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. Introduction

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

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

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

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

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

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- H_2 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- H_2 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.

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

2.2 Data collection

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

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

For MRF, equipment and variable operating cost data were collected from Pressley et al. [21] and WRAP report [40]. On the other hand, the equipment and variable operating cost data for Gasification-H₂ system were adopted from Sadhukhan et al. [38] and NREL report [28]. Lang factors for capital cost estimation and typical factors used for fixed operating cost estimation were obtained from Sadhukhan et al. [38]. The most recent gate fees for landfill and EfW and 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.

$$\frac{COST_{size2}}{COST_{size1}} = \left(\frac{SIZE_2}{SIZE_1} \right)^R \quad (1)$$

where

SIZE₁ is the capacity of the base system,

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

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

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

R is the scaling factor.

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

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

where

C_p is the present cost of equipment,

C_o is the original cost of equipment,

I_p is the present index value,

I_o is the original index value.

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

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

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

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

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

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- H_2 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- H_2 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

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

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

3.2 Material Recovery Facility (MRF)

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

3.2.1 Process description

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

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

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

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

3.2.2 Material and energy balances

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

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

	Subtotal		1.46	Subtotal		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.

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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)

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

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

3.3.2 Material and energy balances

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

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

Note:

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

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

1
2
3
4

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

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

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

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

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

(a)

Total equipment cost: 14.9 million £

(b)

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

Variable operating cost: 3.23 million £/y

(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.

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

4.2.2 Scenario 2: Increasing throughput to Gasification-H₂ system

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

Table 8: Economic analysis of Scenario 2 with increase of MRF rejected materials throughput into Gasification-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

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].

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

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⁾

Note:

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

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

MHSP estimated from the present study was also compared against the MHSP of other hydrogen production technologies obtained from IRENA report [24], including solar PV and wind powered electrolyzers, steam methane reforming (SMR) of natural gas with carbon capture and storage (CCS) and coal gasification with CCS as presented in

Table 10. The base case with lower throughput of MRF rejected materials (~2 dry t/h) has the highest MHSP among all cases, however a higher throughput (100 dry t/h) has the potential of reducing the MHSP to 2.23 £/kg which is competitive with “green” hydrogen generated from an average-cost solar PV powered electrolyser (i.e. 2.27 £/kg). Nevertheless, the MHSP for the waste-to-hydrogen system in the present study is difficult to compete with the conventional fossil-based SMR of natural gas (0.27-0.73 £/kg) and coal gasification (0.14-0.36 £/kg). As gathered from Scenario 2, the MHSP of the Gasification-H₂ case can be further reduced if hydrogen is produced from a large-scale system, i.e. greater than 100 dry t/h of rejected materials.

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

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

5. Conclusions

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

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

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