i)	6.82	wt%
Ash	18.80	wt%
Moisture content	26.80	wt%
Ultimate analysis (dry and ash free)		
C	63.77	wt%
H	8.23	wt%
O	25.79	wt%
N	1.42	wt%
S	0.79	wt%

Net calorific value (as received)	12.0	MJ/kg
Net calorific value (dry)	16.8	MJ/kg

Note:

[i] The compositions of volatile matter and fixed carbon were assumed based on the MSW analysis from He et al. (2009).

3.2 MBT system

A typical MBT, illustrated in Fig. 3, consists of a series of mechanical sorting processes integrated with a biological treatment process (i.e. AD in the present context). The mechanical sorting processes involves six main stages: (1) organic separation; (2) manual sorting; (3) paper/card separation; (4) metal separation; (5) glass separation; and (6) plastic sorting. Recycled products are bailed and sent to recyclers for further processing. Wet organic fraction is further processed on site in AD and CHP facilities to produce biogas (followed by heat and electricity generation) and digestate.

Mechanical sorting: Residual MSW is first loaded onto a conveyor (stream 1: 18.52 t/h) and sent to an organic separation unit. Wet organics such as food waste, garden waste and other undesirable fine inert materials such as glass, mixed rigid plastics and other organic materials (e.g. soil and aggregates) are removed via a trommel. The remaining residual MSW from the organic separation unit (stream 2: 9.25 t/h) undergoes a manual sorting stage to eliminate materials which may cause damage to the downstream mechanical sorting equipment. The wet organic fraction of MSW (stream 3: 7.49 t/h) is converted into biogas and digestate in AD. Biogas is subsequently utilised in CHP to generate heat and electricity. The fine inert materials (stream 4: 1.78 t/h) are rejected from trommel.

At the manual sorting stage, plastic films and bags (stream 5: 1.36 t/h) are recovered through a vacuum, and then sent for baling. The recyclable materials (stream 6: 6.71 t/h) are transferred to ballistic separator (paper/card separation stage) while the non-recyclable materials (stream 7: 1.18 t/h) are rejected. Heavy and light materials are segregated through ballistic separator by oscillations. Light materials such as card and paper (stream 8: 1.28 t/h) are recovered and baled, while heavy materials such as glass, metal cans and plastics (stream 9: 4.54 t/h) are transferred to metal separation stage at which non-recyclable materials (stream 10: 0.9 t/h) are rejected.

At the metal separation stage, metals are separated from glass using a magnet followed by screening through eddy current separator. Eddy current separator allows ferrous metals such as steel cans (stream 11: 0.38 t/h) to be split from non-ferrous metals such as aluminium cans (stream 12: 0.24 t/h). A stream consisting mainly of glass (stream 13: 3.88 t/h) is transferred to a glass separation stage after rejecting non-recyclable materials (stream 14: 0.03 t/h). This non-metal stream is then screened through an air classifier (also known as "wind sifter"), which separates denser materials (e.g. glass) from lighter materials (e.g. paper) based on difference in densities, where glass is recovered (stream 15: 0.6 t/h) and bailed. A plastic-rich stream (stream 16: 0.63 t/h) is obtained after eliminating light papers and other contaminants (stream 17: 2.65 t/h). Plastic-rich stream undergoes a series of screening through optical or near infrared (NIR) sorters at the plastic sorting stage. The principle of separation lies in the identification of different polymers based on detection of absorption of certain wavelengths. A 3-stage NIR sorters are set up to generate a PET bottle stream (stream 18: 0.14 t/h), a HDPE bottle stream (stream 19: 0.09 t/h) and a mixed rigid plastics stream (stream 20: 0.22 t/h). These plastic streams (streams 5, 18, 19 and 20) are bailed separately and sent to the respective plastic reprocessing plants. The remaining non-recyclable materials (stream 21: 0.18 t/h) composed of contaminated plastic materials are rejected. The non-plastic recycled products from mechanical sorting, including card and paper, metals and glass (streams 8, 11, 12 and 15) are delivered to the respective reprocessing plants. The aggregation of rejects from each sorting stage (stream 22: 6.71 t/h) is sent to EfW and landfill. In this study, it was assumed that 70% (4.7 t/h) of the rejects is sent to EfW while the remaining 30% (2.0 t/h) is disposed of to landfill (Note: this is a modelling assumption in order to obtain an amount of rejects to landfill which is 10% of the total input materials, in line with Tolvik Consulting Ltd. (2017)). The material balance for the mechanical sorting facilities, deduced using the separation efficiencies of the equipment given in Supplementary Materials (Table A.1), is presented in Table 3.

The mechanical sorting facilities in the present study requires 197 MWh of electricity per year to run various sorting and baling processes, and 1.1 ML/y of diesel fuel for running the rolling stocks. A detailed breakdown of electricity and fuel requirements are presented in Table A.2 and Table A.3 in the Supplementary Materials.

Biological treatment: The MBT wet organic fraction (stream 3) is collected and processed at a flowrate of 5.11 t/h (on a basis of 8000 h/y operational period) in an AD facility, illustrated in Fig. 4. The material balance of the AD facility is presented in Table 4. Detailed Aspen Plus simulation flowsheet, material balance and model specification can be found in the Supplementary Materials, Fig. A.1, Tables A.4 and A.5. The initial moisture content of the feed is assumed to be 65 wt%. Process water (stream 23: 2.04 t/h) is recycled from the dewatering unit and added to the feed in the slurry preparation stage to make up the moisture content to 75 wt% in order to meet the required solid-liquid ratio for AD equipment specification (Inglezakis et al., 2011). It is assumed that the feed is free from materials that may cause operational issues in AD or affect the quality of digestate. The slurry feed (stream 24: 7.15 t/h) is then treated in AD that operates at a mesophilic temperature of 35 °C. A simple stoichiometric reaction is assumed in AD using the Buswell equation (Achinas and Euverink, 2016) ($C_6H_{10}O_4 + 1.5\ H_2O \rightarrow 3.25\ CH_4 + 2.75\ CO_2$). The organic slurry is converted into biogas (stream 25: 0.66 t/h) and digestate (stream 26: 6.49 t/h). The biogas which consists of 53 mol% methane and 45 mol% carbon dioxide is further utilised in CHP for heat and electricity generation. It is assumed that methane and carbon dioxide are the main products generated from AD, while other components such as hydrogen sulphide (H_2S) and ammonia are not included in the model.

The water-rich digestate (stream 26) contains 80 wt% water and this excess water is removed via a dewatering unit (e.g. centrifuge). Based on the mass balance presented in BALKWASTE report (Inglezakis et al., 2011), 40% of water contained in the digestate is removed as wastewater (stream 27: 2.1 t/h) which is then discharged to an external wastewater treatment plant (WWTP). 2.04 t/h of process water (stream 23) is recycled to make up the moisture content in the feed slurry as discussed above, while the remaining water is embedded in the digestate (stream 28: 2.34 t/h). The digestate contains pathogens and needs to be sterilised through a pasteurisation process at 70 °C for 1 hour (Al Seadi and Lukehurst, 2012). It is assumed that 50% of the stabilised digestate (stream 29: 1.17 t/h) is used as fertiliser of which 20% (0.47 t/h) is sold and 30% (0.7 t/h) is given to farmers free of charge (Farmers Guardian, 2016). The remaining 50% of the stabilised digestate (stream 30: 1.17 t/h) is used for landspreading in agricultural land or disposed of to landfill (Farmers Guardian, 2016).

A summary of the energy production and consumption within the MBT system (including mechanical sorting and AD facilities) is presented in Table 5. In the biogas CHP system, the biogas (stream 25) is first combusted at a temperature of 1300 °C and pressure of 14 bar, assisted by excess oxygen, before entering a gas turbine. The gas turbine generates 895.6 kW of power through expanding the combusted gas stream from 14 bar to 1.1 bar. The outlet temperature of the expanded gas at 739 °C undergoes cooling to a temperature of 180 °C through an exhaust cooler, resulting in exothermic heat generation of 883 kW. The surplus heat generation is utilised to satisfy the heat demands of the feed preheater (45.7 kW from 25 to 35 °C) and pasteurisation process (68.8 kW from 35 to 70 °C). Overall, the AD biogas power generation system generates a net power of 402 kW after satisfying the demand of 493.6 kW by the air compressor. The energy balance in Table 5 shows that the MBT system has achieved energy self-sufficiency while generating surplus electricity of 3019.2 MWh per year.

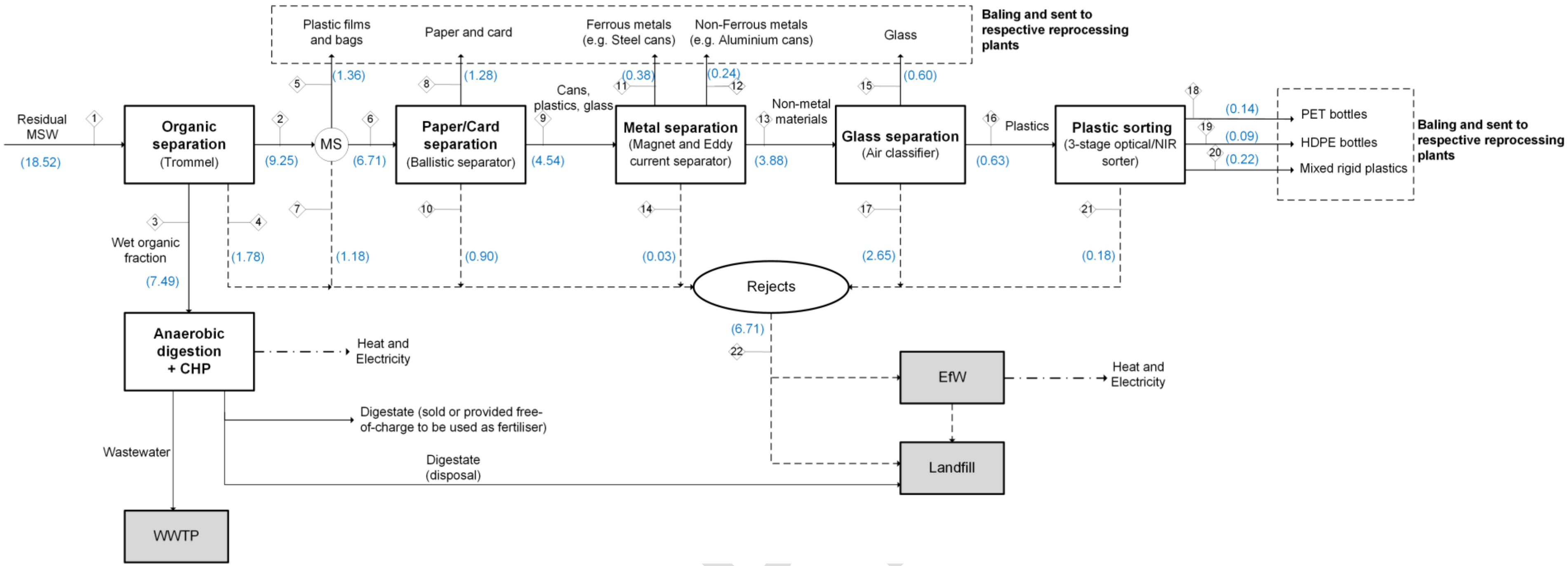

Fig. 3. MBT system for material recycling, organic waste upgrading and CHP generation. The shaded boxes represent external facilities. Mass flowrates are given in brackets (t/h). MS: Manual sorting; CHP: Combined heat and power; EfW: Energy-from-waste; WWTP: Wastewater treatment plant; PET: polyethylene terephthalate (PET); HDPE: high-density polyethylene; NIR: Near infrared.

Table 3: Material balance of the mechanical sorting facilities within MBT.

Separation stage	Input			Output		
	Stream	Stream number	Mass flow (t/h)	Stream	Stream number	Mass flow (t/h)
Organic separation	Residual MSW	1	18.52	Materials entering manual sorting stage	2	9.25
				Wet organic fraction	3	7.49
				Rejects	4	1.78
	Subtotal		**18.52**	***Subtotal***		**18.52**
Manual sorting	Materials entering manual sorting stage	2	9.25	Plastic films and bags	5	1.36
				Materials entering paper/card separation stage	6	6.71
				Rejects	7	1.18
	Subtotal		**9.25**	***Subtotal***		**9.25**
Paper/card separation	Materials entering paper/card separation stage	6	6.71	Paper and card	8	1.28
				Materials entering metal separation stage	9	4.54
				Rejects	10	0.90
	Subtotal		**6.71**	***Subtotal***		**6.71**
Metal separation	Materials entering metal separation stage	9	4.54	Ferrous metals	11	0.38
				Non-ferrous metals	12	0.24
				Materials entering glass separation stage	13	3.88
				Rejects	14	0.03
	Subtotal		**4.54**	***Subtotal***		**4.54**
Glass separation	Materials entering glass separation stage	13	3.88	Glass	15	0.60
				Materials entering plastic sorting stage	16	0.63
				Rejects	17	2.65
	Subtotal		**3.88**	***Subtotal***		**3.88**
Plastic sorting	Materials entering plastic sorting stage	16	0.63	PET bottles	18	0.14
				HDPE bottles	19	0.09
				Mixed rigid plastics	20	0.22
				Rejects	21	0.18
	Subtotal		**0.63**	***Subtotal***		**0.63**
	Total input		**18.52**	**Total output**		**18.52**
				Total rejects	**22**	**6.71**
				Total plastic materials to be recycled	**5+18+19 +20**	**1.81**
				Total non-plastic materials to be recycled	**8+11+12 +15**	**2.50**
				Total wet organic fraction	**3**	**7.49**

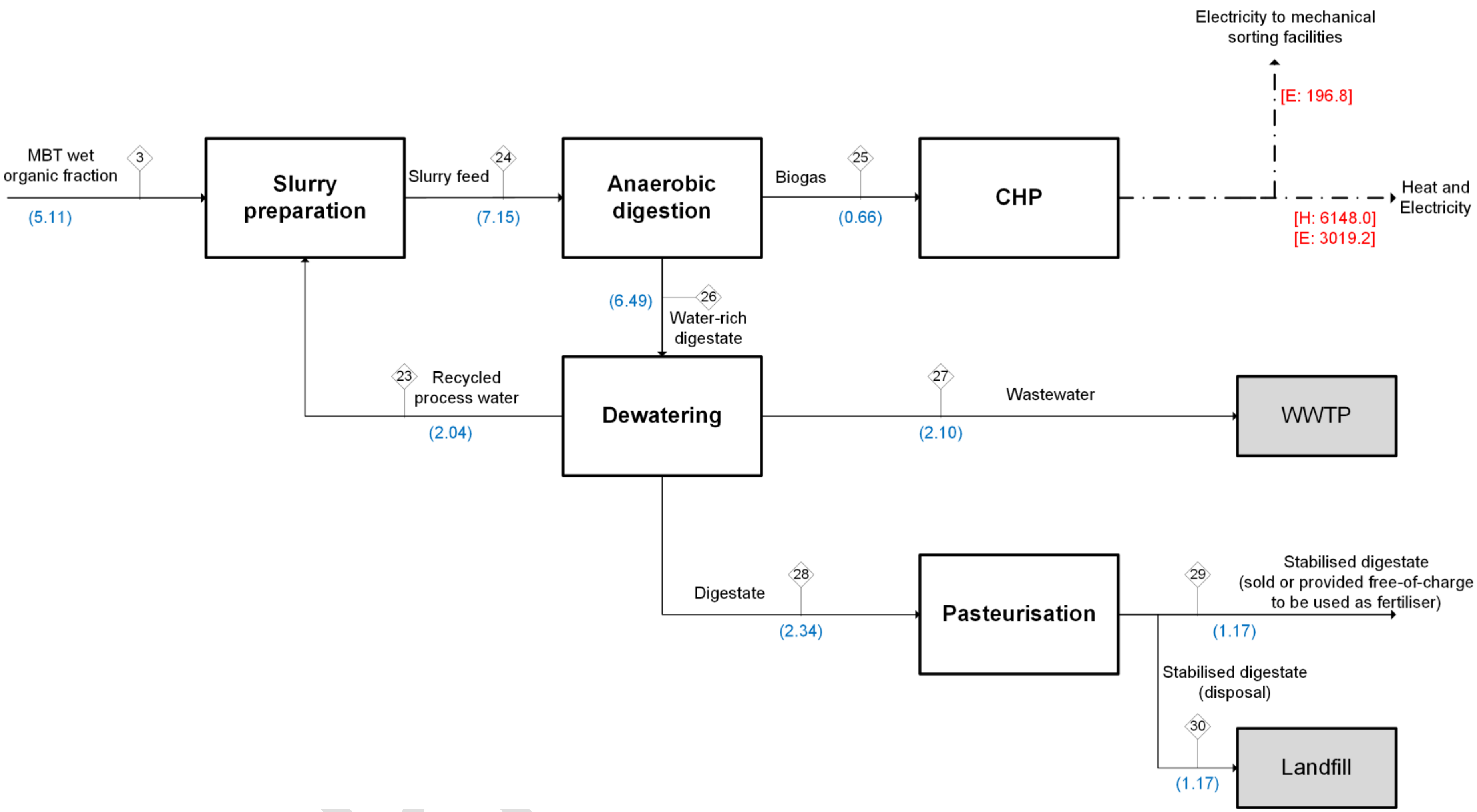

Fig. 4. Biological treatment of wet organic fraction of residual MSW through anaerobic digestion and CHP. The shaded boxes represent external facilities. Mass flowrates are given in (t/h); heat (H) and electricity (E) are given in [MWh per year]. WWTP: Wastewater treatment plant.

Table 4: Material balance of the anaerobic digestion facility within MBT.

Component	Stream								
	3 (i)	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Mass flowrate (t/h)									
MBT wet organic fraction	1.79	0.00	1.79	0.00	1.23	0.00	1.23	0.62	0.62
CH_4	0.00	0.00	0.00	0.20	0.00	0.00	0.000	0.000	0.000
CO_2	0.00	0.00	0.00	0.46	0.00	0.00	0.000	0.000	0.000
H_2O	3.32	2.04	5.36	0.005	5.26	2.10	1.11	0.55	0.55
Total flowrate (t/h)	**5.11**	**2.04**	**7.15**	**0.66**	**6.49**	**2.10**	**2.34**	**1.17**	**1.17**
Temperature (°C)	25	35	35	35	35	35	35	70	70
Pressure (bar)	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013

Table 5: Generation and consumption of steam and power within the MBT system.

Component	Heat consumption		Heat generation		Power/electricity consumption		Power/electricity generation	
	kW	**MWh per year**	**kW**	**MWh per year**	**kW**	**MWh per year**	**kW**	**MWh per year**
Mechanical sorting								
Sorting equipment					33.26	179.60		
Baling equipment					3.18	17.17		
Biological treatment (Anaerobic digestion)								
Exhaust cooler			883.0	7064.0				
Gas turbine							895.60	7164.80
Air compressor					493.60	3948.80		
Feed preheater	45.7	365.6						
Pasteurisation	68.8	550.4						
Total	**114.5**	**916.0**	**883.0**	**7064.0**	**530.04**	**4145.57**	**895.60**	**7164.80**

3.3 MBT-v system

The integrated MBT-v system, presented in Fig. 5, is proposed for valorising the rejected materials from MBT into hydrogen through gasification. The integration of Gasification-H_2 facility with mechanical sorting and AD facilities is an additional feature to the conventional MBT discussed in section 3.2. The material balance for the upgrading system of MBT rejects through Gasification-H_2 facility is presented in Table 6. The detailed Aspen Plus simulation flowsheet, material balance and model specification are provided in Fig. A.2, Table A.6 and Table A.7 in the Supplementary Materials.

The rejected materials from mechanical sorting facility is dried to 10% moisture before entering the gasifier (stream 22: 3.4 t/h). Gasification is essentially a partial oxidation process that takes place at 900 °C and 1.6 bar in this case using steam (stream 31: 4.66 t/h) as the gasifying medium, with a steam-to-feed ratio (weight basis) of 1.04 (He et al., 2009). Syngas (stream 32: 7.22 t/h) consisting primarily of CO, H_2, CO_2 and H_2O with a H_2/CO molar ratio of 2.6 is generated. Solid particulate (i.e. ash) is removed from the hot syngas through a cyclone (stream 33: 0.84 t/h) which is then disposed of to landfill (Note: alternatively, it can be processed into aggregate replacement for construction).

The pressure and temperature of syngas are adjusted to 30 bar and 50 °C before entering the gas cleaning and conditioning processes which comprise an acid gas removal unit and a water-gas shift reactor (see Supplementary Materials, Fig. A.2). It can be assumed that the syngas contains negligible tar since dolomite is used as the catalyst and higher steam-to-feed ratio is applied in the gasification (He et al., 2009). H_2S in the syngas is reduced to 1 ppmv in the acid gas removal unit (represented by LO-CAT followed by ZnO bed) to prevent catalyst poisoning in the subsequent water-gas shift reactor. The hydrogen content in the syngas is raised from 0.46 t/h (stream 32) to 0.64 t/h (stream 35) through the water-gas shift ($CO + H_2O \leftrightarrow H_2 + CO_2$)

reactor. The reactor operates at 200 °C, with medium pressure (MP) steam (stream 34: 1.8 t/h) at 14 bar and 250 °C added to facilitate the reaction. The conditioned syngas is then dewatered through a flash drum after the temperature is reduced to 40 °C. Stream 36 represents the combined outlet streams of acid gas removal unit and flash drum where H_2S (0.02 t/h) and water (2.1 t/h) are removed from these process units. H_2S is commonly removed through Claus process by converting H_2S into elemental sulphur. The hydrogen-rich stream (stream 35: 6.9 t/h) is sent to a pressure swing adsorption (PSA) unit where hydrogen is recovered at 85 mol % with a purity of 99.95 mol% (stream 37: 0.55 t/h), and compressed to 70 bar. A tail gas stream (stream 38: 6.35 t/h) consisting mainly of CO_2 emerges from PSA at 40 °C and 1.013 bar.

Energy integration analysis was conducted to identify energy recovery opportunity within the Gasification-H_2 facility. A summary of the energy production and consumption within the MBT-v system (including mechanical sorting, AD and Gasification-H_2 facilities) is presented in Table 7. The analysis shows that the heat released from syngas cooler and syngas compressor inter/aftercooler can be utilised for very high pressure (VHP) steam generation at flow rates of 4.75 t/h and 5.54 t/h, while water-gas shift reactor can generate 1.51 t/h of low pressure (LP) steam through its jacket. A CHP network diagram is presented in Fig. A.3 in the Supplementary Materials. The steam generation from these processes were estimated using composite curve analysis (Supplementary Materials, Fig. A.4). The Gasification-H_2 facility requires 9 t/h of steam to satisfy the operations in cleaned syngas heater (MP: 2.79 t/h), water-gas shift reactor (MP: 1.60 t/h) and gasifier (LP: 4.66 t/h). The remaining steam is expanded through steam turbines at different pressure levels, resulting in a total electricity generation of 15652.53 MWh per year. The Gasification-H_2 facility has a net power deficit of 948.91 kW after satisfying the power requirement by syngas compressor (2576.94 kW) and hydrogen compressor (328.54 kW). Overall, it has been determined that the MBT-v system requires external electricity supply of 4572.1 MWh per year.

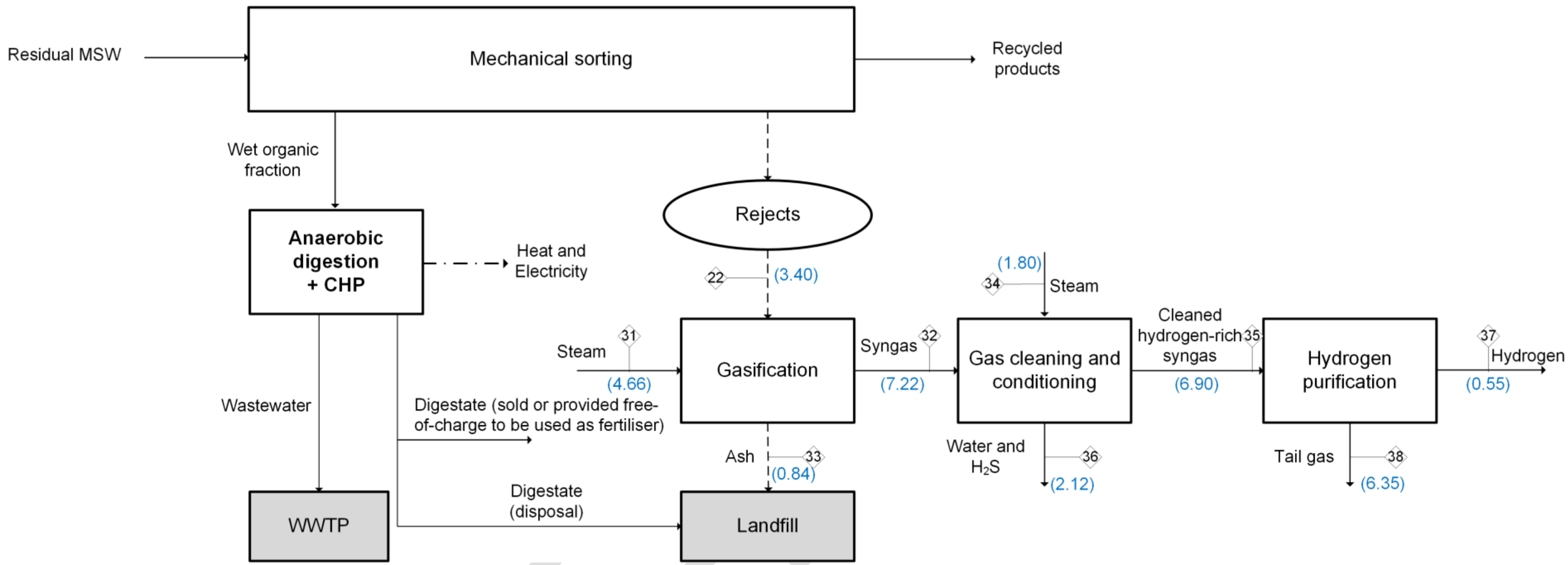

Fig. 5. Integrated MBT and Gasification-H_2 system (MBT-v) for material recycling, energy recovery and hydrogen production. Rejects from MBT are valorised through gasification platform. The shaded boxes represent external facilities. Mass flowrates are given in (t/h). WWTP: Wastewater treatment plant.

Table 6: Material balance of Gasification-H_2 facility using MBT rejects as the feedstock.

Component	**Stream**								
	22 (i)	**31**	**32**	**33**	**34**	**35**	**36 (ii)**	**37**	**38**
Mass flowrate (t/h)									
C	1.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_2	0.20	0.00	0.46	0.00	0.00	0.64	0.00	0.54	0.096
O_2	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N_2	0.035	0.00	0.035	0.00	0.00	0.035	0.00	0.00	0.035
S	0.019	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	0.00	0.00	2.48	0.00	0.00	0.035	0.00	0.00	0.035
CO_2	0.00	0.00	1.80	0.00	0.00	5.64	0.00	0.006	5.63
H_2O	0.12	4.66	2.42	0.00	1.80	0.55	2.10	0.00	0.55
CH_4	0.00	0.00	0.001	0.00	0.00	0.001	0.00	0.00	0.001
H_2S	0.00	0.00	0.021	0.00	0.00	0.00	0.021	0.00	0.000
Ash	0.84	0.00	0.00	0.84	0.00	0.00	0.00	0.00	0.000
Total flowrate (t/h)	**3.40**	**4.66**	**7.22**	**0.84**	**1.80**	**6.90**	**2.12**	**0.55**	**6.35**
Temperature (°C)	250.0	133.5	900.0	900.0	250.0	40.0	50.0/110.0	45.0	40.0
Pressure (bar)	1.6	3.0	1.6	1.6	14.0	1.013	30.0/1.013	70.0	1.013

Note:

(i) The flowrate of rejected materials from mechanical sorting is 4.48 t/h (wet basis; 6.71 t/h operating at 5400 h/y in mechanical sorting converted into 4.48 t/h operating at 8000 h/y in Gasification-H_2 system) and it is subsequently dried to 10% moisture content before entering the gasifier, hence the final flowrate is 3.4 t/h.

(ii) Since there are two processes involved, i.e. acid gas removal and water-gas shift reaction, two sets of temperature and pressure for stream 36 are presented.

Table 7: Generation and consumption of steam and power in the MBT-v system.

Component	Steam consumption	Steam generation	Power/electricity consumption		Power/electricity generation	
	t/h	t/h	kW	MWh per year	kW	MWh per year
Mechanical sorting						
Sorting equipment			33.26	179.60		
Baling equipment			3.18	17.17		
Biological treatment (Anaerobic digestion)						
Gas turbine					895.60	7164.80
Air compressor			493.60	3948.80		
Gasification-H_2						
Syngas cooler		4.75				
Syngas compressor inter/aftercooler		5.54				
Cleaned syngas heater	2.79					
Water-gas shift reactor	1.60	1.51				
Gasifier	4.66					
Syngas compressor			2576.94	20615.52		
Hydrogen compressor			328.54	2628.30		
Steam turbines					1956.57	15652.53
Total	**9.05**	**11.8**	**3435.52**	**27389.39**	**2852.17**	**22817.33**

4. Technical performance and economic analysis of conventional MBT and MBT-v systems

4.1 Technical performance analysis

The technical performances of the conventional MBT and MBT-v systems with respect to mechanical sorting, biological treatment (AD+CHP) and Gasification-H_2 facilities are presented in Table 8, based on the material and energy balances performed in sections 3.2 and 3.3.

The conventional MBT system (mechanical sorting and AD) under consideration recycles 23% of the materials (paper and card, metals, glass and plastics) from the residual MSW through mechanical sorting processes, while rejecting 36% of the materials to EfW (70%) and landfill (30%). Wet organics which consists of 40% of the output stream is upgraded via the AD process, producing 0.13 t biogas, 0.46 t digestate and 0.41 t wastewater/t of wet organics. The biogas is subsequently utilised in CHP, generating a net electricity of 3216.0 MWh per year (629.35 MWh per tonne of wet organics). Overall, the MBT system generates a net electricity of 3019.23 MWh per year, implying that the system is energy self-sufficient and it can be operated without external source of electricity.

The additional feature of MBT-v system is that a considerable amount of the rejected materials from MBT can be diverted from EfW and landfills by upgrading through Gasification-H_2 facility. The MBT-v system produces 0.12 t hydrogen/t MBT rejected materials, assisted by 1.44 t steam/t MBT rejected materials in gasifier and water-gas shift reactor. The system creates a number of waste streams, including wastewater (0.71 t/t MBT rejects), tail gas (1.42 t/t MBT rejects), acid gas (0.005 t/t MBT rejects) and gasifier bottom ash (0.19 t/t MBT rejects). Bottom ash is normally sent to landfill after the embedded metal components are recovered or it can be processed into aggregate replacement for construction. The CHP system within the

Gasification-H_2 facility has a net electricity deficit of 7591.3 MWh/y (1693.7 MWh/t of MBT rejects). The overall MBT-v system is in 4572.06 MWh per year deficit of electricity and this requires external source of electricity. The MBT-v system creates an additional value-added product, i.e. hydrogen, compared to conventional MBT at the expense of additional electricity demand.

Table 8: Technical performance analysis of MBT/MBT-v system.

Mechanical sorting			***Biological treatment (AD+CHP)***			***Gasification-H_2 (only for MBT-v system)***		
Parameter	**Value**	**Normalised value (per tonne basis)**	**Parameter**	**Value**	**Normalised value (per tonne basis)**	**Parameter**	**Value**	**Normalised value (per tonne basis)**
Input flow, residual MSW (t/h)	**18.52**	**1.00**	**Input flow, wet organics (t/h)** [(i)]	**5.11**	**1.00**	**Input flow, MBT rejects (t/h)** [(ii)]	**4.48**	**1.00**
						Steam input (t/h)	**6.46**	**1.44**
						LP steam to Gasifier	4.66	1.04
						MP steam to WGS	1.80	0.40
Output flow (t/h)			**Output flow (t/h)**			**Output flow (t/h)**		
Recycled products	**4.31**	**0.23**	***Biogas***	**0.66**	**0.13**	***Hydrogen***	**0.55**	**0.12**
Paper and card	1.28	0.07						
Metals	0.62	0.03	***Digestate***	**2.34**	**0.46**	***Waste streams***	**10.39**	**2.32**
Glass	0.60	0.03				Wastewater	3.18	0.71
Plastics	1.81	0.10	***Wastewater***	**2.10**	**0.41**	Tail gas	6.35	1.42
						Acid gas	0.02	0.005
Wet organics	**7.49**	**0.40**				Bottom ash	0.84	0.19
Rejects [(iii)]	**6.71**	**0.36**						
to EfW	4.70	0.25						
to landfill	2.01	0.11						
Electricity (MWh per year)			**Electricity (MWh per year)**			**Electricity (MWh per year)**		
Consumption	**196.77**	**10.63**	***Consumption***	**3948.80**	**772.76**	***Consumption***	**23243.82**	**5186.04**
Generation	**0.00**	**0.00**	***Generation***	**−7164.80**	**−1402.11**	***Generation***	**−15652.53**	**−3492.31**
Net	**196.77**	**10.63**	***Net***	**−3216.00**	**−629.35**	***Net***	**7591.29**	**1693.73**

Note:
[(i)] The operating hours for AD was assumed to be 8000 h/y.
[(ii)] This is the mass flow in wet basis (i.e. before drying). Operating hours for Gasification-H_2 facility was assumed to be 8000 h/y.
[(iii)] The rejected materials were not accounted in the MBT-v system as this fraction was upgraded through Gasification-H_2 facility.

4.2 Economic analysis

4.2.1 Economic potential of conventional MBT and MBT-v systems

Table 9 presents a comparison of costs and revenues between the MBT and MBT-v systems where the economic performance is indicated by economic potential (equation (5)). The cost data for capital cost, operating cost and revenue were obtained from various published sources, detailed in section 2. Detailed cost evaluation (Supplementary Materials, Tables A.8-A.19) was carried out using these data and the economic analysis approach (equations (1)-(5)).

The total capital investment of the MBT system was determined to be 6.5 M£. The annual cost of MBT system was estimated to be 7.75 M£/y which includes annualised capital cost of 0.76 (determined using equation (3) where *CRF* = 11.7% by assuming a discount rate of 10% and plant life of 20 years) and operating cost of 6.99 M£/y. The highest equipment cost component in MBT is the biological treatment section where AD and CHP contributes 58% (0.088 M£/y) of the total equipment cost. The reject disposal cost contributes 83% (3.58 M£/y) of the variable operating costs which is the highest cost component in this category. The MBT system generates a total revenue of 11.2 M£/y of which 78.8% (8.8 M£/y) comes from the gate fees, 17.6% (1.97 M£/y) from the recycled products, 3.5% (0.39 M£/y) from the surplus electricity generated from AD biogas and CHP, and 0.17% (0.02 M£/y) from digestate sale. In the present study, it was assumed that 20% of the digestate is sold as fertiliser at a price of 5 £/t; 30% is given to farmers free-of-charge; and 50% is disposed of to landfill or agricultural land (landspreading) at a cost of 13 £/t (Farmers Gurdian, 2016). Digestate has a net cost of 5.5 £/t to the systems, i.e. 0.12 M£/y in this case. The economic potential of the MBT system was estimated to be 3.42 M£/y. This is highly dependent on the incentives from gate fees (Note: gate fees are assumed at 88 £/t in this case (WRAP, 2017)). If gate fees are not provided, the system will not be economically feasible if only relies on the revenues generated from the recycled products from mechanical sorting and electricity from AD and CHP. It has been found that minimum gate fees of 53.7 £/t (i.e. at EP = 0) are needed to support the MBT system so that it can be financially sustainable.

The reject disposal cost of 3.58 M£/y in MBT system can be reduced by 78% to 0.79 M£/y through upgrading the rejected materials in a Gasification-H_2 facility, as demonstrated in the MBT-v system. Integrating a Gasification-H_2 facility with the MBT system creates an additional revenue of 43.9 M£/y from hydrogen production, assuming a hydrogen price of 10 £/kg (Insideevs, 2017). The MBT-v system generates almost 5-fold of revenue (54.7 M£/y) compared to the MBT system (11.2 M£/y). However, this is at the expense of a higher capital costs of 100 M£ (annualised to 11.8 M£/y), i.e. approximately 15-fold higher than a conventional MBT system. The operating cost of the MBT-v system, i.e. 6.5 M£/y, is 6.5% (0.45 M£/y) lower than the MBT system mainly due to the reduction in reject disposal cost. It is noticeable that the MBT-v can still be profitable (EP = 27.6 M£/y) even without the provision of gate fees. The fluctuation in hydrogen price should also be taken into account as ±10% changes in the price would lead to ±4.4 M£/y changes in the economic potential of the MBT-v system. It was estimated that a minimum hydrogen price of 1.7 £/kg (i.e. EP = 0) is required for an economically feasible MBT-v operation in this case.

Overall, the valorisation of MBT rejected materials can be seen as an economically compelling strategy with the potential of generating a diverse range of products (i.e. recycled products, electricity, digestate and hydrogen). It is desirable to have a balanced portfolio of products with both high and low market values in a resource recovery system.

Table 9: Comparison of economic potential of MBT and MBT-v systems based on capital and operating costs and revenue.

MBT		**MBT-v**	
Component	**Cost (M£/y)**	**Component**	**Cost (M£/y)**
Capital cost		***Capital cost***	
Equipment	**0.15**	**Equipment**	**2.34**
Conveyor	0.002	MBT equipment	0.15
Drum feeder	0.006	Dryer	0.18
Vacuum	0.003	Gasifier	0.27
Trommel	0.003	Cyclone	0.12
Ballistic separator	0.006	Acid gas removal	0.004
Magnet	0.004	Water-gas shift reactor	0.16
Eddy current separator	0.005	Water removal unit	0.003
Air classifier	0.001	PSA	0.41
Optical/NIR sorter	0.016	Syngas compressor	0.33
Baler	0.017	H_2 compressor	0.06
AD and CHP	0.088	Heat exchangers	0.44
		Steam turbine + steam system	0.19
Other direct cost	0.31	**Other direct cost**	4.72
Indirect cost	0.19	**Indirect cost**	2.95
Working capital	0.11	**Working capital**	1.75
Annualised capital cost	**0.76**	**Annualised capital cost**	**11.77**
Operating cost		***Operating cost***	
Variable operating cost	**4.30**	**Variable operating cost**	**2.20**
Baling - wire cost	0.06	Baling - wire cost	0.06
Electricity	0.00	Fuel	0.53
Fuel	0.53	Digestate disposal cost	0.12
Rejects disposal cost	3.58	Electricity	0.59
Digestate disposal cost	0.12	Catalyst	0.01
Effluent discharge cost	0.01	LO-CAT chemicals	0.006
		Gasifier bed materials	0.08
		Rejects disposal cost	0.79
		Effluent discharge cost	0.02
Fixed operating cost	**2.68**	**Fixed operating cost**	**4.33**
Operating cost	**6.99**	**Operating cost**	**6.53**
Revenue		***Revenue***	
Recycled product	**−1.97**	**Hydrogen**	**−43.91**
Paper and card	−0.23		
Ferrous metals	−0.17	**Recycled product**	**−1.97**
Aluminium	−0.95		
Glass	0.03	**Digestate sale**	**−0.02**
PET	−0.22		
HDPE	−0.26	**Gate fees for MBT-v**	**−8.80**

Mixed rigid plastics	−0.17		
Electricity generation from AD+CHP	**−0.39**		
Digestate sale	**−0.02**		
Gate fees for MBT	**−8.80**		
Revenue	**−11.17**	**Revenue**	**−54.70**
Economic potential	**3.42**	**Economic potential**	**36.40**

4.2.2 Minimum hydrogen selling price (MHSP)

The MHSP for the Gasification-H_2 facility within MBT-v system was calculated by applying equation (6), using the annualised capital and operating costs presented in Table 9. The production rate of hydrogen was determined to be 4391 t/y (8000 h/y of operational period) as shown in the material balance in Table 6. The MHSP for this system, with a throughput of 3.3 dry t/h of MBT rejected materials, was estimated to be 3.4 £/kg (28.3 £/GJ). The MHSP falls between 0.7 £/kg (5.8 £/GJ) for a system at a higher throughput of 88.2 dry t/h in the NREL study (Spath et al., 2005) and 8.9 £/kg (74.4 £/GJ) for a system at a lower throughput of 0.02 dry t/h in the study by Sara et al. (2016), presented in Table 10. The hydrogen yield in the present study is higher than the others, i.e. 167 kg hydrogen/dry t feedstock compared to 70 kg hydrogen/dry t feedstock, owing to the deployment of a higher steam-to-feed flow rate in the gasifier. The H_2/CO molar ratio of syngas from gasification is typically 0.6-0.8 (Spath et al., 2005), but in this study, the resulting H_2/CO molar ratio is 2.6. IRENA (2019) presented a comparison of MHSP of various hydrogen production technologies. The Gasification-H_2 facility within MBT-v system in the present study has shown a relatively higher MHSP compared to these technologies, including solar power electrolyser (3.9-18.9 £/GJ or 0.5-2.3 £/kg); wind powered electrolyser (5.1-7.8 £/GJ or 0.6-0.9 £/kg); steam methane reforming of natural gas with carbon capture and storage (2.3-6.1 £/GJ or 0.3-0.7 £/kg) and coal gasification with carbon capture and storage (1.2-3.0 £/GJ or 0.1-0.4 £/kg). This suggests that hydrogen production from rejected materials at the current scale is less competitive compared to other production routes and may not be favourable unless significant incentives are provided. Increasing the production capacity could further reduce the MHSP and this will be examined in section 4.2.3.

Table 10: Comparison of minimum hydrogen selling price of Gasification-H_2 facility with other previous studies.

Parameter	**Present study**	**NREL / Spath et al. (2005)**	**Sara et al. (2016)**
Year of study	2020	2005	2016
Feedstock	MBT rejected materials	Hybrid poplar wood chips	Almond shell
Throughput (dry t/h)	3.28	88.17	0.02
Annualised capital cost (M£/y)	11.00 [(i)]	14.23	0.05
Operating cost (M£/y)	3.87 [(i)]	23.40	0.03
Hydrogen production (t/y)	4391.36	54400.00	9.70
Hydrogen yield (kg/dry t feedstock)	167.3	70.4	69.3
Minimum hydrogen selling price (£/kg)	3.39	0.69	8.93
Minimum hydrogen selling price (£/GJ)	28.26	5.75	74.38

Note:

[(i)] The capital and operating costs are only associated with the Gasification-H_2 facility. The costs for mechanical sorting and AD+CHP are excluded.

4.2.3 Economies of scale

The economies of scale of the Gasification-H_2 facility within MBT-v were examined with respect to MHSP, illustrated in Fig. 6. The capacity of Gasification-H_2 facility (i.e. throughput of MBT rejected materials) was varied from 3.3 dry t/h (base case), through 100 dry t/h to 200 dry t/h. The MHSP for these systems were found to be 3.39 £/kg (28.2 £/GJ), 1.51 £/kg (12.6 £/GJ) and 1.34 £/kg (11.2 £/GJ). The results show that MHSP for a Gasification-H_2 facility above 100 dry t/h is comparable to average MHSP of the solar power electrolyser (see section 4.2.2). Further reduction in MHSP to below 1.0 £/kg (8.3 £/GJ) is needed to achieve an economically competitive Gasification-H_2 facility (compared to wind and fossil-based technologies) and this could be attained by increasing the capacity of the system. Regression analysis was performed as shown in Fig. 6 and it was estimated that a capacity of 666 dry t/h of MBT reject materials would be needed to result in an MHSP of 1.0 £/kg.

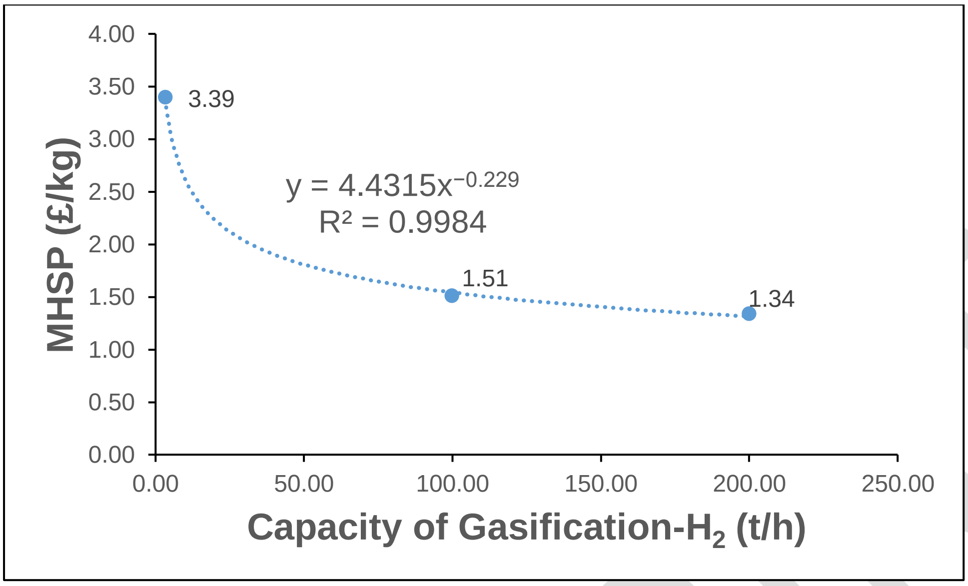

Fig. 6. MHSP at different capacity of Gasification-H_2 facility. The dotted line represents the regression line where the equation and R^2 value are given. *y* refers to MHSP and *x* refers to the capacity of the system.

4.3 Discussions

The main advantages of MBT are its capability of extracting recyclable materials from residual MSW and converting the wet organic fraction of residual MSW into biogas and digestate via the use of AD. The heat and electricity generated from biogas is able to satisfy the energy demand of the system, while any energy surplus can be exported to the grid. The production of digestate and solid rejects from MBT represents a major concern for waste contractors, as the disposal costs can be high due to the constantly rising UK landfill tax and gate fees (~117 £/t in May 2020 (LetsRecycle, 2020)). This makes MBT economically unattractive as revenues are not significant to offset the high operating costs. The present analysis showed that the revenue generated from MBT is dominated by gate fees (78.8%) while recycled products, digestate and electricity contribute to only one-fifth of its revenue.

The limitations of MBT can be overcome by transforming the conventional MBT system into an MBT-v system. The polygeneration features (Ng and Martinez-Hernandez, 2020) of the MBT-v system are promising because it maximises resource recovery from waste and produces a diverse range of high- and low-value products. The MBT-v system diverts more waste from landfills and promotes resource recovery and cleaner energy production through a combination of material recycling and valorisation of the rejected materials into hydrogen. Product diversification exhibited by the MBT-v system ensures that financial risk of the facility is minimised while generating additional products to meet local demands. Producing a higher value product such as hydrogen can improve the economic performance of the MBT system. With the current assumed price of hydrogen of 10 £/kg, the economic potential of MBT-v system is compelling even if the gate fees are not provided.

In the UK, the widespread use of EfW has created a technological lock-in that prevents the extraction of maximum value from waste (Uyarra and Gee, 2013). Complex market, organisational, institutional and technological barriers have hindered the development of a more sustainable approach to residual MSW management (Uyarra and Gee, 2013). The energy generated via EfW is used as an incentive to continue investments in this sector under the false pretence of promoting EfW as a 'cornerstone' of moving towards a resource-efficient, low-carbon, circular economy (Policy Connect, 2020). EfW is currently a preferred option for the waste management industry because it is a well-established process and good for business as it generates worthwhile gains. Whilst our economy will continue to rely to some extent on EfW due to the benefits of treating infectious waste and eliminating hazards, it should not disintegrate efforts to reduce reliance on this option. Instead, prevention, reuse, recycling and alternative options for the management of residual waste that can lead to clean growth and circular economy should be promoted (Iacovidou et al., 2017). Hydrogen is a promising source of clean energy and has the potential to promote clean growth and contribute to the decarbonisation efforts of the waste management industry, as well as other sectors such as heating and transport (IEA, 2019). The proposed MBT-v system generates hydrogen, while it diverts waste from landfills and reduces reliance on EfW, which can further lower carbon emissions, helping the UK meet the net zero emissions target. The deployment of MBT-v system with hydrogen production is likely to gain traction in the near future as the latest Ten-Point Plan for a Green Industrial Revolution has included boosting low-carbon hydrogen production capacity as one of the key agenda by 2030 (Prime Minister's Office, 2020).

A key limitation to the mainstream implementation of the MBT-v system, which deems further investigation is its high capital investment. Although the cost of production of hydrogen can be improved by increasing the scale of the system, the scalability of the system is pertinent to the return of investment potential that would attract investors. It may not always preferable to implement a large-scale system. The scale and optimal configuration of MBT-v needs to be designed based on local conditions, considering the quantity and quality of residual MSW, frequency of collection, seasonality, market availability for secondary resources and energy/fuel, existing waste management infrastructure, local government initiatives in regard to waste collection and management, and investment for innovation and clean energy.

The national agenda has been focusing on reducing greenhouse gas (GHG) emissions in the waste management sector by diverting waste from landfills through improving recycling rates, and increasing the capacity of EfW plants (HM Government, 2018). This study has offered an alternative technology which can be adopted to support the initiatives in minimising waste and promoting resource efficiency. More focus should be placed on creating new market for value-added products from waste and providing sufficient financial support to promote clean growth and decarbonisation in the waste and energy industry. Policy and business stakeholders should be prepared for the transition towards a more sustainable waste management model by employing more robust technologies. It is envisaged that with the advancement in the MBT or

MBT-v technologies, the investment on EfW infrastructure can significantly be reduced and the issues associated with depleting landfill capacity can be addressed.

5. Conclusions

This paper has proposed a novel integrated MBT and valorisation system for residual MSW treatment, incorporating polygeneration strategies. This has addressed the limitation of conventional MBT in terms of the high rejects disposal cost and the associated environmental impact. This study has offered an insight into the potential benefits gained by integrating the MBT and gasification technologies to achieve maximum resource efficiency and diversion of waste from landfills. The proposed MBT-v system has shown its high capability of: (i) improving resource recovery from waste and product diversification; (ii) minimising waste disposal to landfill; (iii) reducing reliance on EfW. This work has contributed to new knowledge in terms of valorising rejected materials from conventional MBT into higher value products, i.e. hydrogen in this context. Hydrogen derived from waste will contribute to future clean fuel demand by replacing fossil fuels. This robust technology can disrupt the deployment of conventional MBT system and EfW, promoting innovation and clean growth.

Although the techno-economic assessment showed that the capital investment for an MBT-v system is higher than a conventional MBT system, this can be counterbalanced by the revenue generated from hydrogen production. Product diversification minimises the financial risk of the MBT-v system and reduces reliance on gate fees. Accelerating the uptake of the MBT-v system in the future could bring the capital costs down and make this option economic attractive and competitive to existing technologies. The scale and adaptability of this option requires further scrutiny in order to ensure that its employment can match local specificities and needs, whilst delivering multiple benefits to the community. Sufficient financial support needs to be provided to support the implementation of MBT-v at pilot scales to explore its usefulness in promoting sustainable waste management, clean growth and the transition to a low-carbon and circular economy. This will highlight ecological, technical, political, economic and social barriers and opportunities associated with the adoption of this technology, and signify areas where interventions are needed.

Future development in advancing MBT-v system should be focused on exploring alternative integration and valorisation pathways, for example, biogas and CO_2 utilisation into higher value products such as methanol. Model validation based on experimental or pilot plant studies and further investigation on the variability of waste composition on the economic performance should be conducted. Improved insights into the potential of MBT-v technology to unlock multiple benefits alongside efforts to make it economically attractive, can disrupt investments on EfW infrastructure and change the waste management industry landscape completely. This requires an effective and coordinated collaboration amongst all stakeholders involved in the production, consumption, management system to ensure that efforts towards resource efficiency, clean growth, and circular, low-carbon economy are well integrated.

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