Supplementary Materials

Appendix A: MRF Material and Energy Balances and Cost Estimation

Appendix B: Gasification-H_2 System Material and Energy Balances and Cost Estimation

Appendix C: Heat Integration and Utility System for Gasification-H_2 System

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							

<u>Assumptions:</u>

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
Direct cost	
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**
Indirect cost	
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	Table A.8 - Table 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 Table A.9 - Table A.*12*.

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

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

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

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

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

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	
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.

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

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.

<u>Cost of personnel</u>

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**

<u>Note:</u>

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).

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

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).

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

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-H_2 System Material and Energy Balances and Cost Estimation

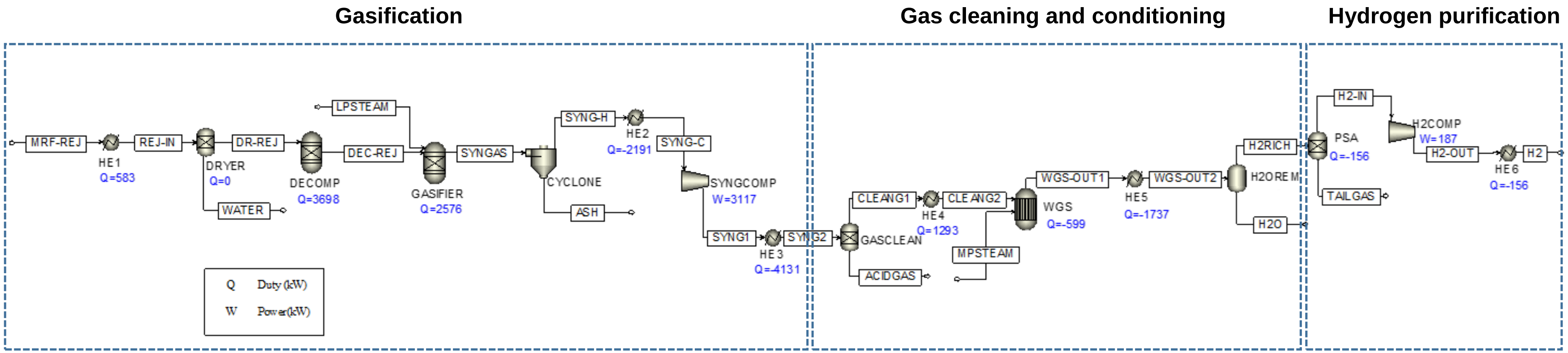

Figure B.1: Aspen Plus simulation flowsheet showing the conversion of MRF rejected materials into hydrogen through gasification system.

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.*2* 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, H_2, CO_2 and H_2O and a H_2/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 H_2S in the syngas (SYNG2) down to 1 ppmv (a split fraction of H_2S 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 H_2S only. The temperature of cleaned syngas (CLEANG1) is then increased to 200°C in HE4 before entering WGS. WGS reaction ($CO + H_2 \rightarrow H_2 + CO_2$), modelled using an equilibrium reactor (REquil) and operated at 200°C is served to increase the yield of H_2. 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 H_2 (H2-OUT) is maintained at 45°C through HE6 upon distribution (H2). The tail gas stream from PSA (TAILGAS) comprises mainly CO_2.

Table B.1: Aspen Plus model specification for Gasification-H_2 system.

Process Unit	**Block name**	**Aspen Plus Model**	**Temperature (°C)**	**Pressure (bar)**	**Other specification**
Dryer	DRYER	Sep			Split fraction; Stream DR-REJ *Substream (Mixed)* H_2O = 0.1 *Substream (NC)* 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_2O = 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_2S = 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 *Substream (Mixed)* 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	MPSTEAM	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
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	130.780	130.780	130.780	130.780	130.780	27.101	0.000	180.672	180.672
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
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	0.706	0.706	0.706	0.706	0.706	0.706	0.000	0.706	0.706
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
CO	0.000	0.000	50.411	50.411	0.000	0.000	0.001	0.001	0.001	0.000	0.519	0.000	0.000	0.000	0.000	50.411	50.411	50.411	50.411	50.411	0.519	0.000	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	23.249	23.249	23.249	23.249	23.249	73.065	0.000	73.140	73.140
H_2O	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	76.558	76.558	76.558	76.558	76.558	17.396	34.161	115.480	115.480
CH_4	0.000	0.000	0.032	0.032	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.000	0.032	0.032	0.032	0.032	0.032	0.032	0.000	0.032	0.032
H_2S	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	0.342	0.342	0.342	0.342	0.342	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
H_2	0.000	0.000	0.464	0.464	0.387	0.000	1.000	1.000	1.000	0.000	0.663	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
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
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	0.006	0.000	0.002	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
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	0.179	0.179	0.179	0.179	0.179	0.004	0.000	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	0.082	0.082	0.082	0.082	0.082	0.615	0.000	0.197	0.197
H_2O	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	0.271	0.271	0.271	0.271	0.271	0.146	1.000	0.312	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
H_2S	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	0.000	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
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	263.638	263.638	263.638	263.638	263.638	54.632	0.000	364.213	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
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	19.767	19.767	19.767	19.767	19.767	19.767	0.000	19.767	19.767
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
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	1412.024	1412.024	1412.024	1412.024	1412.024	14.534	0.000	14.548	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	1023.187	1023.187	1023.187	1023.187	1023.187	3215.573	0.000	3218.894	3218.894
H_2O	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	313.399	615.422	2080.399	2080.399
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	0.520	0.520
H_2S	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	0.000	0.000	0.000	0.000
Mass Fraction																								
C	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
H_2	0.000		0.064	0.064	0.078	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	0.015	0.000	0.064	0.064
O_2	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
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	0.005	0.005	0.005	0.005	0.005	0.005	0.000	0.003	0.003
S	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
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	0.344	0.344	0.344	0.344	0.344	0.004	0.000	0.003	0.003
CO_2	0.000		0.250	0.250	0.000	0.000	0.010	0.010	0.010	0.000	0.819	0.000	0.000	0.000	0.000	0.249	0.249	0.249	0.249	0.249	0.889	0.000	0.565	0.565
H_2O	0.000		0.337	0.337	0.047	1.000	0.000	0.000	0.000	1.000	0.080	1.000	1.000	1.000	1.000	0.336	0.336	0.336	0.336	0.336	0.087	1.000	0.365	0.365
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
H_2S	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	0.003	0.003	0.003	0.003	0.003	0.000	0.000	0.000	0.000
Total Flow (kmol/h)	0.342	0.000	281.736	281.736	146.379	3.796	153.645	153.645	153.645	98.086	272.464	147.295	88.814	37.957	37.957	282.078	282.078	282.078	282.078	282.078	118.819	34.161	370.549	370.549
Total Flow (kg/h)	11.672	0.000	4098.341	4098.341	1456.453	68.380	312.815	312.815	312.815	1767.103	3931.239	2653.560	1600.000	683.802	683.802	4110.013	4110.013	4110.013	4110.013	4110.013	3618.424	615.422	5698.341	5698.341
Total Flow (m^3/s)	0.000	0.000	0.052	0.101	0.549	0.033	0.017	0.052	0.023	0.001	1.944	0.001	0.073	0.000	0.329	2.268	4.778	0.324	0.052	4.778	0.771	0.296	0.132	1.944
Temperature (°C)	50		50	200	250	110	45	20	169.3927	40	40	133.5	250	25	110	80	900	1210.41	50	900	40	110	200	40
Pressure (bar)	30		30	30	1.6	1.013	70	20	70	1.013	1.013	3	14	1.013	1.013	1.013	1.6	30	30	1.6	1.013	1.013	30	1.013
Vapor Fraction	1.000		0.731	1.000	0.497	1.000	1.000	1.000	1.000	0.000	1.000	0.000	1.000	0.000	1.000	1.000	1.000	1.000	0.732	1.000	0.912	1.000	1.000	0.735
Liquid Fraction	0.000		0.269	0.000	0.503	0.000	0.000	0.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000	0.000	0.000	0.000	0.268	0.000	0.088	0.000	0.000	0.265
Solid Fraction	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
Substream: Non-conventional stream																								
Mass Flow (kg/h)																								
ASH	0.000	479.625	0.000	0.000	479.625	479.625	0.000	0.000	0.000	0.000	0.000	0.000	0.000	479.625	479.625	0.000	0.000	0.000	0.000	479.625	0.000	0.000	0.000	0.000
MSW	0.000	0.000	0.000	0.000	0.000	1388.073	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1388.073	1388.073	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mass Fraction																								
ASH	0.000	1.000	0.000	0.000	1.000	0.257	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.257	0.257	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000
MSW	0.000	0.000	0.000	0.000	0.000	0.743	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.743	0.743	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total Flow (kg/h)	0.000	479.625	0.000	0.000	479.625	1867.698	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1867.698	1867.698	0.000	0.000	0.000	0.000	479.625	0.000	0.000	0.000	0.000
Temperature (°C)		900			250	110								25	110					900				
Pressure (bar)	30	1.6	30	30	1.6	1.013	70	20	70	1.013	1.013	3	14	1.013	1.013	1.013		30	30	1.6	1.013	1.013		1.013
Vapor Fraction		0			0	0								0	0					0				
Liquid Fraction		0			0	0								0	0					0				
Solid Fraction		1			1	1								1	1					1				

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_2O	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 H_2 is only 0.01% for additional 100 kg/h of steam .

Table B.5: Equipment cost estimation for Gasification-H_2 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-H_2 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
Direct cost	
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**
Indirect cost	
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-H_2 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/m^3, respectively.

3. 1 mole of H_2S is equal to 1 mole of sulphur removed ($H_2S + 0.5\ O_2 \rightarrow H_2O + S$). 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-H_2 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-H_2 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-H_2 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.

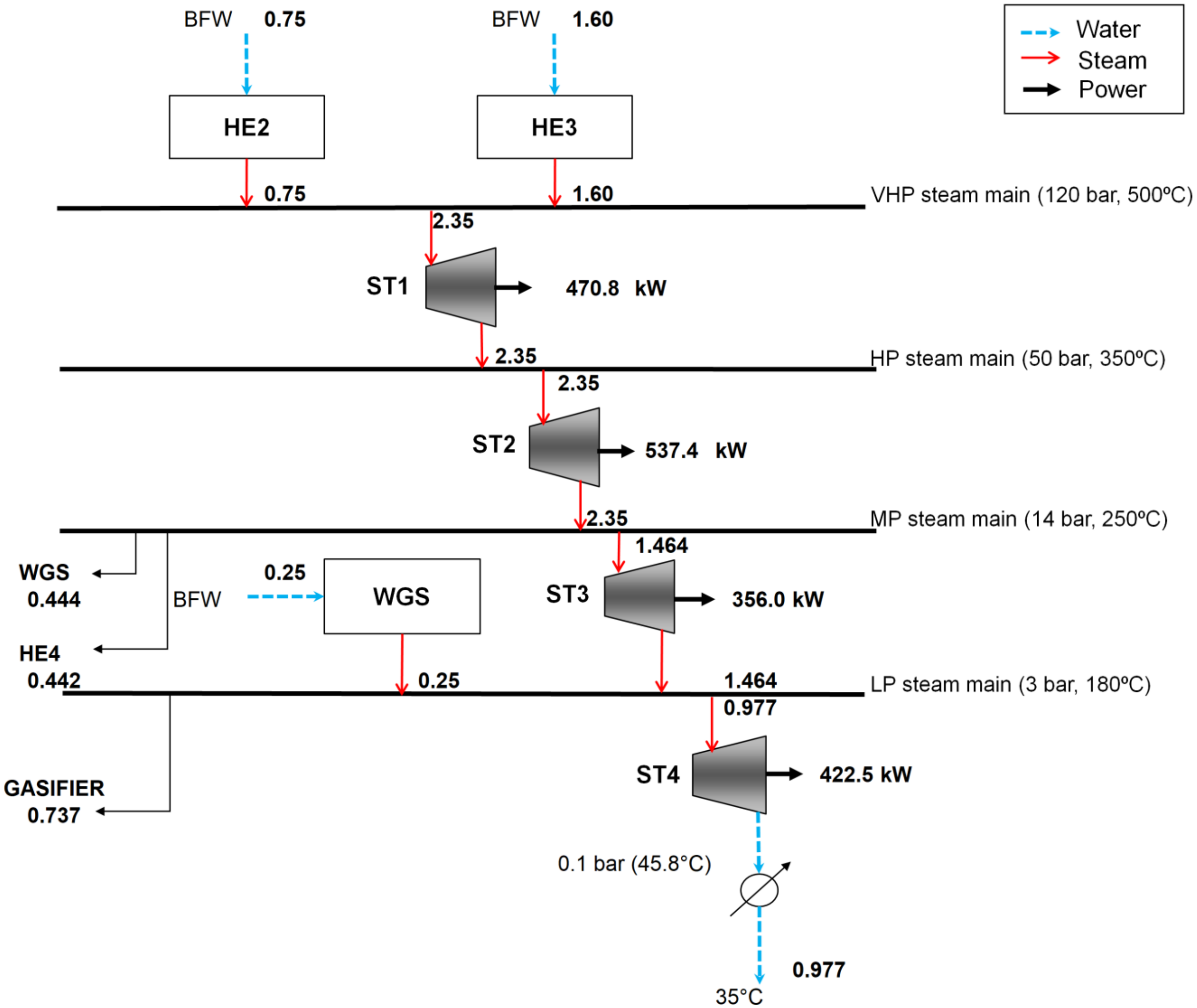

Figure C.1: CHP network design for Gasification-H_2 system.

Table C.2: Power balance of gasification-H_2 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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