

Evaluating the Techno-economic Potential of an Integrated Material Recovery and Waste-to-Hydrogen System

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Abstract

This study proposes a novel integrated material recovery and waste-to-hydrogen concept in view of enhancing resource efficiency and minimising environmental impact. A comprehensive techno-economic evaluation is conducted on an integrated system consisting of material recovery facility (MRF) and gasification of rejected materials for hydrogen production (Gasification-H₂). Valorising these rejected materials through Gasification-H₂ system can potentially offer a saving of 1.6 million £/y on disposal cost while diverting significant amount of waste from landfills. Owing to the high market value of hydrogen, the integrated system with material recovery and hydrogen production generates 4 times more revenues than a conventional MRF, though at the expense of higher capital and operating costs. The minimum hydrogen selling price lies in the range of 2.2 £/kg (100 dry t/h of rejects) and 6.1 £/kg (2 dry t/h of rejects). This study concludes that a larger Gasification-H₂ system is desirable, i.e. greater than 100 dry t/h of rejects, to compete with the production cost of hydrogen generated from fossil-based systems. It is also recommended that an economically competitive production should comprise multiple MRF integrated with a large-scale Gasification-H₂ system.

Keywords: Resource recovery; waste-to-hydrogen; polygeneration; recycling; circular economy; gasification.

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1 **1. Introduction**

2 Household recycling waste is collected by local authorities in the UK and is subsequently sent
3 to material recovery facilities (MRF), which consist of a series of mechanical sorting and
4 screening processes for recovery of marketable products such as paper and card, glass, metals
5 and plastics. So far, MRF is the preferred method of treating recycling stream in view of
6 recovering value from waste while diverting waste from landfills [1]. There are a number of
7 challenges in achieving maximum resource recovery from waste using an MRF. Firstly,
8 segregation of waste at source has its own limitation due to the lack of awareness of local
9 residents and confusion over which materials can be recycled [2, 3]. This results in generation
10 of commingled or contaminated recycling waste streams and creates a significant portion of
11 non-recyclable materials (also referred to as “rejects”). The non-recyclable materials in this
12 context include materials that cannot be reprocessed and those which may cause damage to the
13 sorting equipment. These will need to be sent to energy-from-waste (EfW) facilities and
14 landfills according to the conventional waste management approach. Based on the findings
15 reported in the existing literature, the reject rate (i.e. amount of non-recyclable materials with
16 respect to the amount of incoming recycling waste stream into MRF) is typically 6-8% and can
17 reach up to 27% [2, 3]. Secondly, MRF has its inherent technological constraints in terms of
18 coping with highly contaminated waste streams [4]. Additional equipment needs to be installed
19 or operating conditions need to be altered if the composition of the incoming materials varies
20 significantly. The removal of contaminants prior to MRF and quality control during sorting are
21 labour-intensive processes, leading to higher processing costs [5]. Therefore, it is imperative
22 to explore alternatives that can handle the rejected stream from MRFs.

23 The rejected material stream generated from mechanical treatment processes in MRF (i.e.
24 shredding and sorting) can be converted into refuse derived fuel (RDF) or solid recovered fuel
25 (SDF) [6]. RDF/SDF has high net calorific values (~15-25 MJ/kg or even higher [7]) and
26 suitable for use as a fuel in cement kiln industry and combustion/gasification plants. SDF,
27 typically derived from commercial and industrial (C&I) waste, is a more refined fuel compared
28 to RDF which derived from municipal solid waste (MSW). A number of studies have
29 demonstrated the application of RDF/SDF in thermal conversion technologies such as
30 gasification [8-10], torrefaction or carbonisation [11-13] and pyrolysis [14, 15] for energy
31 generation. Furthermore, there are also a number of studies [2, 16, 17] that recommend the
32 concept of integrating MRF and energy recovery through EfW to improve resource utilisation.
33 However, it remains debatable whether EfW and the application of RDF in heat and electricity

1 (i.e. low value products) generation should be considered as sustainable waste management
2 options [6].

3 The rejected materials from MRF can potentially be valorised into higher value products such
4 as fuels and chemicals. Some examples are polyhydroxybutyrate (PHB) production from the
5 cellulosic fraction of organic residuals [18] and methanol production from gasification of RDF
6 [19]. The life cycle assessment conducted by Kendall [18] shows that the energy consumption
7 and greenhouse gas emissions of using organic residuals from MRF for PHB production are
8 twice lower than using agricultural feedstock such as corn. Borgogna et al. [19] investigated
9 the effect of variability of RDF composition on gasification performance (i.e. syngas quality
10 and composition) and methanol production (i.e. yield, raw material and energy consumptions
11 and emissions). These studies have mainly focused on the technical and environmental aspects
12 of reject valorisation system, without considering a systems perspective which takes into
13 account the impact from the upstream MRF process. The studies conducted by Cimpan et al.
14 [20] and Pressley et al. [21] provide comprehensive techno-economic and life cycle
15 assessments of conventional MRF. It has been shown that the high disposal cost of reject
16 materials poses a significant impact on the revenue of MRF [20]. Hence, there is a strong
17 motivation to avoid the high disposal cost through utilisation of reject materials for value-added
18 production. Overall, there are limited studies on the valorisation pathways of MRF rejected
19 materials and none of these studies have included a comprehensive techno-economic
20 assessment to justify the feasibility and potential of these valorisation pathways. Hydrogen has
21 a wide application in the industry and has the potential to become an important energy carrier
22 and clean fuel for the future [22, 23]. At present, hydrogen is primarily produced from steam
23 reforming of natural gas. The renewable source of hydrogen (e.g. electrolysis of water) is
24 limited mainly due to the cost barriers that is less competitive with fossil based hydrogen from
25 steam reforming of natural gas or coal gasification [24]. Waste-to-hydrogen concept [25-27] is
26 gradually receiving more attention in view of its environmental benefits through replacing
27 fossil-based transportation fuels while contributing towards net zero emission target.
28 Production of hydrogen from gasification of biomass [28, 29] and MSW [30, 31] has been
29 demonstrated in various studies. A review conducted by Shahabuddin et al. [26] report that the
30 production cost of hydrogen from residual waste lies in the range of 1.4-4.8 USD/kg compared
31 to biomass of 2.3-5.2 USD/kg, depending on the gate fees and plant scale. To date, the
32 knowledge related to techno-economic feasibility of gasification of MRF reject materials for
33 hydrogen production has not been developed.

1 Sustainable waste management through deploying a more robust and resilient facility which
2 encompasses resource recovery and valorisation strategies [32, 33] is needed to treat the
3 contaminated and rejected waste stream from MRF. Introducing an additional valorisation
4 system into an existing MRF will inevitably increase the processing costs. Adopting
5 polygeneration strategies in system design (i.e. simultaneous generation of
6 energy/fuels/chemicals/materials in an integrated system) would enhance resource efficiency,
7 leading to an economically competitive production [34-36]. A system-wide understanding on
8 the techno-economic viability of integrating MRF and reject valorisation system is currently
9 lacking. This study, for the first time, proposes a novel integrated system consisting of an MRF
10 for material recovery and gasification for hydrogen (“Gasification-H₂”) production. This
11 research aims to address the gaps of knowledge by conducting a comprehensive techno-
12 economic assessment to explore the future potential of implementing this kind of integrated
13 system. The novelty of this research lies in the proposition of an integrated material recovery
14 and valorisation system using polygeneration strategy which enhances resource efficiency and
15 diverts waste from landfills and incineration. Figure 1(a) shows a conventional recycling
16 approach using MRF and Figure 1(b) shows an integrated MRF and valorisation system. The
17 ultimate goal is to shift from selective recycling (i.e. material recovery through separating
18 specific types of recyclable materials) model into an “omnivorous” recycling (i.e. integrated
19 material recovery of recyclable stream and valorisation of non-recyclable stream) model. The
20 objectives of this study are to (a) establish a conceptual process design and modelling
21 framework; (b) evaluate economic feasibility; and (c) identify strategies for improving the
22 integrated MRF and Gasification-H₂ system. This paper is structured as follows. The
23 methodology for conceptual design and techno-economic assessment is presented in Section 2.
24 Process modelling of conventional MRF and integrated MRF and Gasification-H₂ systems is
25 presented in Section 3, followed by economic assessment presented in Section 4. Conclusions
26 and recommendations of the study are presented in Section 5.

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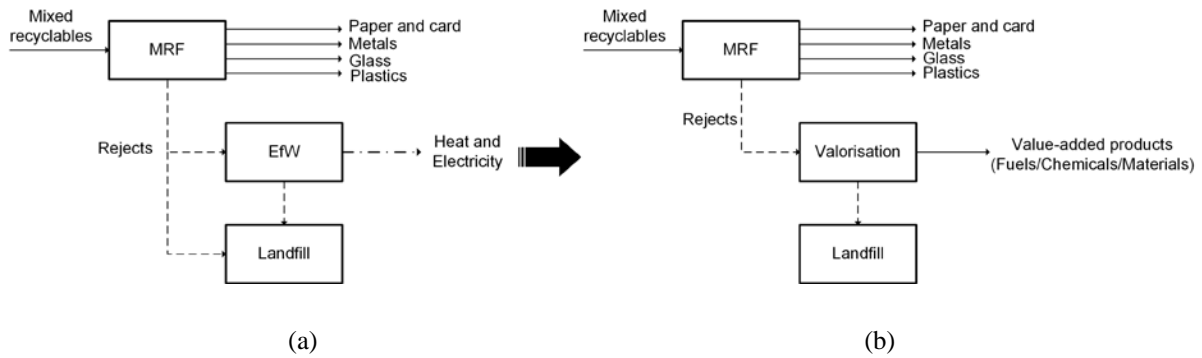


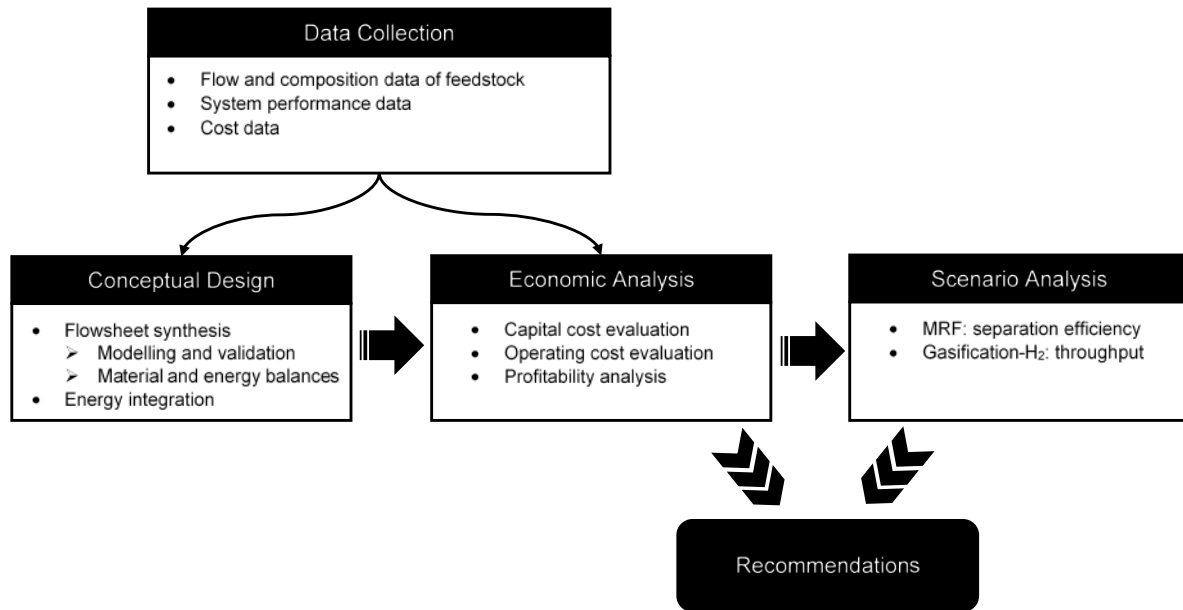
Figure 1: (a) Conventional approach to mixed recyclable management. (b) Proposed integrated MRF and valorisation of mixed recyclable stream.

2. Methodology

This section provides an overview of the methodology (section 2.1), followed by detailed discussion on each stage of techno-economic assessment, including data collection (section 2.2), conceptual design (section 2.3), economic analysis (section 2.4) and scenario analysis (section 2.5).

2.1 Overview of the methodology

A systematic methodology [37, 38] was adopted for conducting techno-economic analysis on an integrated MRF and Gasification-H₂ system as illustrated in Figure 2. Flow and composition data of feedstock as well as system performance and cost data were collected at the outset. These data were used to establish the technical model in the conceptual design stage and economic model in the economic analysis stage. In the conceptual design stage, flowsheet models of the system were constructed and validated against the results published in literature. Material and energy balances in conjunction with energy integration were performed to determine the yield of primary products, the quantity of rejected materials generated and energy requirement of the systems under consideration. The results from material and energy balances (conceptual design stage) alongside the system performance and cost data (data collection stage) were inputted into the economic model which consists of capital and operating costs evaluation and profitability analysis. Scenario analysis was carried out to investigate the impact of varying operating parameters of MRF (i.e. separation efficiency) and Gasification-H₂ system (i.e. throughput of rejected materials) on the economic performance of the systems. The findings generated from economic analysis and scenario analysis were concluded, accompanied by recommendations for further improvement of the systems.



1

2 Figure 2: Techno-economic analysis of integrated MRF and Gasification-H₂ system.

3

4 **2.2 Data collection**

5 The flow and composition data for household recycling streams in the UK were collected from
 6 the WRAP National Household Waste Composition 2017 report [39]. In the present analysis,
 7 the data and waste categories were refined to include only the waste component relevant to
 8 mixed recyclables, i.e. any food and garden wastes were excluded. The household recycling
 9 waste streams include segregated waste from kerbsides, Household Waste Recycling Centres
 10 (HWRC), bring sites, street bins and “other means”.

11 System performance data such as separation efficiencies of sorting/screening equipment in
 12 MRF were collected from Pressley et al. [21], and operating parameters of process units in
 13 Gasification-H₂ system were obtained from the National Renewable Energy Laboratory
 14 (NREL) report [28].

15 For MRF, equipment and variable operating cost data were collected from Pressley et al. [21]
 16 and WRAP report [40]. On the other hand, the equipment and variable operating cost data for
 17 Gasification-H₂ system were adopted from Sadhukhan et al. [38] and NREL report [28]. Lang
 18 factors for capital cost estimation and typical factors used for fixed operating cost estimation
 19 were obtained from Sadhukhan et al. [38]. The most recent gate fees for landfill and EfW and
 20 market prices of recyclable products from MRF were obtained from LetsRecycle.com.

2.3 Conceptual design

This section discusses the methodology for flowsheet synthesis (section 2.3.1) and energy integration (section 2.3.2).

2.3.1 Flowsheet synthesis

The configuration of MRF in the present study was inspired by the works conducted by WRAP [40] and Pressley et al. [21], while the configuration of Gasification-H₂ system was adapted from NREL study [28]. In practice, the unit operations in MRF and gasification can be arranged in various configurations. The main processing steps in these systems were outlined using block diagrams, and information on systems performance such as separation efficiencies and operating conditions of process units were collected from published journal articles and technical reports, discussed in section 2.2. The current flowsheeting approach adopts a generic structure to model changes in flow and composition of materials and also energy consumption and generation. This reduces the complexity of the system configuration while ensuring important features to be captured. The flowsheets were simplified to include only the primary processing steps. Multiple separation stages for recovering same category of materials in MRF were represented as a single block (i.e. paper/card, metal, glass and plastics separation). Manual sorting in different stages was also taken as one unit operation in MRF. In the gasification system, all the auxiliary equipment such as valves and storage tanks was eliminated from the flowsheet during the conceptual design stage. The throughput of rejected materials entering the Gasification-H₂ system was deduced from the MRF model. The modelling of MRF was carried out in Excel environment. In the case of Gasification-H₂ system where more sophisticated reaction-separation processes were involved, simulation modelling approach using Aspen Plus software, a widely used process engineering software in the refinery and petrochemical industries, was adopted. The flowsheets were constructed by adopting an evolutionary approach where simulation models / blocks were introduced starting from reactors, then separators, and finally heat exchangers and utility systems according to the “onion” model for process design [41]. The simulation models of unit operations, particularly the gasification model, were validated against published experimental results [30]. The flowsheet synthesis exercise enables material and energy balances of the conventional MRF and integrated MRF and Gasification-H₂ systems to be established prior to detailed techno-economic analysis.

2.3.2 Energy integration

Systematic energy integration [37, 38] was performed on Gasification-H₂ system in view of enhancing energy efficiency of the system (Note: this has not been done on MRF since there is limited scope for energy recovery within MRF. The system only requires input of electricity). Energy integration strategies adopted here began with data extraction, followed by classification of energy integration tasks, and a combined heat and power (CHP) network design. Data extraction involved collection of temperature and heat duty information of heat exchangers and process units from the flowsheet. By examining the level of temperature and heat duties, these data were then classified into high and low level energy integration tasks. High level tasks refer to steam generation and consumption at different pressures, analysed using composite curve methodology. Low level tasks refer to process-to-process heat exchange and boiler feed water generation, analysed using energy balance. This stream classification procedure maximises opportunities for energy recovery and enables appropriate placement of utilities. Finally, the CHP network was designed by considering steam and power generation and distribution within the Gasification-H₂ system to ensure that all energy supply and demands are satisfied.

2.4 Economic analysis

The economic performances of MRF and Gasification-H₂ systems were evaluated in terms of capital costs (section 2.4.1), operating costs (section 2.4.2) and profitability analysis (section 2.4.3).

2.4.1 Capital cost evaluation

Equation (1) [37, 38] was applied to estimate the purchased costs of equipment for the current system by using the capacity and cost data of the base system reported in the literature.

$$\frac{\text{COST}_{\text{size2}}}{\text{COST}_{\text{size1}}} = \left(\frac{\text{SIZE}_2}{\text{SIZE}_1} \right)^R \quad (1)$$

where

SIZE₁ is the capacity of the base system,

SIZE₂ is the capacity of the system after scaling up/down,

1 $COST_{size1}$ is the cost of the base system,
2 $COST_{size2}$ is the cost of the system after scaling up/down,
3 R is the scaling factor.

4

5 The purchased costs of equipment estimated using Equation (1) were levelised to the present
6 year using Equation (2) [37, 38] by applying the Chemical Engineering Plant Cost Index
7 (CEPCI).

8

$$9 \quad C_p = C_o \left(\frac{I_p}{I_o} \right) \quad (2)$$

10 where

11 C_p is the present cost of equipment,

12 C_o is the original cost of equipment,

13 I_p is the present index value,

14 I_o is the original index value.

15 The total purchased costs of equipment estimated using Equations (1)-(2) were multiplied by
16 Lang factors to obtain the total capital cost (TCC) of the system. TCC includes direct costs
17 (installation, instrumentation and control, piping, electrical systems, building, yard
18 improvements and service facilities), indirect costs (engineering and supervision, construction
19 expenses, legal expenses, contractors' fees and contingency) and working capital.

20 Annualised capital costs (C_{cap}) of the system was determined by multiplying TCC with capital
21 recovery factor (CRF), shown in Equation (3) [42].

$$22 \quad C_{cap} = TCC \times CRF \quad (3)$$

23 CRF , defined in Equation (4), converts present value (TCC is the present value in this context)
24 to annual payment over n years (i.e. plant life) at a specified discount rate of r [42].

$$25 \quad CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (4)$$

26

2.4.2 *Operating cost evaluation*

Operating costs (C_{op}) include fixed (e.g. maintenance, capital charges, insurance, local taxes, royalties, laboratory costs, supervision and plant overheads) and variable (e.g. fuel, electricity, baling wire and catalyst) costs. Fixed operating costs were estimated based on percentage of indirect capital cost or cost of personnel. Variable operating costs were estimated using the latest available price data from published sources.

2.4.3 *Profitability analysis*

The economic performance of the systems was analysed using economic potential (EP) expressed by Equation (5) and minimum hydrogen selling price (MHSP) expressed by Equation (6) [38]. The EP indicates the difference between the revenues generated from the sale of products and the associated costs of production. In the context of MRF, the cost of feed (i.e. mixed recyclables) was assumed to be zero.

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

MHSP is not relevant to MRF case as the value of products is determined by the recycling market. However, this indicator is particularly useful for evaluating minimum value of hydrogen from the Gasification-H₂ system. MHSP indicates the minimum value of hydrogen where the market price of hydrogen must be higher than MHSP to result in an economically feasible processing scenario.

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

2.5 Scenario analysis

In this study, two scenarios were examined: (a) enhancing separation efficiency of MRF sorting/screening processes; and (b) increasing throughput of MRF rejected materials into Gasification-H₂ system. The impact on the economic performance of the system due to variation of the operating parameters were assessed.

3. Process modelling

The basis for feedstock is given in section 3.1. The process description together with material and energy balances for the conventional MRF and integrated MRF and Gasification-H₂ system are presented in sections 3.2 and 3.3, respectively.

3.1 Basis for feedstock

The throughput of mixed recyclables into MRF was 100,000 t/y (18.5 t/h considering 5400 operating hours per year) in the present study. The composition of mixed recyclable stream was refined based on the UK data from WRAP National Household Waste Composition 2017 report [3] (see Table A.1 in the Supplementary Materials, Appendix A) and was categorised into recyclable and non-recyclable fractions as presented in Table 1. The recyclable and non-recyclable fractions for each waste category were deduced using the same ratio as in the study conducted by Pressley et al. [21] since it is not given in the original dataset. In this study, only polyethylene terephthalate (PET) bottles, high-density polyethylene (HDPE) bottles and mixed rigid plastics (i.e. dense plastics non-bottles and plastic film and bags) were considered as recyclable plastics, i.e. other types of plastic materials were classified as non-recyclables.

Table 1: Mass flow and composition of mixed recyclable stream for a 100,000 t/y MRF.

Waste category	Waste component	Mass fraction (%)	Mass flow (t/h)
Paper and card	Paper and card	49.90	9.24
	Non-recyclable	1.99	0.37
Metal	Ferrous metals	6.11	1.13
	Aluminium metals	2.64	0.49
	Non-recyclable	1.40	0.26
Glass	Glass	24.84	4.60
	Non-recyclable	0.43	0.08
Plastics	PET bottles	2.90	0.54
	HDPE bottles	1.45	0.27
	Mixed rigid plastics	3.58	0.66
	Non-recyclable	1.52	0.28
Other materials	Organics and inorganics	3.24	0.60
	Total	100.00	18.52

In the proposed integrated system, the rejected streams from MRF were sent to gasification for hydrogen production. It was assumed that the rejected streams were composed of only combustible materials (i.e. non-combustible materials such as metals and glass were

1 completely removed prior to feeding into the gasifier). The proximate and ultimate analyses of
 2 the rejected materials from MRF are given in Table 2, which were adapted and normalised
 3 based on the original laboratory analysis [43]. Since the compositions of volatile matters and
 4 fixed carbon were not given, these values were assumed based on the MSW analysis from
 5 literature [30].

6 Table 2: Proximate and ultimate analyses of rejected materials from MRF (Adapted from [43] and [30]).

Component	Value	Unit
<i>Proximate analysis (as received)</i>		
Volatile matter	47.59	wt%
Fixed carbon	6.82	wt%
Ash	18.80	wt%
Moisture content	26.80	wt%
<i>Ultimate analysis (dry and ash free)</i>		
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

7

8 **3.2 Material Recovery Facility (MRF)**

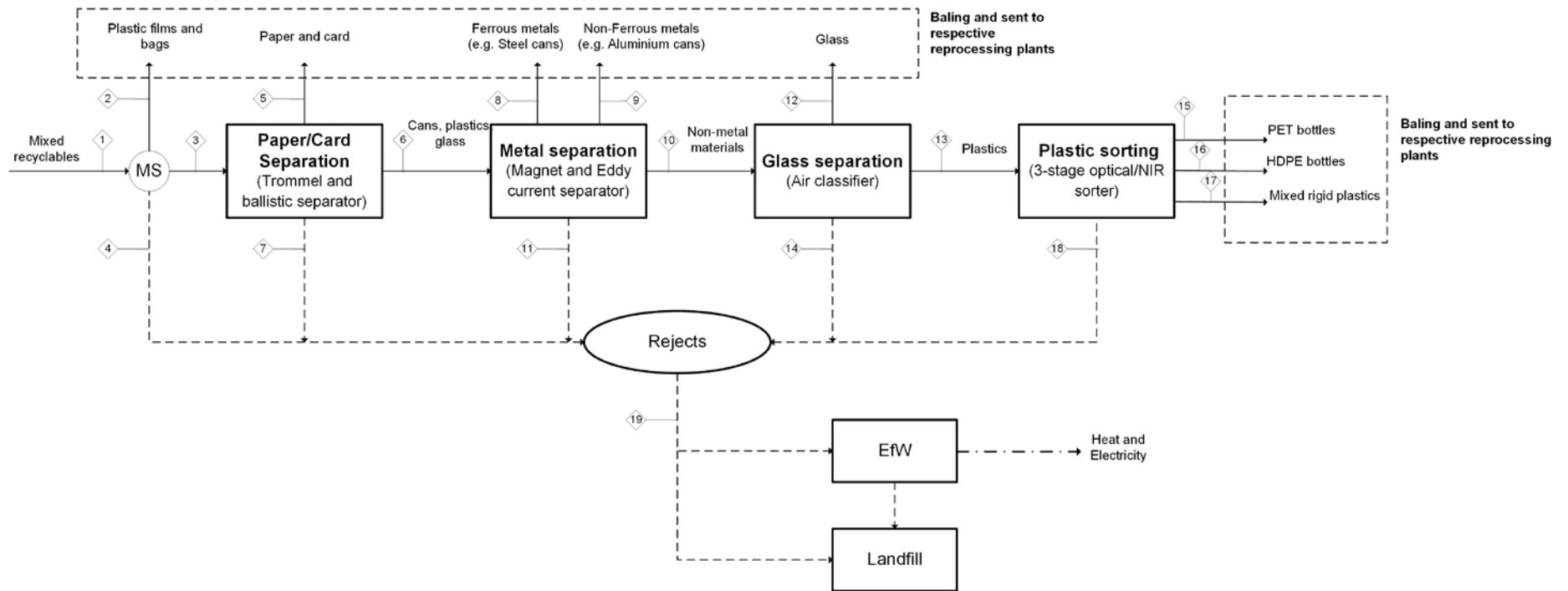
9 The mechanical separation/sorting processes of mixed recyclable stream in MRF is described
 10 in section 3.2.1. The material and energy balances are presented in section 3.2.2.

11 **3.2.1 Process description**

12 A typical MRF as illustrated in Figure 3 consists of five separation/sorting stages for recovering
 13 recyclable materials such as paper/card, metals, glass and plastics into individual streams.
 14 Mixed recyclables are loaded onto a conveyor (stream 1: 18.5 t/h) and manually sorted to
 15 separate recyclable materials from non-recyclable materials or materials which are not
 16 compliant with the MRF equipment. At the manual sorting stage, plastic films and bags (stream
 17 2: 0.5 t/h) are recovered through a vacuum, and then sent for baling. The recyclable materials
 18 (stream 3: 17.7 t/h) which are separated from the rejects (stream 4: 0.28 t/h) are sent to trommel
 19 and ballistic separator (paper/card separation stage). Trommel, a negative sorting process, is
 20 used to remove undesirable fine inert materials such as glass, mixed rigid plastics and organic
 21 materials (e.g. soil and aggregates). Ballistic separator, on the other hand, is used to separate
 22 heavy and light materials by oscillations. Light materials such as card and paper (stream 5: 8.4

1 t/h) are recovered and baled, while heavy materials such as glass, cans and plastics (stream 6:
2 7.9 t/h) are transferred to magnet and eddy current separator (metal separation stage). Any
3 rejected materials (stream 7: 1.4 t/h) from trommel and ballistic separator are removed from
4 the recyclable stream. At the metal separation stage, a magnet is used to separate metals from
5 glass. A further screening through an eddy current separator allows ferrous metals such as steel
6 cans (stream 8: 1.0 t/h) to be split from non-ferrous metals such as aluminium cans (stream 9:
7 0.4 t/h). A non-metal stream comprising mainly glass (stream 10: 6.2 t/h) is obtained after
8 rejecting non-recyclable materials (stream 11: 0.26 t/h). The glass stream which is free from
9 metals is sent through an air classifier (also known as a “wind sifter” at the glass separation
10 stage) to recover glass (stream 12: 3.6 t/h) which is then baled. Air classifier separates denser
11 materials such as glass from lighter materials such as papers based on difference in densities.
12 A plastic-rich stream (stream 13: 1.5 t/h) is obtained after eliminating light paper and other
13 contaminants (stream 14: 1.1 t/h). The plastic-rich stream is screened through a series of optical
14 or near infrared (NIR) sorters (plastic sorting stage), where the separation is operated based on
15 detection of the absorption of certain wavelengths that can be used to distinguish between
16 different polymers. In this design, a 3-stage NIR sorters is assumed to generate a PET bottle
17 stream (stream 15: 0.45 t/h), a HDPE bottle stream (stream 16: 0.2 t/h) and a mixed rigid
18 plastics stream (stream 17: 0.1 t/h). These plastic streams (streams 2, 15, 16 and 17) are baled
19 separately and sent to plastic reprocessing plants. The recycled products including card and
20 paper, metals and glass (streams 5, 8, 9 and 12) are delivered to the respective recycling centres
21 for further processing. The remaining non-recyclable materials including contaminated plastic
22 materials (stream 18: 0.7 t/h) are rejected. The aggregation of residues (rejects) from each
23 sorting stage (stream 19: 3.8 t/h) is sent to EfW and landfill. In this study, it is assumed that
24 90% (3.4 t/h) of the rejects is sent to EfW while the remaining 10% (0.38 t/h) is ended up in
25 landfill.

26 Material and energy balances of the MRF system are presented in section 3.2.2.



1

2 Figure 3: Material recovery facility (MRF) for separation and sorting of mixed recyclable stream. (MS: manual sorting; EfW: Energy-from-Waste facility; NIR: near infrared;

3 PET: polyethylene terephthalate; HDPE: high-density polyethylene)

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1 **3.2.2 Material and energy balances**

2 Table 3 presents the mass flow of mixed recyclable materials into MRF, the recyclable materials recovered from each separation stage, and the
 3 discharge of non-recyclable materials from MRF. The material balance was deduced from the separation efficiencies presented in Table A.2 in the
 4 Supplementary Materials (Appendix A), based on the study conducted by Pressley et al. [21]. A detailed breakdown of the input flow of individual
 5 waste components into each stage is shown in Table A.3 in the Supplementary Materials (Appendix A).

6 Table 3: Material balance of MRF input and output materials for a 100,000 t/y MRF.

Separation stages	Input			Output		
	Stream	Stream number	Mass flow (t/h)	Stream	Stream number	Mass flow (t/h)
Manual sorting	Mixed recyclables	1	18.52	Plastic films and bags	2	0.54
				Materials entering paper/card separation stage	3	17.70
				Rejects	4	0.28
	Subtotal		18.52	Subtotal		18.52
Paper/card separation	Materials entering paper/card separation stage	3	17.70	Paper and card	5	8.41
				Materials entering metal separation stage	6	7.89
				Rejects	7	1.40
	Subtotal		17.70	Subtotal		17.70
Metal separation	Materials entering metal separation stage	6	7.89	Ferrous metals	8	1.00
				Non-ferrous metals	9	0.42
				Materials entering glass separation stage	10	6.21
				Rejects	11	0.26
	Subtotal		7.89	Subtotal		7.89
Glass separation	Materials entering glass separation stage	10	6.21	Glass	12	3.60
				Materials entering plastic sorting stage	13	1.46
				Rejects	14	1.14
	Subtotal		6.21	Subtotal		6.21
Plastic sorting	Materials entering plastic sorting stage	13	1.46	PET bottles	15	0.45
				HDPE bottles	16	0.22
				Mixed rigid plastics	17	0.10
				Rejects	18	0.70

	<i>Subtotal</i>		1.46	<i>Subtotal</i>		1.46
	Total input		18.52	Total output		18.52
				Total rejects	19	3.78
				Total plastic materials to be recycled	2+15+16+17	1.31
				Total non-plastic materials to be recycled	5+8+9+12	13.43

1

2 Based on the material balance, approximately 80% of the input materials to MRF are recovered as recycled products (91% non-plastics and 9%
3 plastics), while 20% non-recyclable materials are rejected to EfW and landfill. A breakdown of the rejected material stream (stream 19) is
4 summarised in Table 4 together with the assumed components embedded in the stream. The rate of rejects falls within 27% reported by WRAP in
5 2012/2013 [3]. In this study, the main source of rejected materials are emerged from paper/card (37%) and glass (30%) separation stages.

6 Table 4: Breakdown of rejected material stream from each MRF separation stage.

Separation stage	Rejected materials	Contribution from each stage (wt%)	Mass flow (t/h)
Manual sorting	non-recyclable plastics	7.44	0.28
Paper/card separation	non-recyclable papers and cards; glass; mixed rigid plastic; other materials.	37.15	1.40
Metal separation	non-recyclable metals	6.86	0.26
Glass separation	papers and cards; ferrous metals; aluminium metals; non-recyclable glass; other materials	30.16	1.14
Plastic sorting	glass; contaminated PET bottles, HDPE bottles and mixed rigid plastics	18.39	0.70
Total		100.00	3.78

7

8 Electricity and fuels are required in MRF. It was estimated that 400 MWh per year of electricity are required to operate the equipment in MRF and
9 2 million L per year of fuel are needed for rolling stocks. The detailed breakdowns of electricity and fuel requirements can be found in the
10 Supplementary Materials (Appendix A), Tables A.13-14 in conjunction with the cost estimation.

11

3.3 Integrated MRF and Gasification-H₂ system

The integrated system consisting of MRF and gasification of MRF rejected materials for hydrogen production is described in section 3.3.1. The material and energy balances are presented in section 3.3.2.

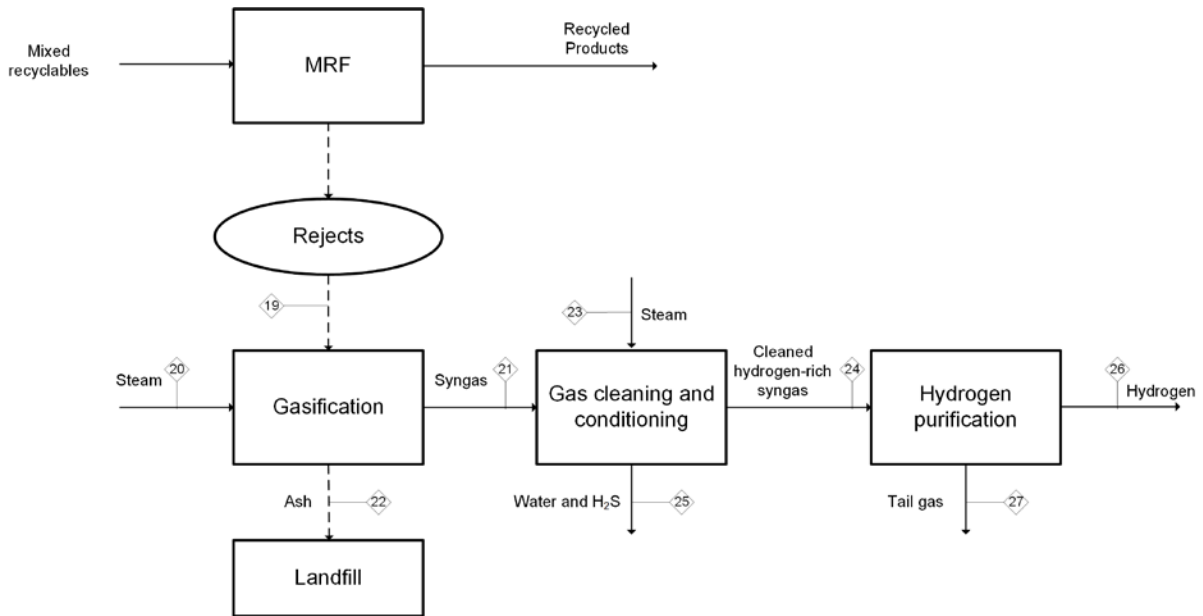
3.3.1 Process description

The rejected materials from MRF (stream 19) are valorised into hydrogen through a steam gasification system as illustrated in Figure 4. The system was modelled using Aspen Plus simulation software where the flowsheet and process description (Figure B.1), modelling specifications (Table B.1) and detailed material balance (Table B.2) can be found in the Supplementary Materials (Appendix B). The gasification model was validated against the experimental study conducted by He et al. [30]. The model validation can be found in Table B.3 in the Supplementary Materials (Appendix B).

The rejected materials contain 26.8 wt% of moisture (Table 2). The flow of rejected materials (stream 19) at 2.55 t/h (wet basis; 8000 operating hours was assumed) or 1.9 t/h after drying at 110°C (dry basis; 10% moisture) is fed into a gasification process where partial oxidation takes place at 900°C and 1.6 bar in this case using steam (stream 20; 2.65 t/h) as the gasifying medium [30]. The steam-to-feed ratio is assumed to be 1.04 on weight basis [30]. Syngas (stream 21: 4.1 t/h) is generated from gasification consisting primarily of CO, H₂, CO₂ and H₂O, with a H₂/CO molar ratio of 2.6. The hot syngas is passed through a cyclone to remove ash (stream 22: 0.48 t/h) which is then disposed of in landfill.

The syngas is cooled down to 80°C and compressed to 30 bar before entering the gas cleaning and conditioning processes. Tar is assumed to be negligible in this case where the steam-to-feed ratio of the gasification is high [30]. The gas cleaning and conditioning processes comprise acid gas removal units and a water-gas shift reactor. The acid gas removal units are needed to remove hydrogen sulphide (H₂S) in the syngas down to 1 ppmv as a measure to prevent catalyst poisoning in the water-gas shift reactor. The water-gas shift reaction ($\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$), operated at 200°C, is served to increase the yield of H₂. Medium-pressure (MP) steam (stream 23: 1.6 t/h) at 14 bar and 250°C is added to facilitate the reaction. The flow rate of hydrogen is increased from 0.26 t/h (stream 21) to 0.36 t/h (stream 24) through the water-gas shift reaction. The amount of steam to be supplied to water-gas shift reactor was determined using sensitivity analysis presented in Table B.4 in the Supplementary Materials (Appendix B). The outlet stream from water-gas shift reaction is cooled down to 40°C so that water (stream 25: 1.77 t/h)

1 can be removed through a flash drum. It should be noted that stream 25 also contains H₂S of
 2 0.012 t/h which is removed from the acid gas removal unit. The hydrogen-rich stream (stream
 3 24: 3.9 t/h) is then sent to a pressure swing adsorption (PSA) unit to recover hydrogen at 85
 4 mol % and obtain a purity of 99.95 mol% (stream 26: 0.3 t/h), compressed to 70 bar. The tail
 5 gas stream (stream 27: 3.6 t/h) from PSA comprises mainly CO₂.



6
 7 Figure 4: Integrated MRF and gasification system for material recovery and hydrogen production.

8

9 **3.3.2 Material and energy balances**

10 The material balance of the gasification system for converting MRF rejects into hydrogen is
 11 presented in Table 5. Detailed material balance estimated from Aspen Plus model can be found
 12 in Table B.2 in the Supplementary Materials (Appendix B). The material balance shows that
 13 0.3 t/h (2502.5 t/y) of hydrogen can be produced from gasification of rejects, resulting in a
 14 yield of 167.5 kg of hydrogen per dry tonne of rejects.

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1 Table 5: Material balance of Gasification-H₂ system with 2 dry t/h MRF rejects input.

Component	Stream								
	19	20	21	22	23	24	25	26	27
Mass flow (t/h)									
C	0.885	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H ₂	0.114	0.000	0.264	0.000	0.000	0.364	0.000	0.310	0.055
O ₂	0.358	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N ₂	0.020	0.000	0.020	0.000	0.000	0.020	0.000	0.000	0.020
S	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO	0.000	0.000	1.412	0.000	0.000	0.015	0.000	0.000	0.015
CO ₂	0.000	0.000	1.023	0.000	0.000	3.219	0.000	0.003	3.216
H ₂ O	0.068	2.654	1.379	0.000	1.600	0.313	1.767	0.000	0.313
CH ₄	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001
H ₂ S	0.000	0.000	0.012	0.000	0.000	0.000	0.012	0.000	0.000
Ash	0.480	0.000	0.000	0.480	0.000	0.000	0.000	0.000	0.000
Total mass flow (t/h)	1.936	2.654	4.110	0.480	1.600	3.931	1.779	0.313	3.618
Temperature (°C)	250.0	133.5	900.0	900.0	250.0	40.0	50.0/40.0	45.0	40.0
Pressure (bar)	1.6	3.0	1.6	1.6	14.0	1.0	30.0/1.0	70.0	1.0

2 Note:

- 3 1. Stream 19 has been dried - assumed 10% moisture content left in the feedstock entering gasification.
 4 2. Stream 25 - 2 processes are involved in different stages, hence the temperature and pressure are different.

5
 6 A comprehensive energy integration was performed on the Gasification-H₂ system by adopting
 7 the methodology discussed in section 2.3.2. Stream data were extracted from the flowsheet and
 8 classification was carried out to identify the optimum strategies for heat utilisation as presented
 9 in Table C.1 in the Supplementary Materials (Appendix C). A CHP network was designed as
 10 illustrated in Figure C.1 in the Supplementary Materials (Appendix C), showing the steam
 11 generation and distribution as well as power generation. The system is able to generate
 12 sufficient steam to satisfy the requirement within the Gasification-H₂ system. The CHP
 13 network generates 1787 kW of power from steam turbines, which satisfies 54% of the total
 14 electricity requirement of the Gasification-H₂ system (3305 kW). Therefore, a net power
 15 requirement of 1518 kW is required, which is equivalent to 12143 MWh per year of electricity
 16 requirement. The power balance is summarised in Table C.2 in the Supplementary Materials
 17 (Appendix C).

4. Economic assessment

Detailed economic assessment and scenario analysis of the conventional MRF and integrated MRF and Gasification-H₂ system are presented in sections 4.1 and 4.2, respectively. The key findings are discussed in section 4.3.

4.1 Economic assessment of conventional MRF and integrated MRF and Gasification-H₂ systems

The EPs (Equation (5)) of conventional MRF and integrated MRF and Gasification-H₂ systems were evaluated in terms of capital and operating costs and revenues as presented in Table 6. Detailed cost evaluation can be found in the Supplementary Materials: Appendix A for MRF (Tables A.4 - A.16) and Appendix B for Gasification-H₂ (Tables B.5 - B.9) systems.

The conventional MRF gives an EP of 4 million £/y and it is highly dependent on the income from gate fees which contributes 42% of the revenues. This poses significant threat to the financial stability of the facility if lower gate fees are paid to the facility. The values of recycled products are determined by the recycling market and they are highly unstable. The proposed integrated system offers the advantage of generating a revenue stream of 25 million £/y attributed to hydrogen production (assuming hydrogen price of 10 £/kg [44]), thus resulting in an EP of 15.9 million £/y. This provides greater financial stability to the facility considering that the facility can be sustained even without receiving income from the gate fees. The analysis in Table 6 suggests that an additional annual cost (capital and operating costs) of 15.2 million £/y is required if a Gasification-H₂ system is to be incorporated. Nevertheless, the integrated MRF and Gasification-H₂ system obviates a reject/solid disposal cost of 1.6 million £/y.

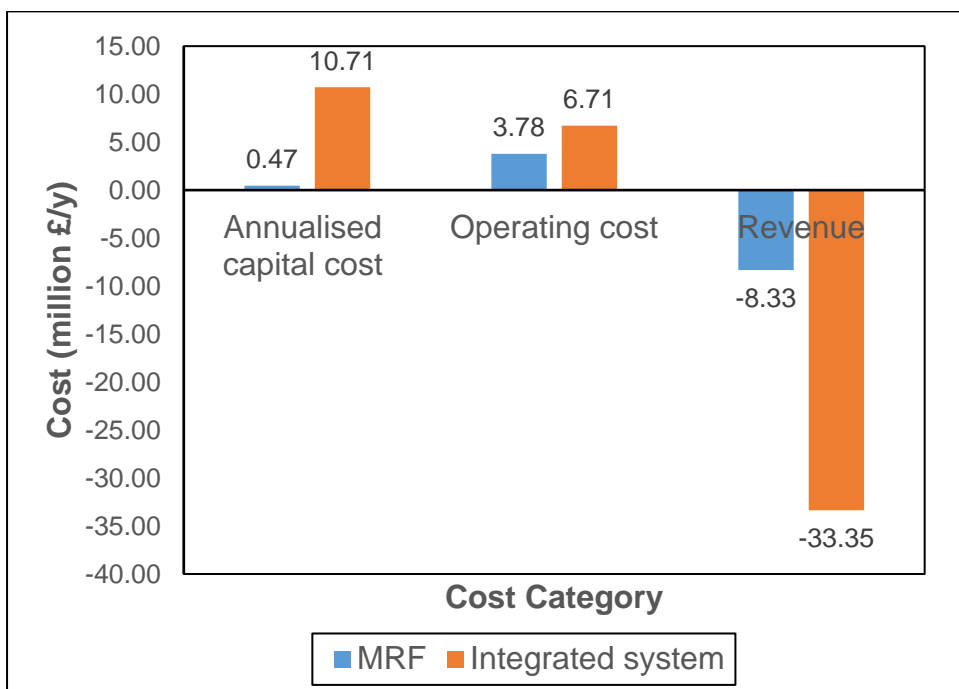
1 Table 6: Economic assessment of conventional MRF and integrated MRF and Gasification-H₂ systems.

MRF		Gasification-H ₂		Integrated MRF and Gasification-H ₂	
Component	Cost (million £/y)	Component	Cost (million £/y)	Component	Cost (million £/y)
<i>Capital cost</i>		<i>Capital cost</i>		<i>Capital cost</i>	
Equipment	0.100	Equipment	1.73	Equipment	1.83
Conveyor	0.003	Dryer	0.12	MRF equipment	0.10
Drum feeder	0.009	Gasifier	0.19	Dryer	0.12
Vacuum	0.002	Cyclone	0.08	Gasifier	0.19
Trommel	0.005	Acid gas removal	0.003	Cyclone	0.08
Ballistic separator	0.011	Water-gas shift reactor	0.10	Acid gas removal	0.003
Magnet	0.006	Water removal unit	0.003	Water-gas shift reactor	0.10
Eddy current separator	0.008	PSA	0.28	Water removal unit	0.003
Air classifier	0.002	Syngas compressor	0.39	PSA	0.28
Optical/NIR sorter	0.027	H ₂ compressor	0.04	Syngas compressor	0.39
Baler	0.029	Heat exchangers	0.35	H ₂ compressor	0.04
		Steam turbine + steam system	0.18	Heat exchangers	0.35
				Steam turbine + steam system	0.18
Other direct cost	0.17	Other direct cost	4.49	Other direct cost	4.66
Indirect cost	0.13	Indirect cost	2.49	Indirect cost	2.62
Working capital	0.07	Working capital	1.54	Working capital	1.61
Annualised capital cost	0.47	Annualised capital cost	10.25	Annualised capital cost	10.71
<i>Operating cost</i>		<i>Operating cost</i>		<i>Operating cost</i>	
Variable operating cost	3.23	Variable operating cost	2.07	Variable operating cost	3.23
Baling - wire cost	0.14	Electricity	1.57	Baling - wire cost	0.14
Electricity	0.05	Catalyst	0.006	Fuel	0.97
Fuel	0.97	LO-CAT chemicals	0.004	Electricity	1.62
Rejects disposal cost	2.07	Gasifier bed materials	0.04	Catalyst	0.006
		Solid disposal cost	0.44	LO-CAT chemicals	0.004

		Effluent discharge cost	0.01	Gasifier bed materials	0.04
				Solid disposal cost	0.44
				Effluent discharge cost	0.01
Fixed operating cost	0.55	Fixed operating cost	2.93	Fixed operating cost	3.49
Operating cost	3.78	Operating cost	5.00	Operating cost	6.71
<u>Revenue</u>		<u>Revenue</u>		<u>Revenue</u>	
Recycled products	-4.83	Hydrogen	-25.03	Recycled products	-4.83
Card and paper	-1.48			Hydrogen	-25.03
Ferrous metals	-0.45			Gate fees for MRF	-3.50
Aluminium	-1.66				
Glass	0.20				
PET	-0.70				
HDPE	-0.67				
Mixed rigid plastics	-0.08				
Gate fees for MRF	-3.50				
Revenue	-8.33	Revenue	-25.03	Revenue	-33.36
Economic potential (EP)	4.08	Economic potential (EP)	9.78	Economic potential (EP)	15.93

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1 A comparison of costs and revenues of conventional MRF and integrated systems is presented
 2 in Figure 5. It is apparent that the capital cost is the major hurdle for introducing an integrated
 3 MRF and Gasification-H₂ system as it requires almost 23-fold of capital investment compared
 4 to a standalone MRF. The operating cost of a Gasification-H₂ system is around 32% higher
 5 than an MRF, hence the cost is doubled for the integrated system. Although higher capital and
 6 operating costs are incurred in the integrated system, the revenue generated is attractive where
 7 it could potentially bring 4 times more revenue compared to a conventional MRF. It should be
 8 noted that gate fees of 3.5 million £/y are paid by the local authorities to MRF, whereas there
 9 are currently no incentives given for advanced thermal systems such as gasification in the UK.



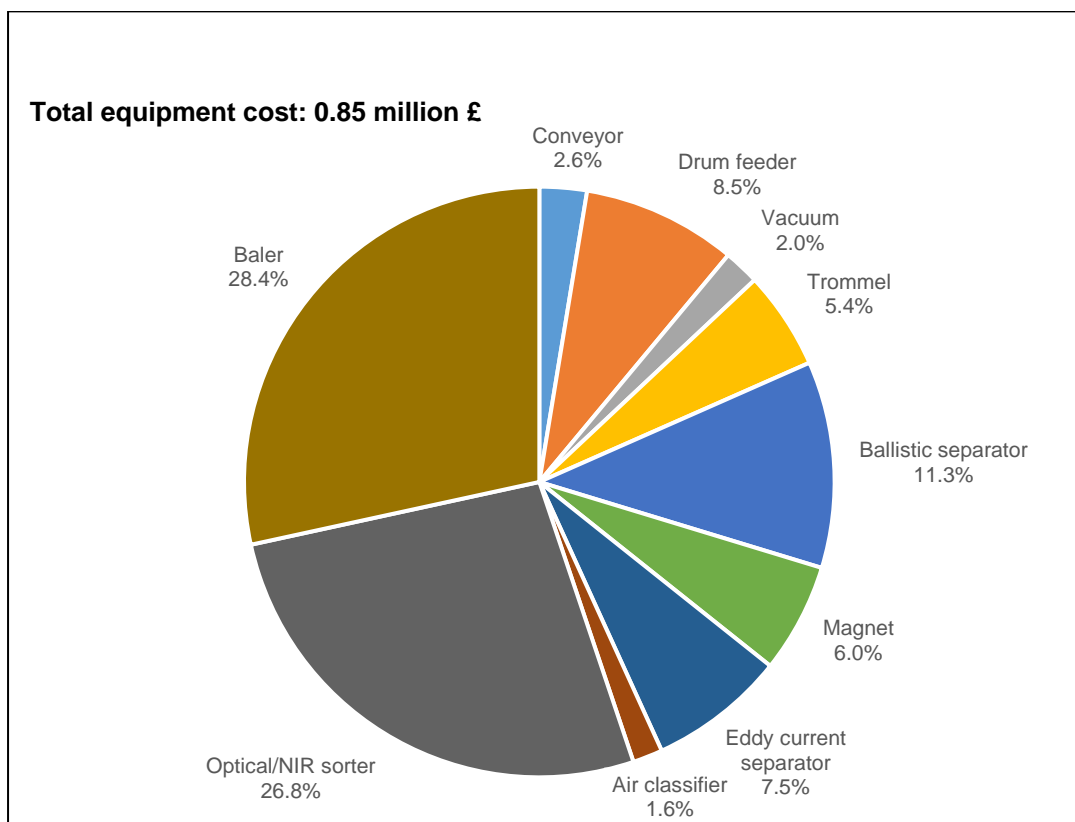
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11 Figure 5: Comparison of annualised capital cost, operating cost and revenue of MRF and integrated systems.

12 Figure 6 provides insights into the capital cost of MRF (Figure 6(a)) and Gasification-H₂
 13 system (Figure 6(b)) by examining the cost contribution of individual piece of equipment. The
 14 equipment cost of MRF is dominated by baler (28.4%), followed by optical/NIR sorter (26.8%)
 15 and ballistic separator (11.3%). On the other hand, the major equipment costs in the
 16 Gasification-H₂ system are contributed by syngas compressor (22.8%), followed by heat
 17 exchangers (20.1%) and PSA unit (16.2%).

18 The variable operating cost of the Gasification-H₂ system (2.07 million £/y) is lower than that
 19 of MRF (3.23 million £/y) in this study as illustrated in Figure 7. For MRF (Figure 7(a)), the
 20 reject disposal cost (64.1%) is the largest contributor of the variable operating costs, followed
 21 by fuel (30%). On the other hand, electricity (75.7%) dominates the variable operating cost of

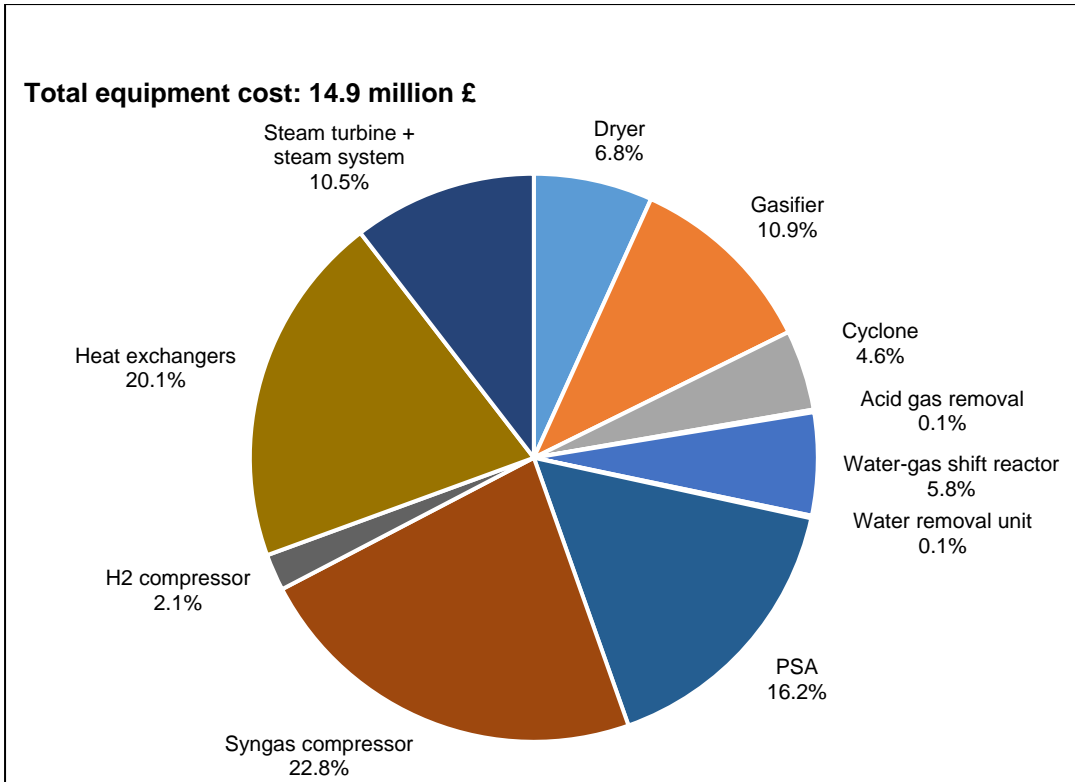
1 Gasification-H₂ system (Figure 7(b)), followed by solid disposal cost (21.2%). Hence, there is
2 a strong motivation to minimise the cost of reject/solid disposal and impact on the environment
3 through recovering the resources embedded in the non-recyclable streams of MRF. The
4 electricity requirement in the Gasification-H₂ system is primarily for syngas (3117.4 kW) and
5 H₂ compressors (187.2 kW). In this study, it was demonstrated that energy integration through
6 CHP generation enables 54% of electricity (1787 kW) in the Gasification-H₂ system to be
7 recovered on-site (Supplementary Materials: Appendix C). This portion of energy recovered is
8 equivalent to 1.8 million £/y of cost saving on electricity, however at the expense of 0.18
9 million £/y on steam turbine and steam system.



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(a)



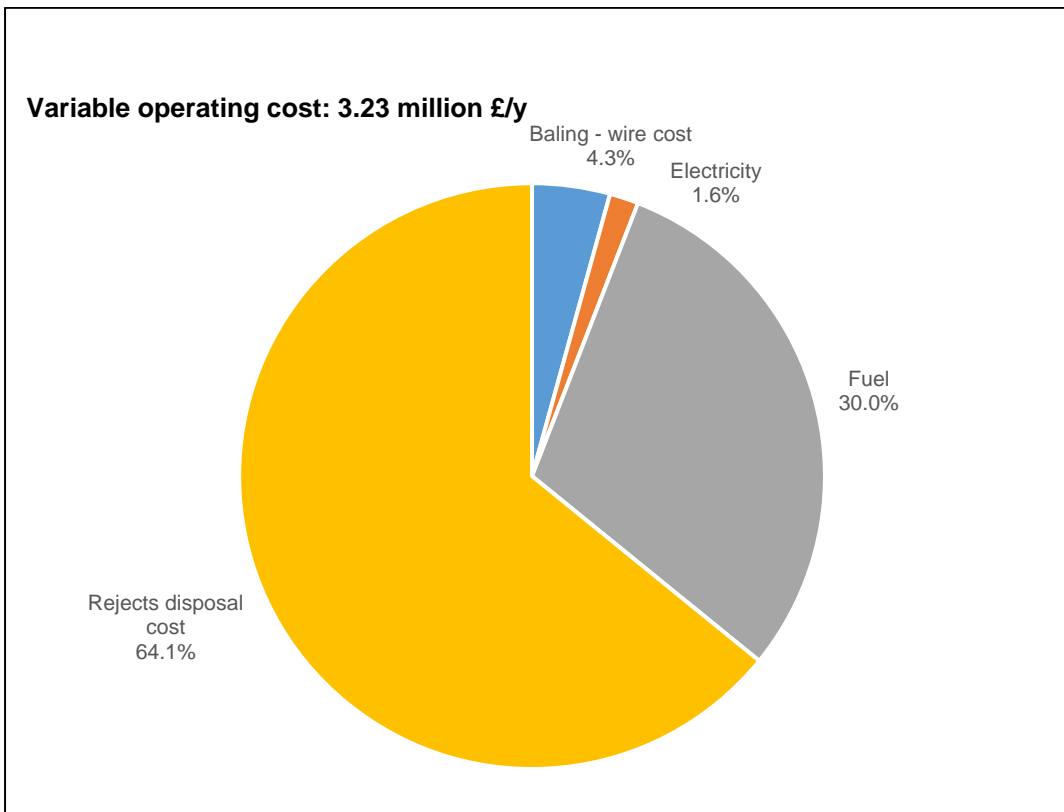
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(b)

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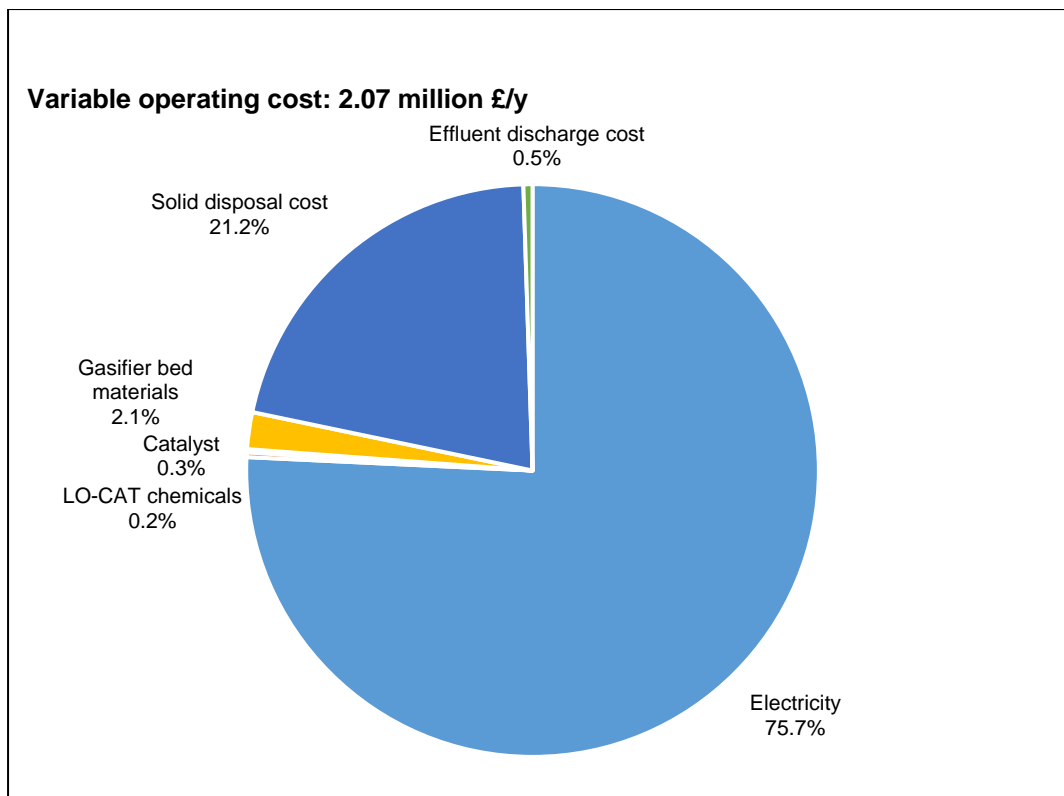
Figure 6: Equipment cost breakdown (a) MRF; (b) Gasification-H₂.



4

5

(a)



(b)

Figure 7: Variable operating cost breakdown (a) MRF; (b) Gasification-H₂.

4.2 Scenario analysis

Economic assessment of the MRF scenario with enhanced separation efficiency (Scenario 1) and the Gasification-H₂ system with increased throughput (Scenario 2) are presented in sections 4.2.1 and 4.2.2, respectively.

4.2.1 Scenario 1: Enhancing separation efficiency of MRF

In this scenario, it was assumed that the separation efficiencies of sorting/screening equipment in MRF (Supplementary Materials: Appendix A, Table A.2) were increased from 83-91% to 98%. It was found that the amount of rejects was reduced by 37.3% (from 3.78 to 2.37 t/h). This implies that 12.8% of rejected materials (relative to the mixed recyclables input) were generated compared to the base case of 20.4%. In this scenario, more materials were recovered and sold, resulting in a 6% increase in revenue (i.e. 0.5 million £/y). Furthermore, an 18% reduction in operating cost was attained and this was mainly attributed to an obviated rejects disposal cost of approximately 0.7 million £/y. The EP was improved by 1.3 million £/y (30%) in this scenario where enhanced separation efficiency of MRF was considered, presented in Table 7.

1

2 Table 7: Economic analysis of Scenario 1 with enhancement of MRF separation efficiency.

Parameter	Unit	Base case	Scenario 1: Enhanced separation efficiency
Throughput (Mixed recyclables)	t/h	18.52	18.52
Total rejects	t/h	3.78	2.37
Percentage of rejects with respect to mixed recyclables input	%	20.42	12.77
Annualised capital cost	million £/y	0.47	0.44
Operating cost	million £/y	3.78	3.07
Revenue	million £/y	8.33	8.85
Economic potential (EP)	million £/y	4.08	5.34

3

4 **4.2.2 Scenario 2: Increasing throughput to Gasification-H₂ system**

5 This scenario examines the economies of scale of the Gasification-H₂ system if the throughput
6 of rejected materials from MRF is increased from 1.87 to 100 dry t/h. As indicated in Table 8,
7 by keeping similar hydrogen yield of approximately 160 kg/dry t feedstock, the annualised
8 capital and operating costs, revenues and EP were increased as expected. The MHSP was
9 reduced considerably from 6.1 £/kg (base case) to 2.2 £/kg. This suggests that economies of
10 scale play a vital role in reducing the MHSP, i.e. improving the economic performance of the
11 system.

12 Table 8: Economic analysis of Scenario 2 with increase of MRF rejected materials throughput into Gasification-
13 H₂ system.

Parameter	Unit	Base case	Scenario 2: High throughput
Throughput (Rejected materials from MRF)	dry t/h	1.87	100.00
Annualised capital cost	million £/y	10.24	169.90
Operating cost	million £/y	5.00	126.56
Revenue	million £/y	25.03	1328.78
Economic potential (EP)	million £/y	9.78	1032.32
Hydrogen production	t/y	2502.52	132877.60
Hydrogen yield	kg/dry t feedstock	167.49	166.10
Minimum hydrogen selling price (MHSP)	£/kg	6.09	2.23
Minimum hydrogen selling price (MHSP)	£/GJ	50.77	18.59

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4.3 Discussions

Plant design and incoming waste composition have strong influence on the MRF performance, as pointed out by Pressley et al. [21]. Changes in MRF and gasification configurations and operating conditions may have an impact on the performance of the system. Hence, techno-economic evaluation needs to be conducted on a case-by-case basis. One of the limitations of this work is the assumptions made for incoming waste composition and rejected materials composition and properties since actual plant data are not available. The UK data for waste composition have not indicated the ratio of recyclable and non-recyclable fractions for each waste category in the mixed recyclable stream, as discussed in section 3.1. An assumption for this ratio was made based on the work of Pressley et al. [21]. This assumption however is sensible for a pre-sorted stream where non-recyclable fraction is typically kept to a minimum. This fraction is not expected to vary significantly unless there is an apparent deficiency in the source-segregation and collection stages. The variability of waste composition (i.e. chemical properties, recyclable/non-recyclable fraction, combustible/non-combustible fraction) has certain impact on the economic performance of the system and this aspect needs to be considered in the design stage. For an MRF plant, reducing 1% of the non-recyclable fraction (i.e. 1% higher in the recyclable fraction) would lead to an increase in revenue from 0.01 million £/y (aluminium; highest unit price) to 0.02 million £/y (cards/papers; lowest unit prices) for the recycled products. Higher non-recyclable fraction implies higher production of rejected materials and thus higher cost for solid disposal, i.e. 1% increase in rejected materials would incur an additional 0.02 million £/y for treatment in EfW and landfill. Introducing the Gasification-H₂ system allows the rejected materials to be valorised into hydrogen, where 1% increase in rejected materials would create an additional revenue of 0.18 million £/y.

MHSP estimated from the present study was compared against previous studies conducted by NREL [28] and Sara et al. [29] as summarised in Table 9. These studies have used biomass as feedstock for the Gasification-H₂ system with different throughput. The current system with 1.87 dry t/h of throughput gives a MHSP of 6.1 £/kg, which falls within the range between 0.7 £/kg at a higher throughput of 88.17 dry t/h and 8.9 £/kg at a lower throughput of 0.02 dry t/h. Although the hydrogen yield predicted in the present study is the highest and more than double compared to those in other studies, i.e. 167 compared to 70 kg hydrogen/dry tonne of feedstock, the MHSP is still the highest among others. It should be noted that the H₂/CO molar ratio of syngas from gasification in this study is 2.6 whereas the typical value is around 0.6-0.8 [28].

1 According to the results from Scenario 2 together with this comparison, it can be concluded
 2 that economies of scale are critical factors in determining the economic viability of hydrogen
 3 production from waste. A preliminary speculation suggests that a throughput of MRF rejected
 4 materials higher than 100 dry t/h is essential to result in an MHSP competitive to the one
 5 estimated by NREL study [28]. In the present study, it was assumed that a single MRF is
 6 integrated with a Gasification-H₂ system. Therefore, it would be more sensible to establish
 7 multiple MRF integrated with a larger scale Gasification-H₂ system.

8 Table 9: Comparison of minimum hydrogen selling price (MHSP).

Parameter	Unit	Present study	NREL [28]	Sara et al. [29]
Year of study		2020	2005	2016
Feedstock		MRF rejects	Hybrid poplar wood chips	Almond shell
Throughput	dry t/h	1.87	88.17	0.02
Annualised capital cost	million £/y	10.24	14.23 ⁽ⁱ⁾	0.05 ⁽ⁱⁱ⁾
Operating cost	million £/y	5.00	23.40 ⁽ⁱ⁾	0.03 ⁽ⁱⁱ⁾
Hydrogen production	t/y	2502.52	54400.00	9.70
Hydrogen yield	kg/dry t feedstock	167.49	70.40	69.29
Minimum hydrogen selling price (MHSP)	£/kg	6.09	0.69 ⁽ⁱ⁾	8.93 ⁽ⁱⁱ⁾
Minimum hydrogen selling price (MHSP)	£/GJ	50.77	5.75 ⁽ⁱ⁾	74.38 ⁽ⁱⁱ⁾

9 Note:

10 ⁽ⁱ⁾ Currency conversion of 1 USD = 0.5 GBP was applied.

11 ⁽ⁱⁱ⁾ Currency conversion of 1 EURO = 0.7 GBP was applied.

12

13 MHSP estimated from the present study was also compared against the MHSP of other
 14 hydrogen production technologies obtained from IRENA report [24], including solar PV and
 15 wind powered electrolyzers, steam methane reforming (SMR) of natural gas with carbon
 16 capture and storage (CCS) and coal gasification with CCS as presented in Table 10. The base
 17 case with lower throughput of MRF rejected materials (~2 dry t/h) has the highest MHSP
 18 among all cases, however a higher throughput (100 dry t/h) has the potential of reducing the
 19 MHSP to 2.23 £/kg which is competitive with “green” hydrogen generated from an average-
 20 cost solar PV powered electrolyser (i.e. 2.27 £/kg). Nevertheless, the MHSP for the waste-to-
 21 hydrogen system in the present study is difficult to compete with the conventional fossil-based
 22 SMR of natural gas (0.27-0.73 £/kg) and coal gasification (0.14-0.36 £/kg). As gathered from
 23 Scenario 2, the MHSP of the Gasification-H₂ case can be further reduced if hydrogen is
 24 produced from a large-scale system, i.e. greater than 100 dry t/h of rejected materials.

25

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1 Table 10: Comparison of MHSP of various hydrogen production technologies.

Hydrogen production technology	£/GJ	£/kg
Base case – Reject gasification-H ₂ (low throughput)	50.77	6.09
Scenario 2 – Reject gasification-H ₂ (high throughput)	18.59	2.23
Average-cost solar PV powered electrolyser	18.89	2.27
Average-cost wind powered electrolyser	7.78	0.93
Low-cost solar PV powered electrolyser	3.89	0.47
Low-cost wind powered electrolyser	5.11	0.61
SMR natural gas with CCS (low cost case)	2.27	0.27
SMR natural gas with CCS (high cost case)	6.07	0.73
Coal gasification with CCS (low cost case)	1.20	0.14
Coal gasification with CCS (high cost case)	3.04	0.36

2

3 The conceptual model and techno-economic results in this study provide comprehensive
 4 comparison between new and existing technologies using best available published data. The
 5 MRF and gasification models developed in this study provide useful information and can be
 6 adapted for future research to investigate different valorisation pathways. The economic
 7 assessment has also identified areas in the integrated system which can be further improved. A
 8 more rigorous model validation with detailed waste feedstock characterisation is needed if the
 9 integrated system concept is to be implemented at pilot or commercial scale in the future.

10

11 5. Conclusions

12 A more robust resource recovery from waste concept through integrating material recovery and
 13 valorisation system is developed. This paper has established a conceptual design and modelling
 14 framework for an integrated material recovery and waste-to-hydrogen system through
 15 combining MRF and Gasification-H₂ system. The analysis consists of flowsheet synthesis,
 16 material and energy balances, energy integration, economic assessment and scenario analysis.
 17 In this study, it is shown that reject/solid disposal not only poses significant impacts on the
 18 economics of MRF but also causes environmental pollution. One of the main advantages of
 19 this integrated system is that the high reject disposal cost in MRF can be obviated by
 20 transforming low-value rejected materials into hydrogen which is a high value-added products.
 21 This has significantly maximised the overall resource utilisation from household mixed
 22 recyclable stream, which is more promising than the conventional approach of using rejected
 23 materials in EfW or landfilling. Scenario analysis has demonstrated that the economic potential
 24 can be further enhanced by increasing separation efficiency of MRF. For the Gasification-H₂
 25 system, economies of scale are the predominant factors in determining an economically viable

1 production of hydrogen from waste. A large-scale system is desirable to achieve a cost-
2 competitive production of hydrogen. It is recommended that an economically compelling
3 waste-to-hydrogen system should comprise multiple MRF integrated with a large-scale
4 Gasification-H₂ system, i.e. greater than 100 dry t/h of MRF rejects input. A more rigorous
5 model validation for mass and energy balances through experimental and pilot plant studies is
6 recommended. This should also incorporate the investigation on the variability of waste
7 composition and associated impact on hydrogen production potential and economic
8 performance of the integrated system.

9 **Acknowledgement**

10 This work was supported by the Natural Environment Research Council (NE/R012938/1)
11 through the UKRI/NERC Industrial Innovation Fellowship Programme.

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4

Supplementary Materials

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Appendix A

MRF Material and Energy Balances and Cost Estimation

Table A.1: UK household recycling stream composition estimates (2017) [1].

Waste category	Waste component	Flow (tonnes/year)						Mass fraction (%)
		Kerbside Household Recycling	HWRC Household Recycling	Bring Site Recycling	Street Bins Recycling	"Other Means" Household Recycling	Total	
Card and paper	Papers	1640101	68471	35690	489	11	1744762	30.05
	Cards	1078003	173283	16608	348	9	1268251	21.84
Metals	Ferrous metals	191947	215862	3761	78	20	411668	7.09
	Non-ferrous metals	68837	107068	1646	27	11	177589	3.06
Glass		1265274	50658	149967	954	9	1466862	25.26
Plastics	PET bottles	153213	13624	1423	68	14	168342	2.90
	HDPE bottles	76849	6833	714	34	7	84437	1.45
	Other plastic bottles	80283	7139	746	36	8	88212	1.52
	Dense plastic non-bottles	169714	15435	1613	77	16	186855	3.22
	Plastic films and bags	19552	1276	170	9	0	21007	0.36
Textiles		15198	82749	46835	3	23	144808	2.49
Other wastes		9152	33007	1005	0	0	43164	0.74
TOTAL							5805957	100.00

Note:

1. HWRC: Household Waste Recycling Centres
2. The data has been refined to suit the present study. Please refer to WRAP National Household Waste Composition 2017 report [1] for the detailed breakdown of waste components and compositions.

Table A.2: Separation efficiencies of MRF processes [2].

Waste component	Separation stage								
	Manual sorting and vacuum	Trommel	Ballistic separator	Magnet	Eddy current separator	Air classifier	Optical/NIR sorter - PET	Optical/NIR sorter - HDPE	Optical/NIR sorter - Mixed rigid plastics
Cards and papers			91						
Ferrous metals				88					
Aluminium					87				
Glass		10				87			
PET							83		
HDPE								83	
Mixed rigid plastics	81	5							83
Other materials		95							

Assumptions:

1. The separation efficiency for ballistic separator was assumed to be the same as disc separator.
2. The separation efficiency for Optical/NIR sorter - Mixed rigid plastics was assumed to be the same as Optical/NIR-PET/HDPE.
3. The separation efficiency for air classifier was assumed to be the same as glass breaker screen.
4. Any non-recyclable materials in each category were separated from the associated separation stage, except:
 - a. The non-recyclable plastics was separated in manual sorting to prevent downstream operational issues.
 - b. The remaining papers and cards, metals and other materials were rejected at the glass separation stage.

Table A.3: Detailed breakdown of MRF stream flow rates into each stage by waste component.

Waste category	Waste component	Input flow to (t/h)				
		Manual sorting	Paper/card separation	Metal separation	Glass separation	Plastic sorting
Card and paper	Cards and papers	9.24	9.24	0.83	0.83	0.00
	Non-recyclable	0.37	0.37	0.00	0.00	0.00
Metal	Ferrous metals	1.13	1.13	1.13	0.14	0.00
	Aluminium metals	0.49	0.49	0.49	0.06	0.00
	Non-recyclable	0.26	0.26	0.26	0.00	0.00
Glass	Glass	4.60	4.60	4.14	4.14	0.54
	Non-recyclable	0.08	0.08	0.08	0.08	0.00
Plastics	PET bottles	0.54	0.54	0.54	0.54	0.54
	HDPE bottles	0.27	0.27	0.27	0.27	0.27
	Mixed rigid plastics	0.66	0.13	0.12	0.12	0.12
	Non-recyclable	0.28	0.00	0.00	0.00	0.00
Other materials	Organics and inorganics	0.60	0.60	0.03	0.03	0.00
	Total	18.52	17.70	7.89	6.21	1.46

Table A.4: Equipment cost estimation for MRF system.

Item no.	Equipment	Reference	Base cost		Base Year	Size			Scale factor	Scaled cost (£)	Present Year	Levelised cost (£)	Levelised cost (million £)
			USD	GBP		Base	Current	Unit					
1	Conveyor	[2]	46000	28980	2012	30	18.52	t/h	0.6	21696.48	2019	22123.29	0.022
2	Drum feeder	[2]	150000	94500	2012	30	18.52	t/h	0.6	70749.41	2019	72141.16	0.072
3	Vacuum	[2]	150000	94500	2012	10	0.54	t/h	0.6	16346.60	2019	16668.16	0.017
4	Trommel	[2]	125000	78750	2012	45	17.70	t/h	0.6	44989.28	2019	45874.29	0.046
5	Ballistic separator	[3]		60000	2009	10	17.70	t/h	0.6	84515.67	2019	96531.50	0.097
6	Magnet	[2]	35000	22050	2012	2	7.89	t/h	0.6	50222.50	2019	51210.46	0.051
7	Eddy current separator	[2]	128000	80640	2012	12	7.89	t/h	0.6	62682.96	2019	63916.04	0.064
8	Air classifier	[2]	62500	39375	2012	36	6.21	t/h	0.6	13712.33	2019	13982.07	0.014
9	Optical/NIR sorter - PET	[2]	225000	141750	2012	10	1.46	t/h	0.6	44756.59	2019	45637.02	0.046
10	Optical/NIR sorter - HDPE	[2]	450000	283500	2012	10	1.46	t/h	0.6	89513.18	2019	91274.05	0.091
11	Optical/NIR sorter - Mixed rigid pl	[2]	450000	283500	2012	10	1.46	t/h	0.6	89513.18	2019	91274.05	0.091
12	Baler - cards and papers	[2]	550000	346500	2012	51	8.41	t/h	0.6	117495.40	2019	119806.72	0.120
13	Baler - ferrous metals	[2]	530000	333900	2012	30	1.00	t/h	0.6	43283.88	2019	44135.34	0.044
14	Baler - non-ferrous metals	[2]	530000	333900	2012	30	0.42	t/h	0.6	25957.90	2019	26468.53	0.026
15	Baler - plastics	[2]	530000	333900	2012	30	1.31	t/h	0.6	50911.76	2019	51913.28	0.052
TOTAL												852955.94	0.853

Note:

1. Equipment costs for MRF were obtained from [2], except ballistic separator which was obtained from [3].
2. Balers include single ram and dual ram ballers. Single ram ballers are used for paper and cardboards while dual ram balers are used for metals and hard plastics. All other materials were assumed to be collected on loose packing.
3. Papers and cardboards were screened by ballistic separator instead of disc screen.
4. The cost for optical/NIR for mixed rigid plastics was assumed to be the same as optical/NIR for HDPE.
5. Base cost included equipment and installation costs.
6. CEPCI (2009) = 521.9; CEPCI (2012) = 584.6; CEPCI (2019, November Prelim.) = 596.1.
7. Currency conversion rate of 1 USD = 0.63 GBP (2012) was assumed.

Table A.5: Lang factor for solid processing system [4].

Component	Factor
<i>Direct cost</i>	
Delivered cost of equipment	1.00
Installation	0.45
Instrumentation and control	0.18
Piping	0.16
Electrical systems	0.10
Buildings (including services)	0.25
Yard improvements	0.15
Service facilities	0.40
Total direct cost	2.69
<i>Indirect cost</i>	
Engineering and supervision	0.33
Construction expenses	0.39
Legal expenses	0.04
Contractor's fee	0.17
Contingency	0.35
Total indirect cost	1.28
Working capital	0.70
Total capital investment	4.67

Table A.6: Variable operating cost for MRF system.

No.	Component	Estimation	Cost (million £/y)
1	Baling - wire cost	Tables A.8 - A.12; Eq. (A.1)-(A.5)	0.14
2	Electricity	Table A.13; Eq. (A.6)	0.05
3	Fuel	Table A.14; Eq. (A.6)	0.97
4	Rejects disposal cost	Landfill gate fees and tax = 114.35 £/t; EfW gate fees = 100 £/t (March 2020) [5]	2.07
	Total variable cost		3.23

Table A.7: Fixed operating cost for MRF system [4].

No.	Specification	Estimation	Unit	Cost (million £/y)
1	Maintenance	10%	indirect capital costs	0.013
2	Personnel	Table A.15; Eq. (A.7) and (A.8)		0.287
3	Laboratory costs	0%	personnel costs	0.000
4	Supervision	0%	personnel costs	0.000
5	Plant overheads	50%	personnel costs	0.143
6	Capital charges	10%	indirect capital costs	0.013
7	Insurance	1%	indirect capital costs	0.001
8	Local taxes	2%	indirect capital costs	0.003
9	Royalties	1%	indirect capital costs	0.001
	Direct production cost			0.461
10	Sales expense	20%	direct production cost	0.092
	General overheads			
	Research and developments			
	Total fixed operating costs			0.553

Note:

1. No laboratory cost is required in MRF. The cost of supervision was accounted in personnel.
2. Indirect capital cost is 0.13 million/y (capital recovery factor = 0.117 assuming discount rate of 10% and plant life of 20 years).

Cost of baling

Table A.8: Cost of baling wire for different type of recyclable materials.

Materials to be baled	Type of wire	Wire cost per bale, $C_{w,b}$ (£/bale)	Wire cost per mass of bale, $C_{w,m}$ (£/t)	Mass of waste component, $m_{R,i}$ (t/y)	Wire cost, C_w (£/y)
Papers and cards	Black annealed	2.20	2.08	45410.9	94606.01
Ferrous metals	Galvanised	2.55	2.12	5379.0	11425.83
Non-ferrous metals	Galvanised	2.55	3.87	2294.1	8886.63
Plastics	Galvanised	2.55	3.39	7049.9	23896.06
Total				60133.8	138814.52

Eqs. (A.1) – (A.5) were used to estimate the wire cost for baling recyclable materials. The associated parameters can be found in Tables A.9 - A.12.

$$\text{wire cost per bale, } C_{w,b} \left(\frac{\text{£}}{\text{bale}} \right) = \text{wire length required per bale, } L_{w,b} \left(\frac{\text{m}}{\text{bale}} \right) \times \text{price per unit length of wire, } C_{w,l} \left(\frac{\text{£}}{\text{m}} \right) \quad (\text{A.1})$$

$$\text{where wire length require per bale, } L_{w,b} \left(\frac{\text{m}}{\text{bale}} \right) = [(2 \times H_b) + (2 \times W_b)] \times N_s \quad (\text{A.2})$$

$$\text{mass of materials per bale, } m_{R,b} \left(\frac{\text{kg}}{\text{bale}} \right) = (W_b \times L_b \times H_b) \left(\frac{\text{m}^3}{\text{bale}} \right) \times \text{density of baled materials, } \rho_{R,i} \left(\frac{\text{kg}}{\text{m}^3} \right) \quad (\text{A.3})$$

$$\text{wire cost per mass of bale, } C_{w,m} \left(\frac{\text{£}}{\text{kg}} \right) = \frac{\text{wire cost per bale, } C_{w,b} \left(\frac{\text{£}}{\text{bale}} \right)}{\text{mass of materials per bale, } m_{R,b} \left(\frac{\text{kg}}{\text{bale}} \right)} \quad (\text{A.4})$$

$$\text{wire cost, } C_w \left(\frac{\text{£}}{\text{y}} \right) = \text{wire cost per mass of bale, } C_{w,m} \left(\frac{\text{£}}{\text{kg}} \right) \times \text{mass of waste component, } m_{R,i} \left(\frac{\text{kg}}{\text{y}} \right) \quad (\text{A.5})$$

Basis for estimating baling wire cost

Table A.9: Unit price of baling wire [6].

Parameter	Specification	
Type of baler	Single ram	Dual ram
Type of wire	Black annealed	Galvanised
Length of wire per bundle (m/bundle)	480	480
Mass of wire per bundle (kg/bundle)	25	25
Price per bundle (£/bundle)	52.8	52.8
Price per unit length of wire, $C_{w,l}$ (£/m)	0.11	0.11
Price per unit mass of wire (£/kg)	2.11	2.11
Note	a, c	b, c

Note:

- a. Wire long black annealed 3mm diameter, pre-cut and looped.
- b. Wire long galvanised 3mm diameter, pre-cut and looped.
- c. Price includes VAT of 20%.
- d. Length of wire is 4.8 m. There are 100 wires in one bundle.

Table A.10: Baling specification [7].

Parameter	Specification	
Types of baler	Single ram	Dual ram
Bale width, W_b (m)	1	1.14
Bale length, L_b (m)	2	1.63
Bale height, H_b (m)	1	0.79
Straps per bale, N_s	5	6

Table A.11: Baled material density, $\rho_{R,i}$ [7].

Parameter	Density (kg/m ³)
Cardboard	528
Steel cans	817
Aluminium cans	448
Plastics	512

Table A.12: Specification of wire per bale of materials.

Parameter	Specification	
	Single ram	Dual ram
Type of baler	Single ram	Dual ram
Type of wire	Black annealed	Galvanised
Wire length required per bale, $L_{w,b}$ (m/bale)	20.0	23.2
Mass of materials per bale, $m_{R,i}$ (kg/bale)		
- Cardboard	1056.0	
- Steel cans		1199.3
- Aluminium cans		657.7
- Plastics		751.6

Cost of electricity

Table A.13: Cost of electricity for different MRF equipment.

Item no.	Equipment	Reference	Rated motor capacity, $e_j^{MaxMotor}$ (kW)	Fraction of motor rated capacity utilised, f_j^{MC}	Maximum throughput, m_j^{MTP} (t/h)	Fraction of equipment capacity utilised, f_j^{MTP}	Electricity requirement, E_j (kWh/t)	Current throughput (t/h)	Annual electricity requirement (kWh/y)	Annual cost of electricity (£/y)
1	Conveyor	[2]	5.6	0.5	30	0.85	0.110	18.52	10980.4	1416.47
2	Drum feeder	[2]	15	0.5	30	1	0.250	18.52	25000.0	3225.00
3	Vacuum	[2]	5	0.5	10	0.85	0.294	0.54	852.9	110.03
4	Trommel	[2]	62	0.5	45	0.85	0.810	17.70	77464.1	9992.87
5	Ballistic separator	[8]	22	0.5	30	0.85	0.431	17.70	41230.9	5318.79
6	Magnet	[2]	4	0.5	2	0.85	1.176	7.89	50098.1	6462.65
7	Eddy current separator	[2]	9	0.5	12	0.85	0.441	7.89	18786.8	2423.49
8	Air classifier	[2]	164	0.5	36	0.85	2.680	6.21	89799.3	11584.11
9	Optical/NIR - PET	[2]	13	0.5	10	0.85	0.765	1.46	6045.7	779.89
10	Optical/NIR - HDPE	[2]	40	0.5	10	0.85	2.353	1.46	18602.1	2399.67
11	Optical/NIR - Mixed rigid plastics	[2]	40	0.5	10	0.85	2.353	1.46	18602.1	2399.67
12	Baler - cards and papers	[2]	63	0.5	51	1	0.618	8.41	28047.9	3618.18
13	Baler - ferrous metals	[2]	59	0.5	30	1	0.983	1.00	5289.3	682.32
14	Baler - non-ferrous metals	[2]	59	0.5	30	1	0.983	0.42	2255.8	291.00
15	Baler - plastics	[2]	59	0.5	30	1	0.983	1.31	6932.4	894.28
	TOTAL								399987.8	51598.42

Note:

1. The rated motor capacity for optical/NIR for mixed rigid plastics was assumed to be the same as optical/NIR for HDPE.
2. Balers include single ram and dual ram ballers. Single ram ballers are used for paper and cardboards while dual ram balers are used for metals and hard plastics. All other materials are assumed to be collected on loose packing.
3. Price of electricity = 0.129 £/kWh (2019, including CCL) [9]

Eq. (A.6) was applied to estimate the electricity requirement for MRF equipment.

$$E_j = \frac{(e_j^{MaxMotor} \times f_j^{MC})}{(m_j^{MTP} \times f_j^{MTP})} \quad (A.6)$$

where

E_j is the electricity requirement of equipment j , kWh/t;

$e_j^{MaxMotor}$ is the rated motor capacity of equipment j , kW;

f_j^{MC} is the fraction of motor rated capacity utilised;

m_j^{MTP} is the maximum throughput of equipment j , t/h;

f_j^{MTP} is the fraction of equipment capacity utilised.

Cost of Fuel

Table A.14: Cost of fuel required for rolling stock.

Item no.	Equipment	Reference	Diesel use (L/t)	Maximum throughput (t/h)	Fraction of equipment capacity utilised	Current throughput (t/h)	Fuel requirement (L/h)	Annual fuel requirement (L/y)	Annual cost of fuel (£/y)
1	Rolling stock - mixed recyclables	[2]	10	24	0.85	18.52	185.19	1000000.0	483829.89
2	Rolling stock - cards and papers	[2]	10	24	0.85	8.41	84.09	454108.8	219711.43
3	Rolling stock - ferrous metals	[2]	10	24	0.85	1.00	9.96	53789.6	26025.00
4	Rolling stock - non-ferrous metals	[2]	10	24	0.85	0.42	4.25	22940.5	11099.32
5	Rolling stock - glass	[2]	10	24	0.85	3.60	36.01	194470.3	94090.52
6	Rolling stock - plastics	[2]	10	24	0.85	1.31	13.06	70499.3	34109.65
7	Rolling stock - rejects	[2]	10	24	0.85	3.78	37.81	204191.6	98793.98
	Total							2000000.0	967659.77

Note:

1. The rolling stock has been broken down into different categories of stocks to be moved. It does not represent the actual number of rolling stocks on site.
2. Maximum throughput and fraction of equipment capacity utilised were used as reference and not in the calculation as long as the current throughput adhere to the given capacity.
3. Price of diesel = 0.484£/L (gas oil, 2019) [9]

Equation (A.6) was used to estimate the fuel requirement, using the same analogy as the estimation for electricity.

Cost of personnel

Table A.15: Cost of personnel for MRF.

Category of personnel	MRF stage	Maximum throughput, m_j^{MTP} (t/h)	Fraction of equipment capacity utilised, f_j^{MTP}	Number of personnel required for maximum throughput, $n_j^{personnel}$	Personnel hour per tonne of throughput, P_j	Current throughput (t/h)	Personnel required	Hourly rate of salary per person (£/h)	Annual salary for personnel (£/y)
Driver	Rolling stock	24	0.85	1	0.049	37.04	1.82	11	107843.14
Equipment-specific labour	Vacuum	10	0.85	2	0.235	0.54	0.13	9	6141.01
	Baler - cards and papers	51	1	1	0.020	8.41	0.16	9	8013.69
	Baler - ferrous metals	30	1	1	0.033	1.00	0.03	9	1613.69
	Baler - non-ferrous metals	30	1	1	0.033	0.42	0.01	9	688.22
	Baler - plastics	30	1	1	0.033	1.31	0.04	9	2114.98
Sorter	Manual sorting						1.29	9.29	64797.22
Supervisor									95605.97
Total									286817.91

Note:

1. Hourly wages for drivers, equipment-specific labours and sorter were obtained from Jobsite based on the latest rate in 2020 (<https://www.jobsite.co.uk/jobs/recycling>)
2. Hourly wages for supervisor was assumed to be 50% of the total salary of the above [2].

The numbers of driver and equipment-specific labour were estimated using equation (A.7).

$$P_j = \frac{n_j^{personnel}}{m_j^{MTP} \times f_j^{MTP}} \quad (A.7)$$

where

P_j is the personnel requirement for equipment j , personnel h/t throughput;

$n_j^{personnel}$ is the number of personnel required to operate equipment j ;

m_j^{MTP} is the maximum throughput of equipment j , t/h;

f_j^{MTP} is the fraction of equipment capacity utilised.

The number of manual sorter was estimated using equation (A.8).

$$P_j^{MS} = \frac{m_j^{removed}}{m_j^{TP} \times r_j^{picking}} \quad (A.8)$$

where

P_j^{MS} is the personnel requirement for manual sorting, personnel h/t throughput (1.6 personnel-h/t estimated using values below);

$m_j^{removed}$ is the mass of materials removed at picking station j , t/h (0.82 t/h);

m_j^{TP} is the throughput of material entering picking station j , t/h (18.52 t/h);

$r_j^{picking}$ is the picking rate of equipment capacity utilised, kg/personnel-h (28 kg/personel-h).

Table A.16: Revenues generated from recyclable products from MRF.

Recyclable materials	Unit price (£/t)	Flow (t/h)	Flow (t/y)	Revenue (million £/y)
Cards and papers	32.5	8.41	45410.88	1.48
Ferrous metals	83.0	1.00	5378.96	0.45
Aluminium	725.0	0.42	2294.05	1.66
Glass	-10.5	3.60	19447.03	-0.20
PET	290.0	0.45	2406.56	0.70
HDPE	555.0	0.22	1207.08	0.67
Mixed rigid plastics	145.0	0.10	536.36	0.08
Total				4.83
Gate fees for MRF	35	18.52	100000	3.50
Total revenue				8.33

Note:

1. The average price of papers and cardboards has been taken to be the unit price of the collective component. Mixed papers and cardboard prices are based on Domestic Mill (ex-works) in April 2020. (<https://www.letsrecycle.com/prices/waste-paper/uk-domestic-mill-prices/2020-domestic-mill-prices/>)
2. Ferrous scrap metals prices have been taken from a range of scraps, in April 2020. (<https://www.letsrecycle.com/prices/metals/ferrous-metal-prices/ferrous-scrap-metal-prices-2020/>)
3. Non-Ferrous metals consider aluminium cans, in March 2020. (<https://www.letsrecycle.com/prices/metals/aluminium-cans/aluminium-can-prices-2020/>)
4. MRF glass price in March 2020. (<https://www.letsrecycle.com/prices/glass/glass-prices-2020/>)
5. PET bottles - assumes clear and light blue PET, April 2020. (<https://www.letsrecycle.com/prices/plastics/plastic-bottles/plastic-bottles-2020/>)
6. HDPE bottles - assumes HDPE natural, April 2020. (<https://www.letsrecycle.com/prices/plastics/plastic-bottles/plastic-bottles-2020/>)
7. Mixed rigid plastics - assumes mixed plastics, April 2020. (<https://www.letsrecycle.com/prices/plastics/plastic-bottles/plastic-bottles-2020/>)
8. Negative price means that there is a charge to haul them away from MRF.

Appendix B

Gasification-H₂ System Material and Energy Balances and Cost Estimation

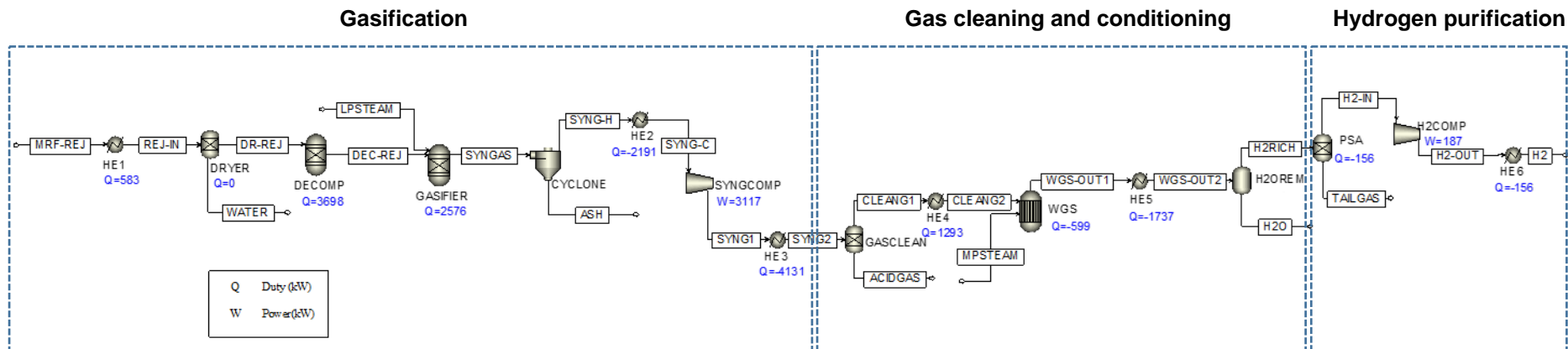


Figure B.1: Aspen Plus simulation flowsheet showing the conversion of MRF rejected materials into hydrogen through gasification system.

Process description

The process modelling of the gasification system has been carried out in Aspen Plus V8.0 environment, using PR-BM (Peng-Robinson equation of state with Boston–Mathias modification) property method [10]. Aspen Plus model specification is provided in Table B.1 and the detailed material balance of the gasification system is presented in Table B.2.

The MRF rejected material stream (MRF-REJ) has been modelled using the proximate and ultimate analyses presented in Table 2. The specification of this stream has been defined in such a way that the Mixed substream consists of water, and the Non-conventional substream includes MSW and ASH. The MSW stream at a flow rate of 2.55 t/h is preheated to 110°C in HE1 and the REJ-IN stream is fed into the DRYER, modelled using a separator (Sep) where 90% of the moisture is removed (WATER stream: 0.615 t/h). The dried rejected materials stream (DR-REJ) is sent to the gasification process. In this study, gasification has been modelled using a decomposition unit (DECOMP) and a main gasification unit (GASIFIER). DECOMP, modelled using a yield reactor (RYield), is not a physical process unit and it is used for decomposing the rejected materials into C, H, O, N and S elements for subsequent modelling purposes [10]. The decomposed rejected materials (DEC-REJ) is then gasified at 900°C and 1.6

bar, modelled using a Gibbs reactor (RGibbs), using low-pressure steam (LPSTEAM) as the gasifying medium [11]. The gasifier has been assumed to be a fluidised bed reactor (i.e. indirect heated, BCL type) where char is combusted to provide sufficient heat to the gasification. It should be noted that char separation and combustion has not been modelled here and it has been assumed that the energy balance around gasification has achieved self-sufficiency (i.e. endothermic energy requirement of gasifier is met). The steam-to-feed ratio has been assumed to be 1.04 on weight basis and thus tar formation has been assumed to be negligible [11]. The validation of gasification model against experimental results [11] is presented in Table B.3. Syngas generated from gasification (SYNGAS) consists primarily of CO, H₂, CO₂ and H₂O and a H₂/CO molar ratio of 2.6 is obtained. The hot syngas is passed through a cyclone (CYCLONE, modelled using a Splitter model or SSplit) to remove ash (ASH) which is then disposed to landfill. The syngas (SYNG-H) is cooled down to 80°C in HE2 and SYNG-C is further compressed in a syngas compressor (SYNGCOMP) to 30 bar. HE3 represents the compressor inter/after cooler for maintaining the outlet stream (SYNG1) temperature of SYNGCOMP at 50°C before entering the gas cleaning processes (GASCLEAN).

GASCLEAN, modelled using a separator (Sep) represents a series of acid gas removal units (LO-CAT and ZnO bed). GASCLEAN removes H₂S in the syngas (SYNG2) down to 1 ppmv (a split fraction of H₂S has been specified at 0.999999) as a measure to prevent catalyst poisoning in the water-gas shift reactor (WGS). The ACIDGAS stream consists of H₂S only. The temperature of cleaned syngas (CLEANG1) is then increased to 200°C in HE4 before entering WGS. WGS reaction ($\text{CO} + \text{H}_2 \rightarrow \text{H}_2 + \text{CO}_2$), modelled using an equilibrium reactor (REquil) and operated at 200°C is served to increase the yield of H₂. MP steam (MPSTEAM; 1.6 t/h) at 14 bar and 250°C is added to facilitate the reaction. The amount of steam to be supplied to water-gas shift reactor has been determined using sensitivity analysis presented in Table B.4. The flow rate of hydrogen has been increased from 0.26 t/h (CLEANG2) to 0.36 t/h (WGS-OUT1). WGS-OUT1 is cooled down to 40°C (WGS-OUT2) in HE5 so that water (H₂O) can be removed in a flash drum (H2OREM, modelled using Flash2).

The hydrogen-rich stream (H2RICH) is sent to a pressure swing adsorption (PSA) unit, modelled using a separator (Sep) to recover hydrogen at 85 mol % and obtain a purity of 99.95 mol% (H2-IN). H2-IN is then compressed to 70 bar in a hydrogen compressor (H2COMP). The temperature

of compressed H₂ (H2-OUT) is maintained at 45°C through HE6 upon distribution (H2). The tail gas stream from PSA (TAILGAS) comprises mainly CO₂.

Table B.1: Aspen Plus model specification for Gasification-H₂ system.

Process Unit	Block name	Aspen Plus Model	Temperature (°C)	Pressure (bar)	Other specification
Dryer	DRYER	Sep			Split fraction; Stream DR-REJ <i>Substream (Mixed)</i> H ₂ O = 0.1 <i>Substream (NC)</i> Ash = 1.0 MSW = 1.0
Decomposition	DECOMP	RYield	250	1.6	Component yields (mass basis) C = 0.6077 H ₂ = 0.0784 O ₂ = 0.2458 N ₂ = 0.01357 S = 0.0754 H ₂ O = 0.0469
Gasifier	GASIFIER	RGibbs	900	1.6	
Cyclone	CYCLONE	SSplit			Stream: ASH Split fraction (NC) = 1.0
Acid gas removal	GASCLEAN	Sep			Split fraction; Stream ACIDGAS H ₂ S = 0.999999
Water-gas shift reactor	WGS	REquil	200	1.013	

Water removal unit	H2OREM	Flash2	40	1.013	
Pressure swing adsorption column	PSA	Sep			Split fraction; Stream H2 <i>Substream (Mixed)</i> H ₂ = 0.85 CO = 0.001 CO ₂ = 0.001 CH ₄ = 0.001
Syngas compressor	SYNGCOMP	Compr		30	Isentropic efficiency = 85%
H ₂ compressor	H2COMP	Compr		70	Isentropic efficiency = 85%
Heat exchanger (Feed preheater)	HE1	Heater	110	1.013	
Heat exchanger (Syngas cooler)	HE2	Heater	80	1.013	
Heat exchanger (Syngas compressor inter/aftercooler)	HE3	Heater	50	30	
Heat exchanger (Cleaned syngas heater)	HE4	Heater	200	30	
Heat exchanger (WGS outlet gas cooler)	HE5	Heater	40	30	
Heat exchanger (H ₂ compressor inter/aftercooler)	HE6	Heater	45	70	

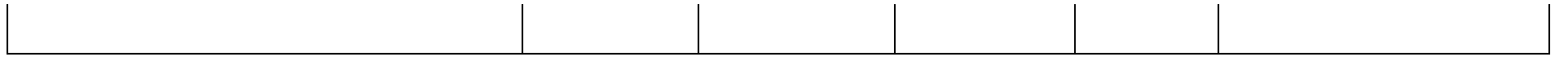


Table B.2: Material balance of the conversion of MRF rejected materials into hydrogen through gasification system.

Component	Stream																											
	ACIDGAS	ASH	CLEANG1	CLEANG2	DEC-REJ	DR-REJ	H2	H2-IN	H2-OUT	H2O	H2RICH	LPSTEAM	MPS	TEAM	MRF-REJ	REJ-IN	SYNG-C	SYNG-H	SYNG1	SYNG2	SYNGAS	TAILGAS	WATER	WGS-OUT1	WGS-OUT2			
Substream: MIXED																												
Mole Flow (kmol/h)																												
C	0.000	0.000	0.000	0.000	73.692	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H ₂	0.000	0.000	130.780	130.780	56.655	0.000	153.571	153.571	153.571	0.000	180.672	0.000	0.000	0.000	0.000	0.000	130.780	130.780	130.780	130.780	130.780	27.101	0.000	180.672	180.672	0.000	0.000	0.000
O ₂	0.000	0.000	0.000	0.000	11.188	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N ₂	0.000	0.000	0.706	0.706	0.706	0.000	0.000	0.000	0.000	0.000	0.706	0.000	0.000	0.000	0.000	0.000	0.706	0.706	0.706	0.706	0.706	0.706	0.000	0.000	0.706	0.706	0.000	0.000
S	0.000	0.000	0.000	0.000	0.342	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO	0.000	0.000	50.411	50.411	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	50.411	50.411	50.411	50.411	50.411	0.519	0.000	50.411	50.411	0.519	0.519	0.519
CO ₂	0.000	0.000	23.249	23.249	0.000	0.000	0.073	0.073	0.073	0.002	73.138	0.000	0.000	0.000	0.000	0.000	23.249	23.249	23.249	23.249	23.249	73.065	0.000	73.140	73.140	0.000	0.000	0.000
H ₂ O	0.000	0.000	76.558	76.558	3.796	3.796	0.000	0.000	0.000	98.083	17.396	147.295	88.814	37.957	37.957	37.957	76.558	76.558	76.558	76.558	76.558	17.396	34.161	115.480	115.480	0.000	0.000	0.000
CH ₄	0.000	0.000	0.032	0.032	0.000	0.000	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.000	0.000	0.032	0.000	0.032	0.032	0.032	0.032	0.000	0.000	0.032	0.032	0.000	0.000	0.032
H ₂ S	0.342	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.342	0.342	0.342	0.342	0.342	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mole Fraction																												
C	0.000	0.000	0.000	0.000	0.503	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H ₂	0.000	0.000	0.464	0.464	0.387	0.000	1.000	1.000	1.000	0.000	0.863	0.000	0.000	0.000	0.000	0.000	0.464	0.464	0.464	0.464	0.464	0.228	0.000	0.488	0.488	0.000	0.000	0.000
O ₂	0.000	0.000	0.000	0.000	0.076	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N ₂	0.000	0.000	0.003	0.003	0.005	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.003	0.003	0.003	0.003	0.003	0.003	0.008	0.000	0.002	0.002	0.000	0.000	0.002
S	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO	0.000	0.000	0.179	0.179	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.179	0.179	0.179	0.179	0.179	0.004	0.000	0.001	0.001	0.001	0.001	0.001
CO ₂	0.000	0.000	0.083	0.083	0.000	0.000	0.000	0.000	0.000	0.000	0.268	0.000	0.000	0.000	0.000	0.000	0.082	0.082	0.082	0.082	0.082	0.615	0.000	0.197	0.197	0.000	0.000	0.197
H ₂ O	0.000	0.000	0.272	0.272	0.026	1.000	0.000	0.000	0.000	1.000	0.064	1.000	1.000	1.000	1.000	1.000	0.271	0.271	0.271	0.271	0.271	0.146	1.000	0.312	0.312	0.000	0.000	0.312
CH ₄	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H ₂ S	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mass Flow (kg/h)																												
C	0.000	0.000	0.000	0.000	885.117	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H ₂	0.000	0.000	263.638	263.638	114.209	0.000	309.581	309.581	309.581	0.000	364.213	0.000	0.000	0.000	0.000	0.000	263.638	263.638	263.638	263.638	263.638	54.632	0.000	364.213	364.213	0.000	0.000	364.213
O ₂	0.000	0.000	0.000	0.000	358.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N ₂	0.000	0.000	19.767	19.767	19.767	0.000	0.000	0.000	0.000	0.000	19.767	0.000	0.000	0.000	0.000	0.000	19.767	19.767	19.767	19.767	19.767	19.767	0.000	0.000	19.767	19.767	0.000	0.000
S	0.000	0.000	0.000	0.000	10.982	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO	0.000	0.000	1412.024	1412.024	0.000	0.000	0.015	0.015	0.015	0.000	14.548	0.000	0.000	0.000	0.000	0.000	1412.024	1412.024	1412.024	1412.024	1412.024	14.534	0.000	14.548	14.548	0.000	0.000	14.548
CO ₂	0.000	0.000	1023.187	1023.187	0.000	0.000	3.219	3.219	3.219	0.103	3218.792	0.000	0.000	0.000	0.000	0.000	1023.187	1023.187	1023.187	1023.187	1023.187	3215.573	0.000	3218.894	3218.894	0.000	0.000	3218.894
H ₂ O	0.000	0.000	1379.205	1379.205	68.378	68.380	0.000	0.000	0.000	1767.000	313.399	2653.560	1600.000	683.802	683.802	1379.205	1379.205	1379.205	1379.205	1379.205	1379.205	615.422	2080.399	2080.399	615.422	2080.399	2080.399	615.422
CH ₄	0.000	0.000	0.520	0.520	0.000	0.000	0.001	0.001	0.001	0.000	0.520	0.000	0.000	0.000	0.000	0.520	0.520	0.520	0.520	0.520	0.520	0.000	0.000	0.520	0.520	0.000	0.000	0.520
H ₂ S	11.672	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.672	11.672	11.672	11.672	11.672	11.672	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mass Fraction																												
C	0.000	0.000	0.000	0.000	0.608	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
H ₂	0.000	0.064	0.064	0.078	0.387	0.000	0.990	0.990	0.990	0.000	0.093	0.000	0.000	0.000	0.000	0.064	0.064	0.064	0.064	0.064	0.064	0.015	0.000	0.064	0.064	0.000	0.000	0.064
O ₂	0.000	0.000	0.000	0.000	0.246	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
N ₂	0.000	0.005	0.005	0.014	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.000	0.005	0.005	0.005	0.005	0.005	0.005	0.000	0.000	0.003	0.003	0.000	0.000	0.003
S	0.000	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CO	0.000	0.345	0.345	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.344	0.344	0.344	0.344	0.344	0.344	0.004	0.000					

Table B.3: Gasification model validation using MSW composition.

Component	Simulation model		Experiment [11]	R ²
	Mole fraction (mol%, wet)	Mole fraction (mol%, dry)	Mole fraction (mol%, dry)	
C	0.0000	0.0000	0.0000	0.0000
H ₂	0.4530	0.5866	0.5322	0.0104
O ₂	0.0000	0.0000	0.0000	0.0000
N ₂	0.0007	0.0009	0.0000	0.0000
S	0.0008	0.0011	0.0000	0.0000
CO	0.2276	0.2947	0.2572	0.0213
CO ₂	0.0901	0.1167	0.2061	0.1882
H ₂ O	0.2277	0.0000	0.0000	0.0000
CH ₄	0.0001	0.0001	0.0023	0.9297
Total	1.0000	1.0000	0.9978	1.1496
H ₂ /CO		1.99	2.07	
CO/CO ₂		2.53	1.25	

Table B.4: Sensitivity analysis of WGS steam requirement.

Steam flow rate (kg/h)	Component flowrates at WGS-OUT1 (kg/h)		Relative changes in H ₂ (%)	Relative changes in CO (%)
	H ₂	CO		
100	361.80	48.07	0.00	0.00
200	362.26	41.72	0.13	13.21
300	362.61	36.82	0.10	11.74
400	362.89	32.94	0.08	10.54
500	363.12	29.79	0.06	9.55
600	363.30	27.19	0.05	8.73
700	363.46	25.01	0.04	8.03
800	363.59	23.15	0.04	7.43
900	363.71	21.55	0.03	6.91
1000	363.81	20.16	0.03	6.46
1100	363.90	18.94	0.02	6.06
1200	363.97	17.86	0.02	5.71
1300	364.04	16.90	0.02	5.39
1400	364.11	16.03	0.02	5.11
1500	364.16	15.25	0.02	4.86
1600	364.21	14.55	0.01	4.63
1700	364.26	13.91	0.01	4.42
1800	364.3011	13.31846	0.01	4.22
1900	364.3398	12.77944	0.01	4.05
2000	364.3756	12.28294	0.01	3.89

MPSTEAM flowrate at 1600 kg/h was selected since the increase of H₂ is only 0.01% for additional 100 kg/h of steam .

Table B.5: Equipment cost estimation for Gasification-H₂ system.

Item no.	Equipment	Reference	Base cost		Base Year	Size			Scale factor	Scaled cost (million £)	Present Year	Levelised cost (million £)
			million USD	million GBP		Base	Current	Unit				
1	Dryer	[4]	7.6	5.168	2001	33.5	2.55	wet t/h feed	0.8	0.66	2019	1.00
2	Gasifier	[4]	16.3	11.084	2001	68.8	1.87	dry t/h feed	0.65	1.06	2019	1.61
3	Cyclone	[4]	2.6	1.768	2001	34.2	4.78	m ³ /s gas input	0.7	0.45	2019	0.67
4	Acid gas removal	[4]	30	20.4	2001	74.1	0.05	m ³ /s gas input	1	0.01	2019	0.02
5	Water-gas shift reactor	[4]	36.9	25.092	2001	15.6	0.18	Mmol/h CO+H ₂ input	0.85	0.57	2019	0.86
6	Water removal unit (flash drum)	[12]	0.015	0.010	2002	3.168	5.70	t/h input	0.6	0.01	2019	0.02
7	Pressure swing adsorption column	[4]	28	19.04	2001	9600	272.46	kmol/h throughput	0.7	1.57	2019	2.38
8	Syngas compressor	[4]	11.1	7.548	2001	13.2	3.12	MW compression work	0.85	2.21	2019	3.35
9	H ₂ compressor	[4]	11.1	7.548	2001	13.2	0.19	MW compression work	0.85	0.20	2019	0.31
10	Heat exchanger (Feed preheater, HE1)	[12]	0.022	0.015	2002	2581	582.58	kW heat duty	0.6	0.01	2019	0.01
11	Heat exchanger (Syngas cooler, HE2)	[12]	0.022	0.015	2002	2581	2190.83	kW heat duty	0.6	0.01	2019	0.02
12	Heat exchanger (Syngas compressor inter/aftercooler, HE3)	[12]	0.022	0.015	2002	2581	4130.97	kW heat duty	0.6	0.02	2019	0.03
13	Heat exchanger (Cleaned syngas heater, HE4)	[12]	1.022	0.695	2002	2581	1293.10	kW heat duty	0.6	0.46	2019	0.69
14	Heat exchanger (WGS outlet gas cooler, HE5)	[12]	2.022	1.375	2002	2581	1737.39	kW heat duty	0.6	1.08	2019	1.63
15	Heat exchanger (H ₂ compressor inter/aftercooler, HE6)	[12]	3.022	2.055	2002	2581	156.18	kW heat duty	0.6	0.38	2019	0.58
16	Steam turbine and steam system	[4]	5.1	3.468	2001	10.3	1.79	MW electrical output	0.7	1.02	2019	1.54
TOTAL												14.71

Note:

1. Equipment costs for Gasification-H₂ system were obtained from [4] and [12].
2. CEPCI (2001) = 394.3; CEPCI (2002) = 395.6; CEPCI (2019, November Prelim.) = 596.1.
3. Currency conversion rate of 1 USD = 0.68 GBP (2001/2002) was assumed.

Table B.6: Lang factor for fluid processing system [4].

Component	Factor
<i>Direct cost</i>	
Delivered cost of equipment	1.00
Installation	0.47
Instrumentation and control	0.36
Piping	0.68
Electrical systems	0.11
Buildings (including services)	0.18
Yard improvements	0.10
Service facilities	0.70
Total direct cost	3.60
<i>Indirect cost</i>	
Engineering and supervision	0.33
Construction expenses	0.41
Legal expenses	0.04
Contractor's fee	0.22
Contingency	0.44
Total indirect cost	1.44
Working capital	0.89
Total capital investment	5.93

Table B.7: Variable operating cost for Gasification-H₂ system.

No	Specification	Quantity	Unit	Estimation	Unit	Note	Cost (million £/y)
1	Electricity	1517.94	kW	0.129	£/kWh	1	1.567
2	Catalyst					2	0.006
3	LO-CAT chemicals	0.00548	t/h	84.0	£/t sulphur	3	0.004
4	Gasifier bed materials	0.05547	t/h	96.8	£/t olivine	4	0.043
5	Solid disposal cost	0.47963	t/h	114.35	£/t (Ash)	5	0.439
6	Effluent discharge cost	2.1034	m ³ /h	0.629	£/m ³	6	0.011
	Total variable operating cost						2.07

Note:

1. Price of electricity was obtained from BEIS Quarterly Energy Price, March 2020 [9].
2. Costs of catalyst include ZnO and shift catalysts. It was assumed that both catalysts have a gas hourly space velocity (GHSV) of 4000 h⁻¹ and lifetime of 5 years and price of 8.24 £/kg (10.3 \$/kg) [12]. The densities of ZnO and shift catalysts are 1090 and 1300 kg/m³, respectively.
3. 1 mole of H₂S is equal to 1 mole of sulphur removed ($\text{H}_2\text{S} + 0.5 \text{O}_2 \rightarrow \text{H}_2\text{O} + \text{S}$). The cost of LO-CAT chemicals was estimated based on 84 £/t sulphur (150 \$/t sulphur) [12].
4. The olivine circulating rate in gasification was assumed to be 27 kg/kg dry feed and the fresh olivine was taken to be 0.11% of the circulating rate [12]. The price of olivine was assumed to be 96.8 £/t (172.9 \$/t) [12].
5. Ash from gasification was sent to landfill. Landfill gate fees and tax = 114.35 £/t [5].
6. Wastewater was sent to off-site treatment facility. The effluent discharge cost was estimated using Mogden formula based on the latest Trade Effluent Charge (2020/21) [13].

Table B.8: Fixed operating cost for Gasification-H₂ system [4].

No	Specification	Estimation	Unit	Cost (million £/y)
1	Maintenance	10%	indirect capital costs	0.25
2	Personnel	Table B.9		0.79
3	Laboratory costs	20%	personnel costs	0.16
4	Supervision	20%	personnel costs	0.16
5	Plant overheads	50%	personnel costs	0.40
6	Capital charges	10%	indirect capital costs	0.25
7	Insurance	1%	indirect capital costs	0.02
8	Local taxes	2%	indirect capital costs	0.05
9	Royalties	1%	indirect capital costs	0.02
	Direct production cost			4.17
10	Sales expense	20%	direct production cost	0.83
	General overheads			
	Research and developments			
	Total fixed operating costs			2.93

Note:

1. Indirect capital cost is 2.49 million/y (capital recovery factor = 0.117 assuming discount rate of 10% and plant life of 20 years).

Table B.9: Basis for estimating cost of personnel required in Gasification-H₂ system [4].

Parameter	Value	Note
Number of processing steps	4	Gasification; Gas cleaning and conditioning; PSA; utility systems
Number of personnel per processing steps	1	continuous, fluid processing
Number of personnel per shift	4	
Number of shifts	5	
Working hours per week	40	
Number of weeks per year	52	
Hourly wages (£/h)	19	(Average chemical engineer salary in the UK, https://www.payscale.com/research/UK/Job=Chemical_Engineer/Salary)
Cost of personnel (million £/y)	0.79	

The cost of personnel was estimated using Eq. (B.1).

$$\text{Cost of personnel} = \text{Number of personnel per shift} \times 5 \text{ shift} \times 40 \text{ hours/week} \times 52 \text{ weeks/year} \\ \times \text{hourly wages} \quad (\text{B.1})$$

where the number of personnel per shift is correlated with the number of processing steps depending on the nature of the process, given in Eq. (B.2).

$$\text{Number of personnel per shift} \\ = \text{number of processing steps} \times \text{number of personnel per processing step} \quad (\text{B.2})$$

Appendix C

Heat Integration and CHP Network for Gasification-H₂ System

Table C.1: Stream data and classification.

Heat exchanger/Process unit	Supply temperature, T_s (°C)	Target temperature, T_T (°C)	Heat duty, ΔH (kW)	Supply/Demand	Level of task	Task
HE2	900	80	2190.83	Supply	High	VHP steam generation
HE3	1351.27	50	4130.97	Supply	High	VHP steam generation
HE5	200	40	1737.39	Supply	Low-Medium	Process-to-process heat exchange (with HE1)
HE6	169.4	45	156.177	Supply	Low	Hot water generation
WGS	200	199.9	599.123	Supply	Medium	LP steam generation
HE1	25	110	582.577	Demand	Low	Process-to-process heat exchange (with HE5)
HE4	50	200	1293.1	Demand	Medium	Heated by MP steam

The stream data presented in Table C.1 was extracted from the flowsheet illustrated in Figure B.1, modelled in Aspen Plus. The heat supply and demand for each stream were classified into different level of tasks based on temperature and heat duties. The methodology for classifying the streams is presented in section 2.3.2.

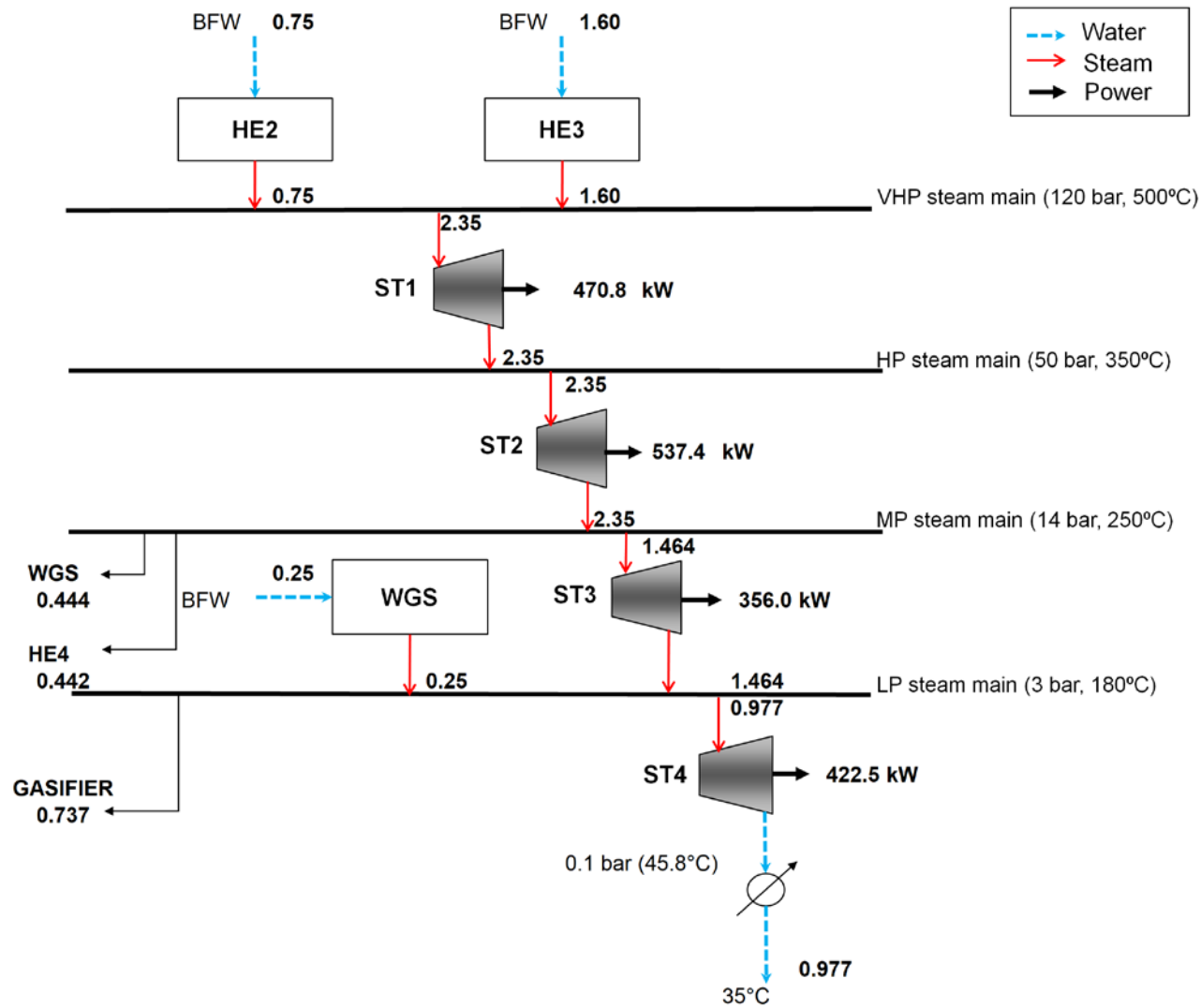


Figure C.1: CHP network design for Gasification-H₂ system.

Table C.2: Power balance of gasification-H₂ system.

Component	Turbine/compressor	Power (kW)	Power consumption/generation
ST1	Steam turbine	470.76	Generation
ST2	Steam turbine	537.40	Generation
ST3	Steam turbine	356.04	Generation
ST4	Steam turbine	422.46	Generation
SYNGCOMP	Compressor	-3117.36	Consumption
H2COMP	Compressor	-187.22	Consumption
		-1517.94	

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