DELIVERABLE D4.1

SYSTEM MODELS CONSIDERING COMPONENT OPERATING WINDOWS AND PLANT CHP OPERATING SCENARIOS

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GLOSSARY

AOG	Anode off-gas
BLAZE	Biomass Low cost Advanced Zero Emission small-to-medium scale integrated gasifier-fuel cell combined heat and power plant
C	Cooler
CHP	Combined heat and power
DBFBG	Double bubbling fluidised bed gasifier
DP	Pressure loss
FU	Fuel utilisation
GCU	Gas cleaning units
H	Heater
HEN	Heat exchanger network
HX	Heat exchanger
LHV	Lower heating value
LPG	Liquefied petroleum gas
PFD	Process flow diagram
RR	Recirculation ratio
SOFC LSM	Solid oxide fuel cell large stack module
VL	Vapour liquid

1 EXECUTIVE SUMMARY

BLAZE (Biomass Low cost Advanced Zero Emission small-to-medium scale integrated gasifier-fuel cell combined heat and power plant) aims at developing an innovative highly efficient and fuel flexible small and medium-scale biomass CHP (Combined Heat and Power generation) technology. This report summarises the work corresponding to T4.1. In Section 3, we point out the biomass types that has been selected in D2.1 to be used in the BLAZE plant. In Section 4, we summarise the relevant input regarding contaminants from D3.2. The BLAZE plant layout is described in Section 5, before explaining the operating windows in Section 6, the operating scenarios in Section 7, and the preliminary plant models and results, in Section 8.

The results show that the combined heat and power efficiency can go up to 70 % within the selected working conditions and layouts. The importance of selecting the most favourable operating conditions and layout for the (i) gasifier and the (ii) SOFC large stack module (LSM) individually is pointed out, as the system evaluation of different plant layouts show in fact similar final results. At system level, under the current hypotheses and pre-determined heat exchanger network (HEN), the best option is the process flow diagram (PFD) B (not only in terms of efficiency, but also in terms of layout simplicity compared with PFD F). However, note that the final results do not point out a “much better” and a “much worst” solution but, it can be said that, due to the trade-offs identified in terms of auxiliaries’ consumption, final temperatures, heating and cooling needs, the results of PFD’s B, D2 and F do not differ too much from each other (except for the layout and operating conditions differences).

2 INTRODUCTION

The BLAZE plant uses a double bubbling fluidised bed gasifier (DBFBG) and an SOFC large stack module (LSM) as main technologies. The DBFBG with inserted sorbent and catalysts can gasify biomass with high moisture content, low ash melting point, high tar, sulphur and chlorine contents. However, the properties of the produced ash at high temperature is relevant to the proper operation of the gasifier. Moreover, the SOFC LSM, even though its high working temperatures, has several restrictions regarding syngas contaminants. That is the reason why the gas cleaning units, between the DBFBG and the SOFC LSM, are particularly relevant. The purpose of the plant is to produce electricity from biomass waste, while being optimally integrated.

The BLAZE pilot plant uses an existing 100 kW_{th} DBFBG and the already tested SOFC LSM that delivers 25 kW_e. The modelling task developed within WP4 will support the needs of the pilot plant on the one side, and will perform the plant optimisation on the other side, dealing with different anode off-gas (AOG) recirculation options.

The combined heat and power generation (CHP) capacity of the plant is an important characteristic, since BLAZE plant design will consider the possible integration with specific heating demands of external units. The current deliverable set the basis for the modelling (WP4) and the experimental (WP5 and 6) work.

2.1 Objectives and scope of the document

The present document corresponds to Task 4.1 “Component operating windows and plant operating scenarios”, and its main purpose is to:

(i) summarise the spectrum of biomass feedstocks of interest for the BLAZE plant, together with the contaminants limits of the SOFC LSM,

(ii) define the operating windows for each one of the BLAZE plant units: gasifier, gas conditioning units, recirculator and SOFC, and

(iii) define the plant operating scenarios; i.e. based on different feedstocks and possible plant layout schemes.

The document is structured as follows: the first two sections summarise the relevant input for the current deliverable from D2.1 (Section 3) and D3.2 (Section 4). The BLAZE plant layout is described in Section 5, before explaining the operating windows in Section 6, the operating scenarios in Section 7, and the preliminary plant models and results, in Section 8. In the conclusions we summarise the main outcomes of this deliverable.

3 BIOMASS WASTE FEEDSTOCKS

The following section is a summary from D2.1, led by USGM.

After an exhaustive study of biomass characteristics:

- Specifications for gasification,
- availability at EU28,
- CHP potential,
- supply chain cost.

The authors selected 10 biomass types and 5 biomass mixtures representative of the most available European biomass species suitable for the BLAZE plant, based on 3 criteria: (i) biomass availability, (ii) biomass repartition per typology in terms of energy available, and (iii) biomass cost. The 15 samples were exhaustively characterised by their moisture content, proximate analysis, calorific value, ultimate analysis, major and minor metal elements, combustion parameters (ignition and burn-out temperatures), thermogravimetric properties, ash melting temperature (and process), and ash fouling tendency.

Considering not only the technical but also the economic aspects, the authors concluded that in order to proceed with the experimental tasks of the BLAZE plant, the selected biomass types are six:

- Secondary residues of industry utilising agricultural products: almond shell or similar.
- Wild crops and agricultural residues: Arundo donax, straw or similar.
- Primary residues from forest: sawmill waste and wood chips.
- Secondary residues from wood industry: swarf and sawdust.
- Waste from wood: multi-essence wood chips.

The following tables (Table 1 to Table 7) summarise the characteristics of the six specific biomass types selected, to be further used in WP4 and WP5 and 6.

Feedstock	Moisture content (%-wt, as received)	(%-wt, dry basis)			$MJ/kg_{feedstock}$, dry basis	
		Ash	VM	FC	HHV	LHV
Almond shells	10.0	1.31	80.35	18.33	19.02	17.68
Arundo donax	10.1	3.43	79.50	16.22	17.70	16.25
Sawmill waste	11.2	0.41	81.8	17.8	20.16	18.89
Wood chips	8.9	0.54	81.20	18.26	18.09	16.74
Swarf and sawdust	6.6	0.43	84.66	14.91	18.48	17.14
Multi-essence wood chips	24.5	1.45	81.50	17.05	19.14	17.88

Table 1. Moisture content, proximate analysis and calorific value of the biomass types selected (from D2.1).

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Feedstock	%-wt, dry basis					
	C	H	N	S	Cl	O
Almond shells	48.79	6.14	0.51	<0.01	<0.01	43.24
Arundo donax	45.05	6.17	0.55	0.11	0.29	44.40
Sawmill waste	49.40	5.84	0.43	<0.01	<0.01	43.92
Wood chips	45.81	5.85	0.1	<0.01	<0.01	47.69
Swarf and sawdust	47.07	6.15	0.1	<0.01	<0.01	46.24
Multi-essence wood chips	49.88	5.80	1.06	0.02	<0.01	41.79

Table 2. Ultimate analysis of the biomass types selected (from D2.1).

Feedstock	$mg/kg_{feedstock}$							
	Al	Ca	Fe	Mg	K	Si	Na	Ti
Almond shells	98.0	610.0	178.0	280.0	4100.0	2650.0	250.0	10.0
Arundo donax	74.3	1183.7	722.1	834.8	8965.0	8907.4	256.9	5.0
Sawmill waste	190.3	1181.5	112.1	222.2	498.0	150.4	53.3	33.0
Wood chips	6.2	830.6	<2	303.9	1030.5	56.9	43.0	<3
Swarf and sawdust	44.7	1181.4	4.5	342.3	860.8	101.6	56.5	<3
Multi-essence wood chips	58.3	5529.0	125.9	542.5	1694.0	872.6	133.8	<3

Table 3. Content of the major inorganic elements in the biomass types selected (from D2.1).

Feedstock	$mg/kg_{feedstock}$							
	Cd	Cr	Cu	Mn	Ni	Pb	V	Zn
Almond shells	<0.5	<2	5.1	56.2	<3	<3	7.8	18.9
Arundo donax	2.3	14.9	3.2	33.1	12.7	4.8	<3	107.8
Sawmill waste	<0.5	3.0	<3	35.5	1.0	3.8	<3	6.4
Wood chips	<0.5	<2	<3	1.8	0.4	<3	<3	2.9
Multi-essence wood chips	<0.5	6.3	12.0	7.2	3.8	5.3	3.2	22.4

Table 4. Content of the minor inorganic elements in the biomass types selected (from D2.1).

Feedstock	Combustion temperatures (°C)	
	T_i	$T_{burn\text{-}out}$
Almond shells	269.1	604.1
Arundo Donax	265.9	529.4
Sawmill waste	322.6	580.7
Wood chips	309.1	556.0
Swarf and sawdust	315.6	556.8
Multi-essence wood chips	297.4	517.7

Table 5. T_i (ignition temperature) and $T_{burn\text{-}out}$ for the biomass types selected (from D2.1).

Feedstock	Ash melting temperatures (°C)			
	SST	DT	HT	FT
Almond shells	915	1000	1180	1210
Arundo donax	1005	1185	1290	>1385
Sawmill waste	1250	1300	>1385	>1385
Wood chips	1110	>1385	>1385	>1385
Swarf and sawdust	1225	>1385	>1385	>1385
Multi-essence wood chips	1335	1370	>1385	>1385

Table 6. Characteristic ash melting temperatures for the biomass types selected; shrinkage starting temperature (SST), deformation temperature (DT), hemisphere temperature (HT) and flow temperature (FT) (from D2.1).

Feedstock	Fu	Tendency to fouling
Almond shells	47.0	High
Arundo donax	25.8	Medium
Sawmill waste	48.4	High
Wood chips	205.5	High
Swarf and sawdust	282.4	High
Multi-essence wood chips	85.3	High

Table 7. Fouling tendency for all the biomass types selected, with Fu being the index of fouling (from D2.1).

4 OPERATION OF SOFCS WITH CARBONACEOUS FUELS

The following section is a summary from D3.1, led by SP YV.

The syngas from biomass waste gasification has different proportions of CO, H_2, CO_2, H_2O and CH_4, and different amounts of impurities; in case of air gasification, N_2 is also present. The impurities in the produced gas directly derive from the biomass composition (ultimate analysis), the fraction and characteristic of the ashes and the inorganic elements, as well as from the specific process conditions to which the biomass is subjected. These are mainly lower hydrocarbons, tars, particulate matter (PM), sulphur compounds, halogen compounds, alkali metal species and nitrogen compounds. Char can also affect the SOFC longevity, thus affecting the anode microstructure and/or the nickel mesh.

Apart from the potential contaminants that may be present in the syngas composition and their impact, carbonaceous fuels used in SOFC systems may produce carbon deposition due to is CHO composition (in combination with steam). In general terms, the risk of carbon formation decreases with temperature, while H_2 and CO productions increase. The ternary diagram in Figure 1 represents the carbon deposition boundary at 750 °C. As example, it indicates that all the considered carbonaceous fuels fall in the carbon free region for this temperature, for an O/C equal to 2.

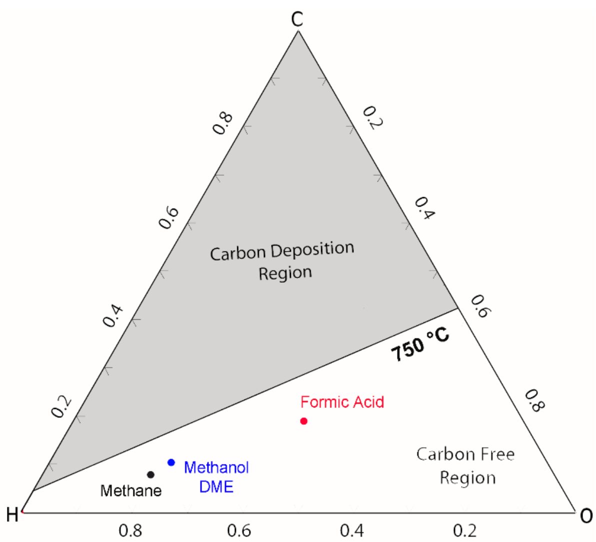

Figure 1. Equilibrium carbon deposition boundaries for the CHO system for 750 °C and O/C = 2, for different carbonaceous fuels (source: EU BALANCE project, D5.1).

Table 8 summarises the syngas relevant contaminants and their selected representative species for experimental work (WP3) and for modelling (WP4). In the table, we can also find the reference contaminants levels regarding SOFC tolerable levels or DBFBG expected values. The representative contaminants and levels come from an exhaustive literature search performed in D3.2.

- Slow tars (i.e. tars with slow conversion kinetics) are represented by naphthalene ($C_{10}H_8$). The investigated contaminant levels are in line with the literature values reported for experimental work on SOFC.
- Fast tars (i.e. tars with relatively fast conversion kinetics) are represented by toluene (C_7H_8). Tolerable toluene values for SOFC are less clear than for naphthalene, so the selected limits are from BFB steam gasifiers with catalytic filters.
- Sulphur compounds are represented by H_2S, and the limits correspond to those reported in literature for experimental work on SOFC.
- Halogen compounds and alkali metal species are represented by KCl, and the limits correspond to those reported in literature for experimental work on SOFC.

Contaminant	Represented by	Levels
Slow tars	$C_{10}H_8$	25 mg/Nm^3 (5 ppm) and 75 mg/Nm^3 (15 ppm)
Fast tars	C_7H_8	250 mg/Nm^3 (50 ppm) and 750 mg/Nm^3 (150 ppm)
Sulphur compounds	H_2S	1 ppm and 3 ppm
Halogen and alkali compounds	KCl	50 ppm and 200 ppm

Table 8. Representative tars and contaminants to be tested in the SOFC lab scale facilities and to be considered in the modelling task (from D3.2).

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5 BLAZE PLANT LAYOUT

The goal of BLAZE plant is to convert biomass waste at high efficiency into electrical and thermal energy. The plant is aimed to mainly work at nominal conditions (maximum power), even though other conditions may be desirable and possible, in the case the BLAZE plant is used as a flexible plant supporting grid balancing. The DBFBG produces a relatively clean syngas with a high calorific value, at high temperature. The SOFC LSM works at high temperatures as well. The connection among both main units can be made at high temperatures; however, as seen in the previous section, the syngas stream after the gasifier will have to be cooled down to the gas cleaning units (GCU) temperature, which are important to secure the long lasting functioning of the fuel cell. BLAZE plant combines components from already known technologies (gasification, hot gas cleaning and conditioning and SOFC) with more novel concepts, like the anode off-gas (AOG) recirculator (which has been tested in a pilot plant of 6 kW_e produced by a SOFC stack from SP YV).

The project benefits from already existing facilities, the DBFBG of 100 kW_{th}, and from the experience gained at SP YV during the execution of the EU CH2P project in the conception and construction of a 25 kW_e SOFC LSM. The syngas produced excesses the SOFC LSM needs; therefore, the syngas that is not used in the SOFC LSM will be burnt (in the pilot plant). Figure 2 summarises the BLAZE plant concept: different biomass waste types feed the gasifier, producing the syngas that is sent to the GCU or to the burner. The cleaned syngas goes to the SOFC LSM. After this unit, the AOG recirculator sends a fraction of AOG to the gasifier or to the SOFC LSM inlet. Both, the gasifier and the recirculator need steam. This steam is generated within the plant and, if excess heat is still available, it can be provided to agricultural or industrial partners, or building. Flue gases, AOG and syngas, are the heat sources. Steam, syngas and inlet air are the heat sinks.

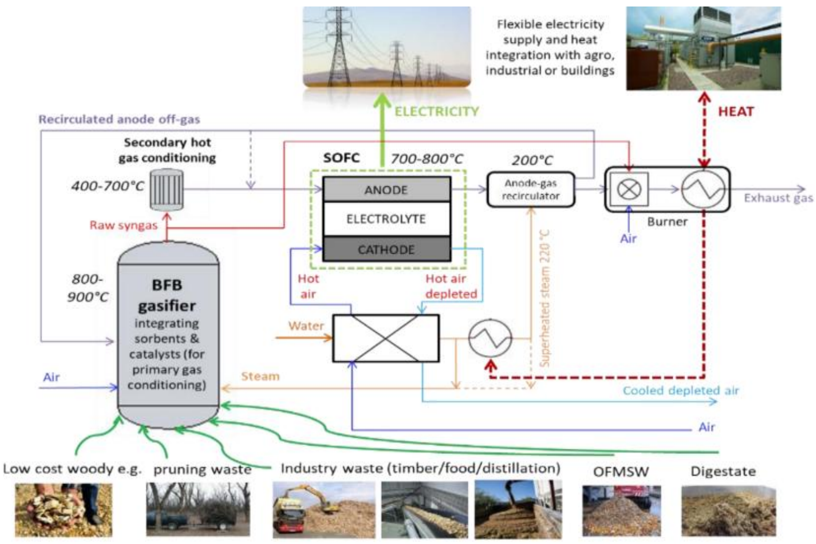

Figure 2. BLAZE plant concept.

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The nominal conditions of the BLAZE plant are:

- Biomass type: hazelnut shell
- Gasification temperature: 850 °C
- Steam to biomass ration (S/B) = 0.5
- Fuel utilisation (FU) = 0.6
- To produce around 25 kW_e in the SOFC LSM.

The 100 kW_{th} DFBFG produces approximately 30 kg/h of syngas (~20 kg/h of biomass + ~10 kg/h of steam). About half of the syngas produced by the gasifier will be sent to the SOFC LSM to produce electricity.

The BLAZE consortium has decided to divide the modelling work into two lines, given the several plant configurations (see the different options in Figure 7):

- Pilot plant modelling support (Tasks 4.1, 4.2 and 4.3). The BLAZE consortium will implement one of the options, selected after the first preliminary calculations and commercial research, taking into account efficiency, cost and reliability.
- BLAZE plant optimisation (Tasks 4.2 and 4.5), matching SOFC LSM and gasifier scales, taking into account all the possible layout options (superstructure and variables).

All the reported pressure values in this deliverable, refer to absolute pressure in bar(a).

5.1 Specific unit's characteristics

In Section 4 we described the SOFC LSM needs and concerns regarding contaminants and carbon deposition. This directly affects the BLAZE plant layout (i.e. GCU selection; Cl removal unit, S removal unit, and a –gasifier- external tar reformer). In the following paragraphs, the specific characteristics of the gasifier and the AOG recirculator are pointed out, as they influence the decisions taken in the definition of the BLAZE layout(s) or BLAZE plant process flow diagrams (PFDs).

The gasifier is a DFBFG, as described in Figure 3. Not represented in the figure, the unit includes an in-bed gas cleaning step using calcined dolomite, and the catalytic filter candles at the outlet. The dual fluidised bed is also called indirectly heated steam gasifier, biomass steam reformer or allothermal gasifier. In such gasifier, steam gasification is separated from combustion. In the combustor, residual char from gasification and liquefied petroleum gas (LPG) are burnt to meet the gasification thermal needs. The heat is transferred from the combustion to the gasification reactor by a sand bed, which acts as heat carrier (for instance, olivine). A flue gas is produced in the combustor, acting as a heat source. The current configuration of the DFBFG counts with a steam generator fuelled by LPG (producing up to

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20 kg/h of steam). The steam is superheated before entering the gasifier. Two of the purposes of the BLAZE plant are:

- Decrease LPG consumption by recycling AOG towards the (i) combustor or towards the (ii) gasifier.
- Decrease LPG consumption by increasing the steam produced in the BLAZE plant via an optimum heat integration.

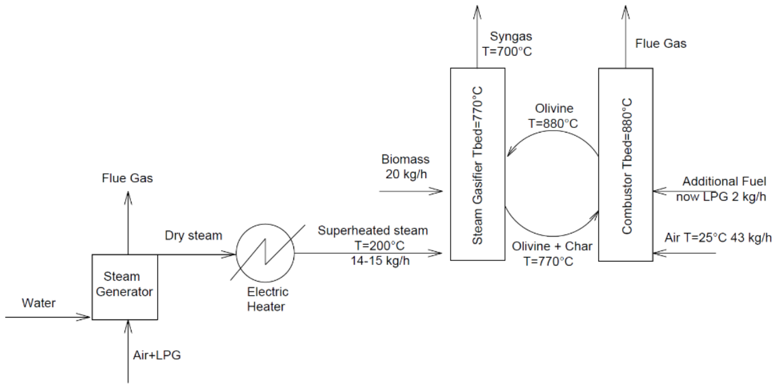

Figure 3. Detail of the DFBFG (provided by UNIVAQ).

Regarding the syngas split after the gasifier and the filter candles, to match SOFC LSM syngas demand, a system has been designed (Figure 4). It comes with:

- A flow meter in the excess syngas stream that goes to the burner (operating at ~400 °C).
- A gate valve after the filter candles.
- A flow meter after the GCU (operating at ~400 °C).
- A fan before the SOFC LSM (see the discussion in next section).

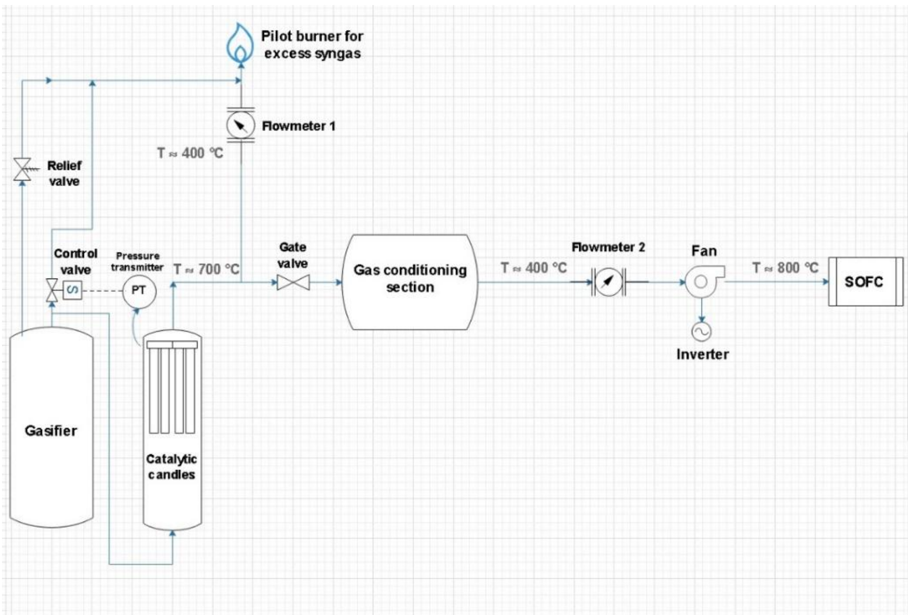

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Figure 4. Detail of the syngas split (provided by USGM).

An AOG recirculator has been identified as a promising option to increase the overall BLAZE system efficiency, by recycling the AOG, which (i) is rich in steam and (ii) has a calorific value (it contains H_2 an CO that has not reacted in the SOFC LSM). The AOG recirculator has been proven to work at 200 – 300 °C (in a SOFC system using methane as feedstock, using the AOG recirculator to provide the needed steam in the reformer [1]). The recirculator allows the recycling of a stream at a high temperature, and the recycling of steam without water condensation, all oil free. Figure 5 shows the block diagram of the pilot plant built at EPFL LAMD. Note that the AOG recirculator fan is powered by a turbine that works with generated steam from waste heat in the system. The same approach is followed in the BLAZE plant.

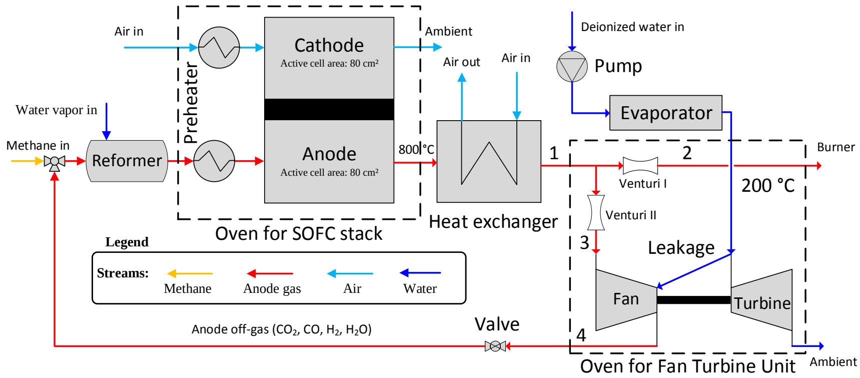

Figure 5. Recirculator integrated for a 6 kW_e stack with natural gas as feedstock (provided by EPFL LAMD).

5.2 Pressure loss along the flowsheet

To design the AOG recirculator and the compression strategy of the syngas line, the pressure losses are crucial. Table 9 summarises the estimated pressure losses through the main BLAZE plant units (pressure loss along heat exchangers are mainly disregarded). A stream circulating through the gasifier + filter candles, the GCU and the SOFC LSM, would have a pressure loss of 250 mbar. See in Figure 6 an overview of the pressure loss along a simplified BLAZE plant flowsheet, and thus what the maximum compression value that the AOG recirculator has to handle is. Note that in the configuration proposed, the gasifier works under pressure.

Unit	ΔP (mbar)
Gasifier + filter candles	100
GCU	120
SOFC LSM anode	30
SOFC LSM cathode	45
Gasifier combustor	100
Downstream combustor	30-50
VL separator	20

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AOG heater	10

Table 9. Pressure loss along the flowsheet, per unit.

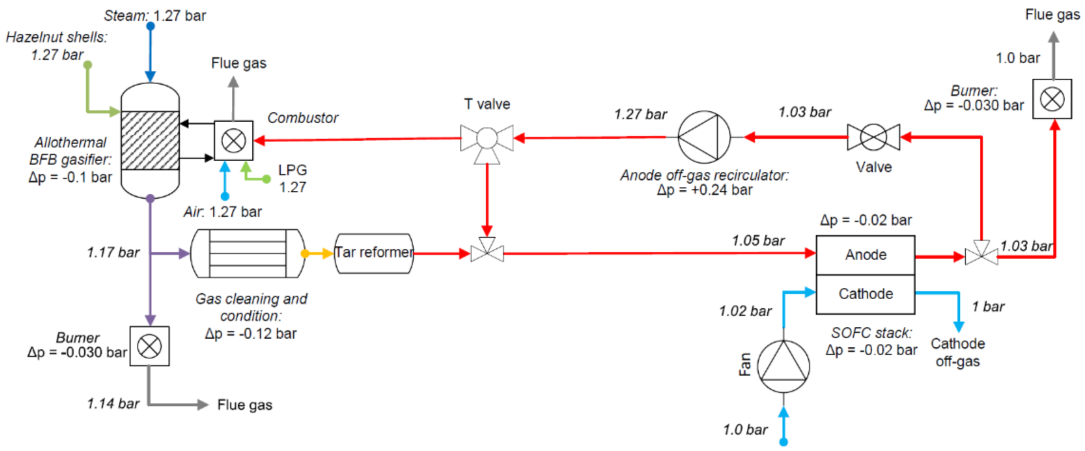

Figure 6. Example of calculation of the pressure drop / rise along the relevant BLAZE plant streams, considering a pressurised gasifier (provided by EPFL LAMD).

The SOFC LSM and the gasifier have pressure limitations. In the SOFC LSM the anode pressure should always be above the cathode pressure, in a range of 5 – 30 mbar. The maximum absolute pressure that the cathode can tolerate is 1.09 bar. The air and steam streams enter the gasifier (combustion and gasification chambers, respectively) at 1.07 bar in the existing DBFBG. At higher inlet pressures (which can be obtained in the existing plant, as the air line is at 7 bar, and the steam generator produces steam up to 6 bar), some of the inner hot gas can flow back in the screw feeder, pyrolysing inlet biomass in the screw. In order to avoid this phenomenon, nitrogen can be fed in the screw. Moreover, a specific high pressure screw feeding system should be bought or built for that purpose.

5.3 Process flow diagrams (PFDs)

The current section describes in more detail the different layouts of the BLAZE plant (pilot plant and modelling and optimization task) proposed till the date.

According to the main places where the AOG can be recirculated, the PFD in Figure 7 points out recirculation options A, B and C. The gasification unit consists of the gasifier, the combustor that provides heat for gasification, and the catalytic candles. Biomass waste and steam are fed to the gasifier. The excess syngas is sent to the flare. The main syngas stream moves towards the GCU, after cooling, where different units intervene to remove Cl compounds, S compounds and tars. The clean syngas is then preheated to the required SOFC LSM inlet temperature. The air supply to the gasifier and the fuel cell is controlled by two blowers; both streams are preheated to the desired gasification and fuel cell temperatures. The temperature gradient across the SOFC module is a critical design parameter which is tightly controlled. This determines the mass flow rate of the cathodic air. The cathode outlet stream is sent to the AOG burner. The AOG is separated into two streams: one goes to the burner (to fulfil at least plant heating/steam needs) and the other one is cooled to the temperature required by the AOG recirculator, and it can be either injected at the anode inlet stream (Option A), at the combustion chamber of the gasifier (Option B) or at the gasification chamber of the gasifier (Option C).

Option A is seen as a promising configuration that can increase the efficiency of the overall BLAZE plant (by producing more electricity with the same inlet amount of biomass) and by increasing the global FU of the SOFC LSM (considering recirculation), by keeping local FU at 0.6 (single pass, without considering recirculation). On the other side, there is a risk of contaminants deposition at the anode side, and a decrease of the inlet anode gas calorific value, as the inlet gas (H_2, CO, CO_2, H_2O) is diluted with the AOG (with less fraction of H_2 and CO and more fraction of H_2O and CO_2).

Option B has the potential to decrease the LPG consumption. However, the calorific value of the AOG is lower than the calorific value of the LPG (~3 MJ/kg vs ~46 MJ/kg).

Option C has the potential to decrease external steam needs, thus, LPG consumption. Nevertheless, gasification efficiency may be affected (as we are not only injective steam, but also H_2, CO and CO_2).

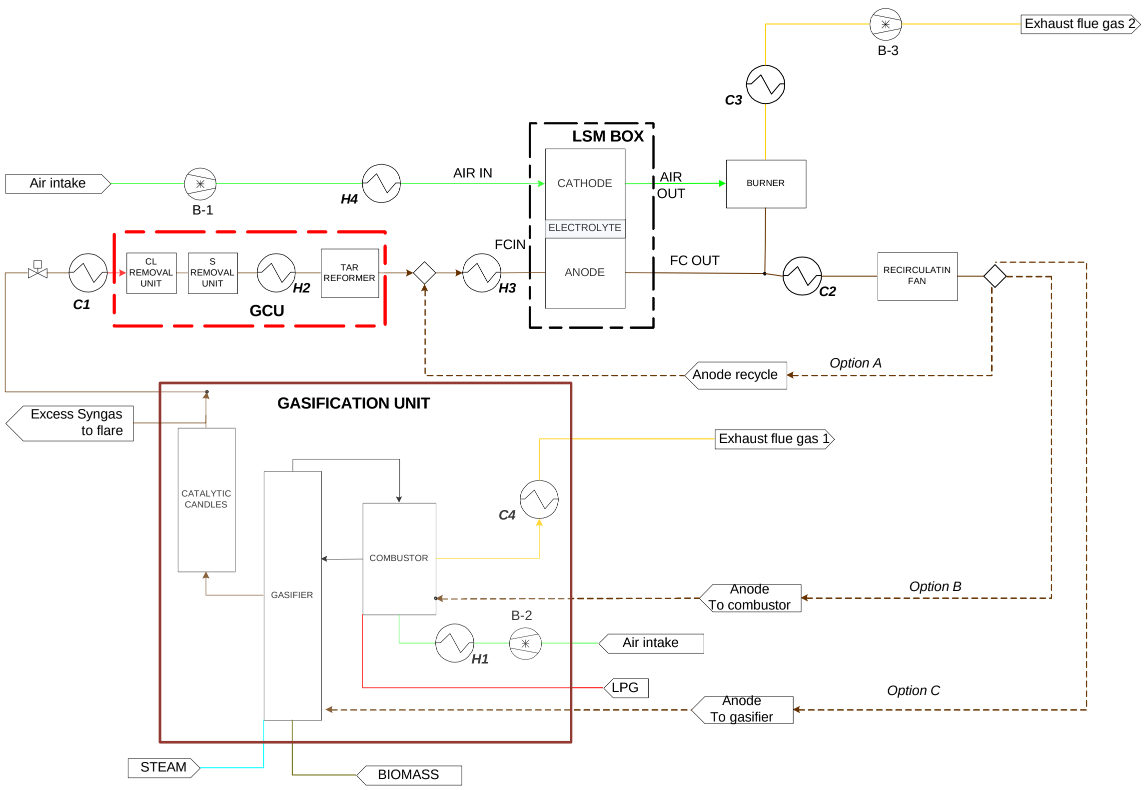

Figure 7. Process flow diagram of the BLAZE plant prototype system, showing the multiple recirculation options A, B and C (provided by HyGear, modified by EPFL GEM). C: cooler; H: heater.

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More specifically, the pressure loss along the flowsheet, drives the pressure increase of the recirculation fan. The SOFC LSM has to operate above atmospheric pressure; thus, the pressure loss of the gasification unit and the GCU have to be overcome in the anode inlet stream. Looking at the pressure issue, the BLAZE consortium has had further discussions about the experimental plant layout. Figure 8 is a step forward towards the realisation of the BLAZE pilot plant. Three options are possible. With the aim of decreasing uncertainty in the results, Option C is not considered in the following plant layouts.

Options 1 and 2 make use of the AOG recirculator that sends AOG towards the anode inlet or towards the combustion chamber in the gasifier. The two recirculation options can be inspected during the experimental work by the use of a high temperature T-valve, which can change the recirculation configuration during the operation of the plant. In Option 1, the pressure is provided by a commercial high temperature blower before the GCU, and in Option 2, the pressure is provided by a pressurised gasification step, feeding biomass with nitrogen or by means of a pressurised screw.

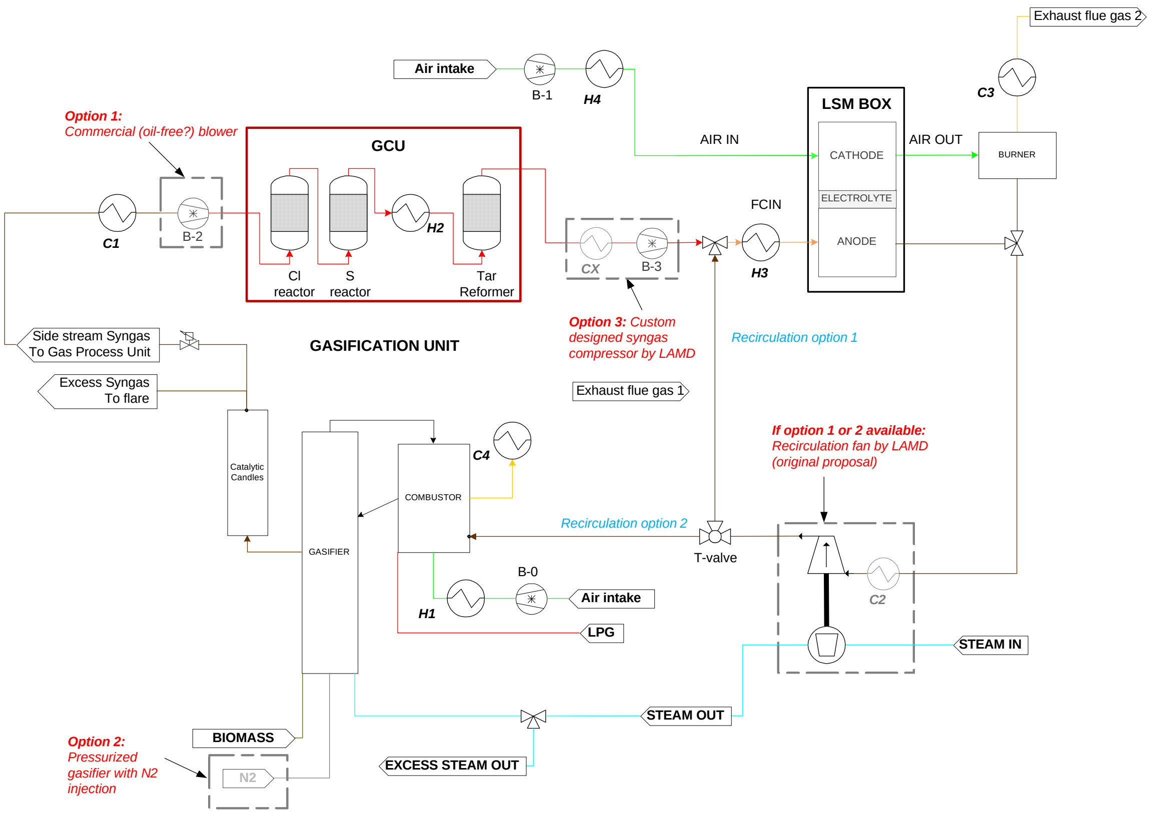

Figure 8. Process flow diagram of the BLAZE pilot plant, showing the recirculation options 1 and 2 and the possible custom designed compressor (option 3) (provided by HyGear, modified by EPFL LAMD). C: cooler; H: heater.

Option 3 counts with a custom designed syngas compressor, which adequately increases the pressure after the GCU, oil-free. If not using a pressurised gasifier, this option implies working slightly below atmospheric pressure in the GCU (with the subsequent risk of air entering in the gas cleaning equipment). This option would not implement the AOG recirculation, and thus will avoid the uncertainties related to contaminants deposition and LSM operation. However, it implies a larger use of steam in the syngas compressor, compared with options 1 and 2, due to a higher pressure drop to overcome and to a potentially larger flow to move. Steam consumption may vary between 80 kg/h, and 25 and 56 kg/h, for options 3, 1 and 2 (and a recirculation ratio – RR- of 0.6), respectively.

Observe in Figure 8 a proposal of steam integration between the turbine of the recirculator and the gasifier: in the pilot plant, the existing steam generator in the gasifier can be used to provide steam at about 5 bar to the turbine which, once expanded, can be sent to the gasifier. Alternatively, steam can be generated via process heat integration (which is indeed the long term solution). Options 1 and 2 lead to a lower steam demand (thus lower external heat consumption) increasing the heat efficiency of the overall system. However, steam consumption of the recirculator turbine and the gasifier has to be linked (with the consequent increase of complexity and dependency). This implies a functional range of recirculation ratios and FU. After further discussion among the members of the BLAZE consortium, Option 3, due to its considerably large steam consumption (around 80 kg/h, when the amount of steam needed in the gasifier is in the order of 10 kg/h), is not considered for further analysis.

In the next step, seven PFD's were proposed (PFD's from A to G, Figures 9 to 12), taking into account the combination of:

- Gasifier pressurisation / use of a downstream gasifier suction blower
- Use of the recirculator
- Recirculation points
- Use of a downstream burner.

A preliminary heat exchanger network has been proposed by HyGear and agreed by SP YV, in terms of convenience for control during operation and during system start-up (see HX1, HX2, HX3 and HX4 in Figures 9 to 12).

- HX1 and HX4 recover heat from the hot air (cathode outlet) and the hot AOG (anode outlet), back into the cold air and cold inlet syngas to the SOFC LSM.
- HX2 and HX3 provide additional heat to the inlet air and syngas to the SOFC LSM. The heat comes from the gasifier combustor flue gas. These exchangers are appropriate to be used during the SOFC LSM start-up, and to keep the SOFC LSM in a hot stand-by condition, if needed.
- A parallel configuration is selected (instead of an in-series configuration in the flue gas stream) because of the easiness to control temperature via a low/medium temperature valve downstream each heat exchanger.
- HX2 and HX3 might not be needed during operation at full power; in this case, the low/medium temperature valve downstream each heat exchanger, ca be closed.

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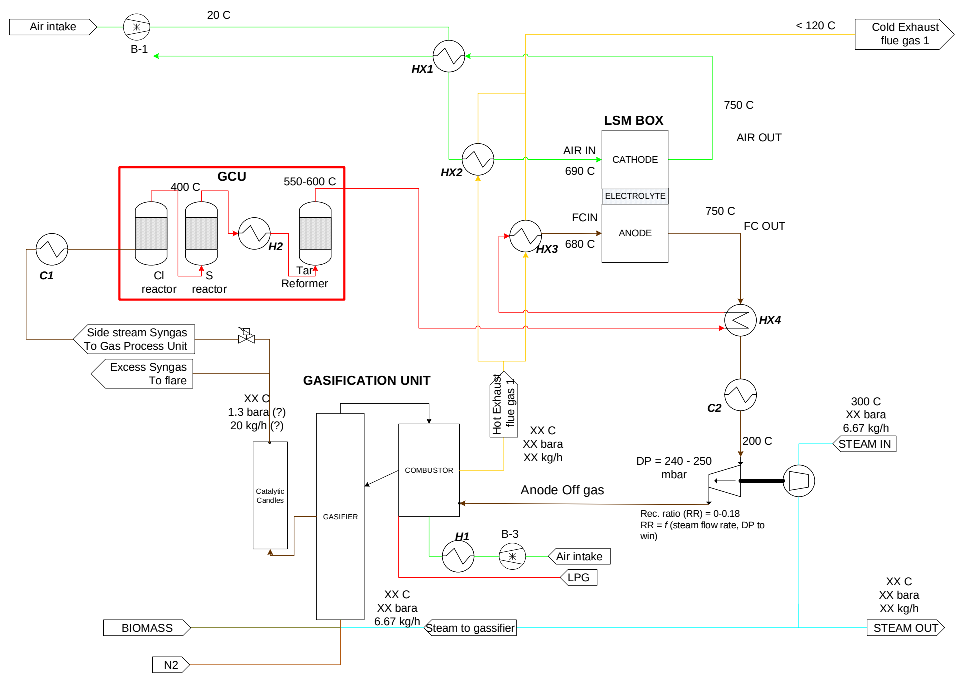

Figure 9. Option A process flow diagram of the BLAZE pilot plant, with a pressurised gasifier. Option E is analogous; instead of using a pressurised gasifier, it counts with a suction blower B2, after C1. All the AOG is sent to the gasifier combustor (provided by HyGear, modified by EPFL LAMD). C: cooler; H: heater.

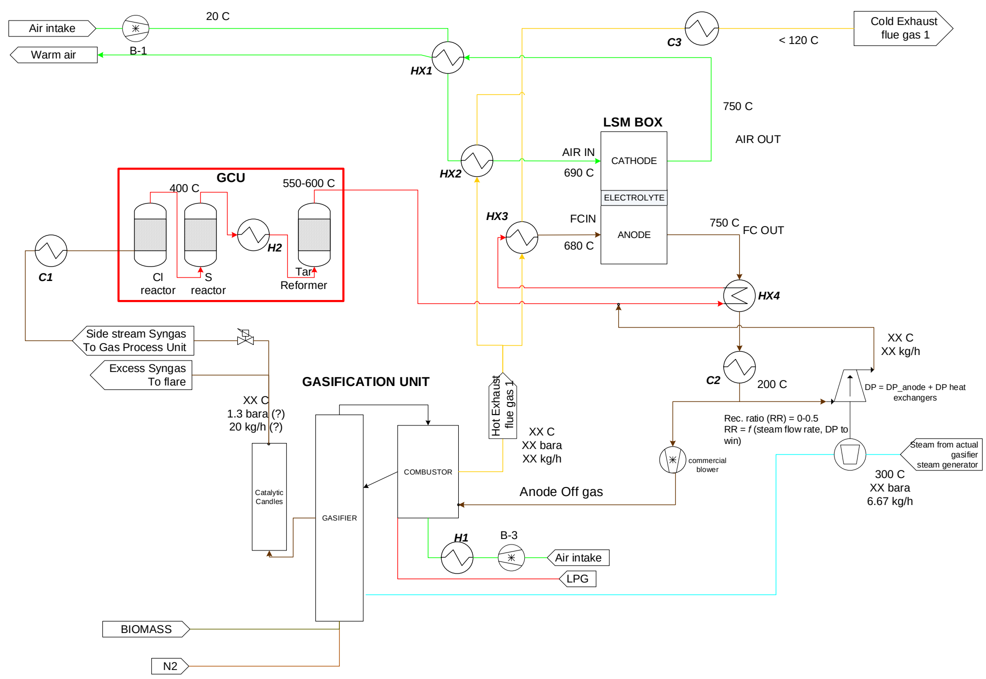

Figure 10. Option B process flow diagram of the BLAZE pilot plant, with a pressurised gasifier. Option F is analogous; instead of using a pressurised gasifier, it counts with a suction blower B2, after C1. The AOG is sent to the gasifier combustor and to the SOFC LSM inlet stream (RR = 0.5) (provided by HyGear, modified by EPFL LAMD). C: cooler; H: heater.

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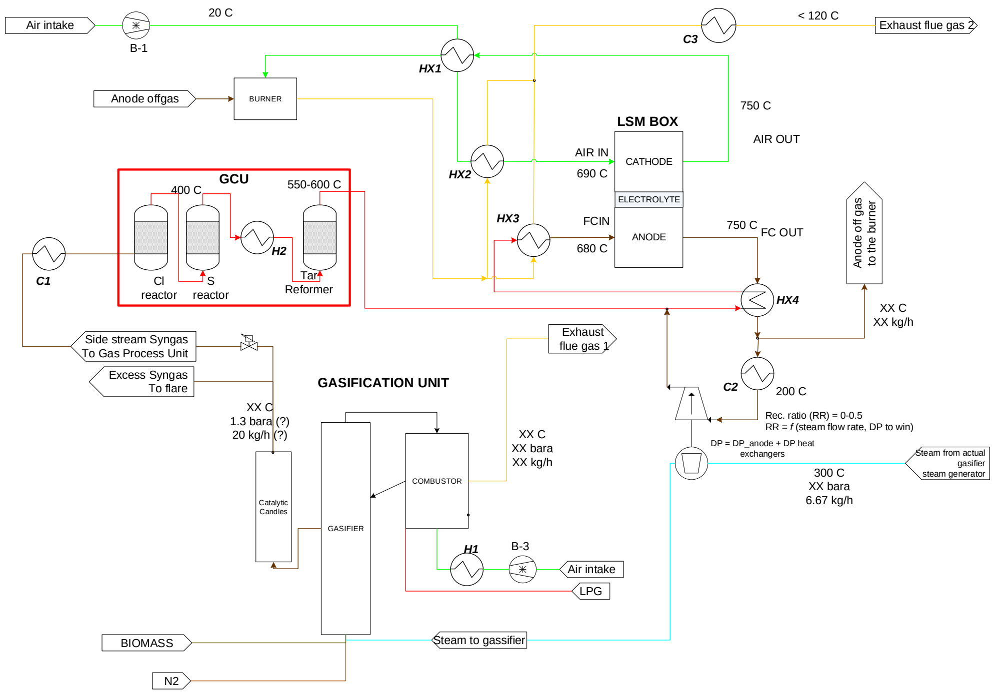

Figure 11. Option C process flow diagram of the BLAZE pilot plant, with a pressurised gasifier. Option G is analogous; instead of using a pressurised gasifier, it counts with a suction blower B2, after C1. The AOG is sent to the SOFC LSM inlet stream (RR = 0.5) and the rest is burnt in a downstream burner (provided by HyGear, modified by EPFL LAMD). C: cooler; H: heater.

The selected PFD's for further analysis are: PFD's B, D and F. The reasons to select these are:

- As with the previous set of PFD's, one priority is to minimise the consumption of steam in the turbine of the recirculator, while keeping it in the range of the gasifier needs. Among all the possible options, PFD's A and E propose to recirculate all the AOG towards the combustor, thus consuming the largest amount of steam. Preliminary calculations show that in order to be in the range of the 10 kg/h of steam consumed by the 100 kW_{th} gasifier, the RR is ~0.18 in PFD A, and ~0.42 in PFD E.
- Following as well the premise of keeping as simple as possible layout, PFD's C and G are not selected, as they need a SOFC LSM downstream extra burner. This premise is valid under the assumption that the gasifier burner can be easily adapted to accept AOG (decreasing the use of LPG).

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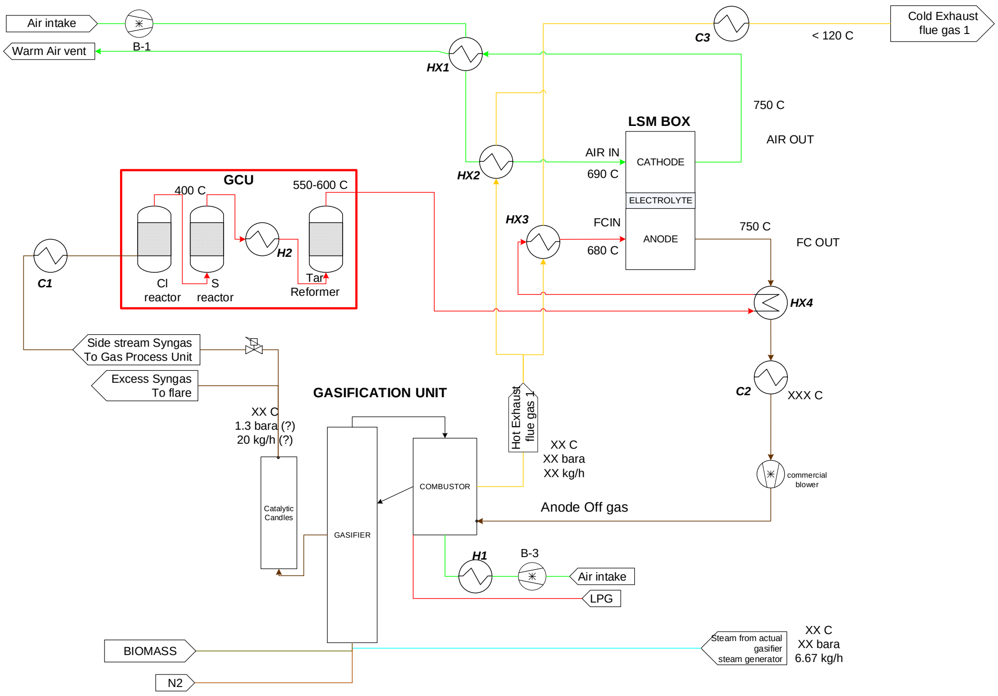

Figure 12. Option D process flow diagram of the BLAZE pilot plant, with a pressurised gasifier. The AOG is exclusively burnt into the gasifier combustor. The recirculator is not used (provided by HyGear, modified by EPFL LAMD). C: cooler; H: heater.

PFD's B, D and F (Figures 13, 14 and 15) present the following characteristics:

- PFD B and F have a smaller recirculator design, with a RR ~0.5 which corresponds to ~6.67 kg/h of steam (lower than 10 kg/h), which is the estimated steam that could be consumed in a gasifier with a size matched to fulfil the requirements of the SOFC LSM.
- The difference among PFD option B and F is the use of N_2 (with the subsequent upstream equipment) or a pressurised screw for gasifier pressurisation. In the second option, a small amount of N_2 in the syngas, ~ 5 % in mole basis, would be expected, which is anticipated to have an impact in the SOFC LSM (i.e. effect of contaminants dilution). In option F, the suction blower is placed after the GCU (after a market research, the working temperature of commercial blowers is ~200 °C).
- PFD D is the simplest configuration. All the AOG is sent towards the gasifier combustor, decreasing the need of LPG. The recirculator is not used; this PFD aims at pointing out the benefits of the recirculator, from a system point of view.
- The recirculator layout has a heat exchanger (C2) that decreases the temperature down to 50 °C to allow for water condensation in a vapour-liquid (VL) separator. The AOG is then separated. The recirculated stream towards the gasifier combustor uses a commercial blower to adequately adapt the pressure. The stream that goes to the SOFC LSM is heated up via H3

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(200 °C) to be compressed in the recirculator fan. This temperature is needed to avoid steam condensation (and thus gas bearings blockage) in the turbine expansion. The condensation of steam in the AOG stream decreases the demand of steam in the turbine; note now that for a RR=0.5, the steam flow needed in the turbine is lower than the abovementioned value of 6.67 kg/h (steam should be added in the gasifier).

- First simulations of the SOFC performance with a discretised stack model pointed out the benefit of <u>steam condensation in the case of AOG recirculation</u> (as steam is not needed internally for steam reforming, for example, and therefore it lowers the Nernst potential). Indeed, the efficiency of the stack is lower with AOG recirculation and without steam condensation, compared with a single pass, by 3.2 % (global FU = 0.75 and RR = 0.5, compared with global FU = 0.75 and RR = 0). This penalisation can be lowered up to 1.2 % if water is condensed (50 °C).

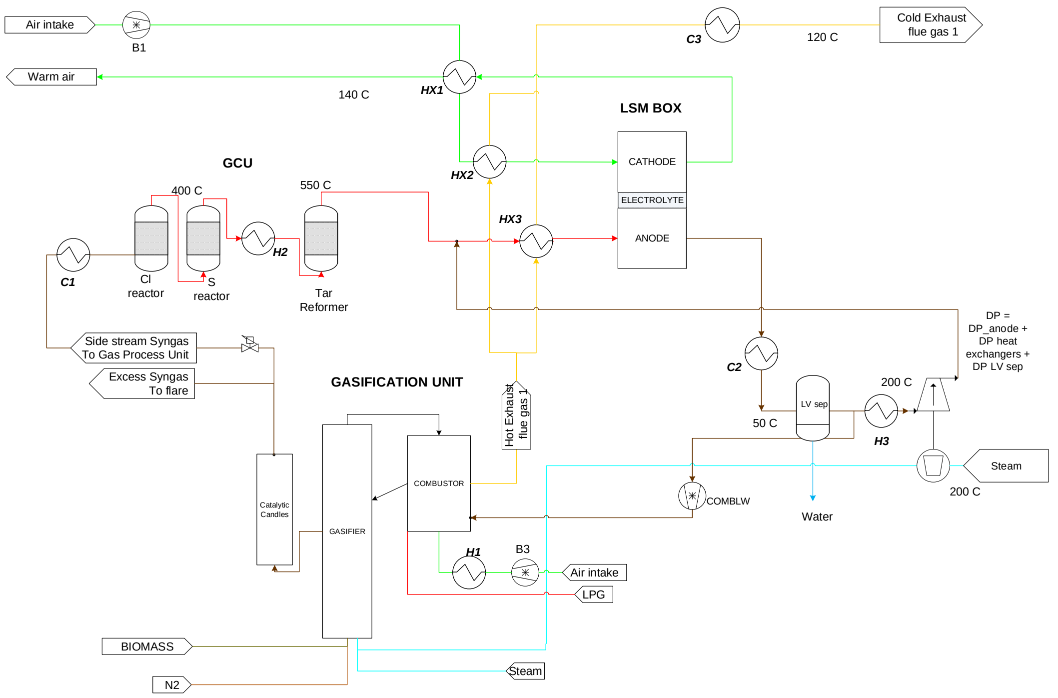

Figure 13. Option B process flow diagram of the BLAZE pilot plant. The AOG is sent to the SOFC LSM inlet stream (RR = 0.5) and the rest is burnt in the gasifier combustor. The recirculator condenses water before recycling (provided by HyGear, modified by EPFL LAMD and GEM). C: cooler; H: heater.

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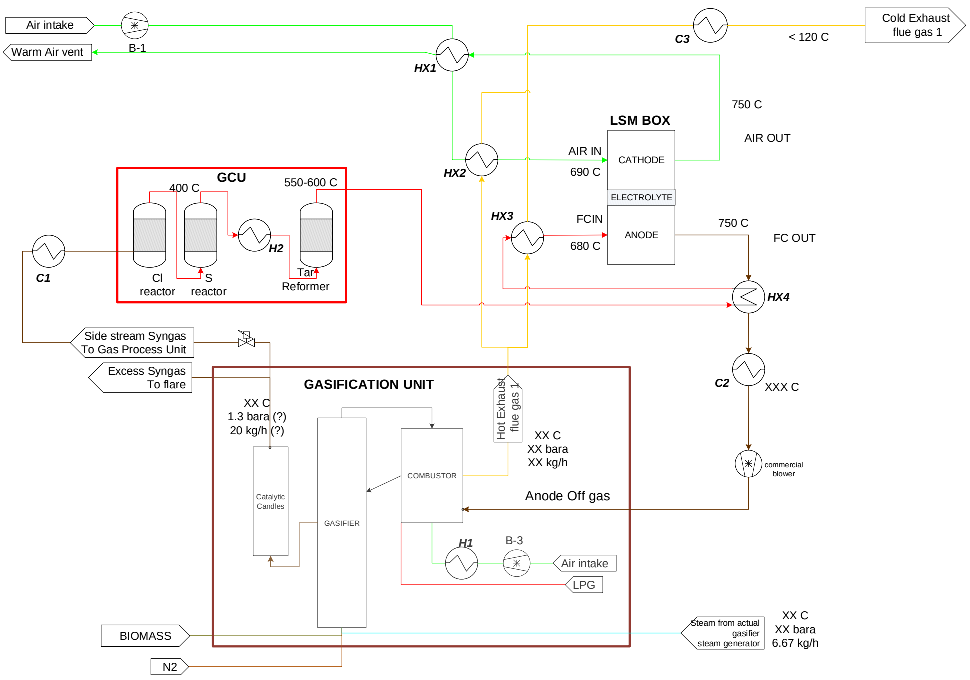

Figure 14. Option D process flow diagram of the BLAZE pilot plant. The AOG is sent to the gasifier combustor. The recirculator is not used (provided by HyGear, modified by EPFL LAMD and GEM). C: cooler; H: heater.

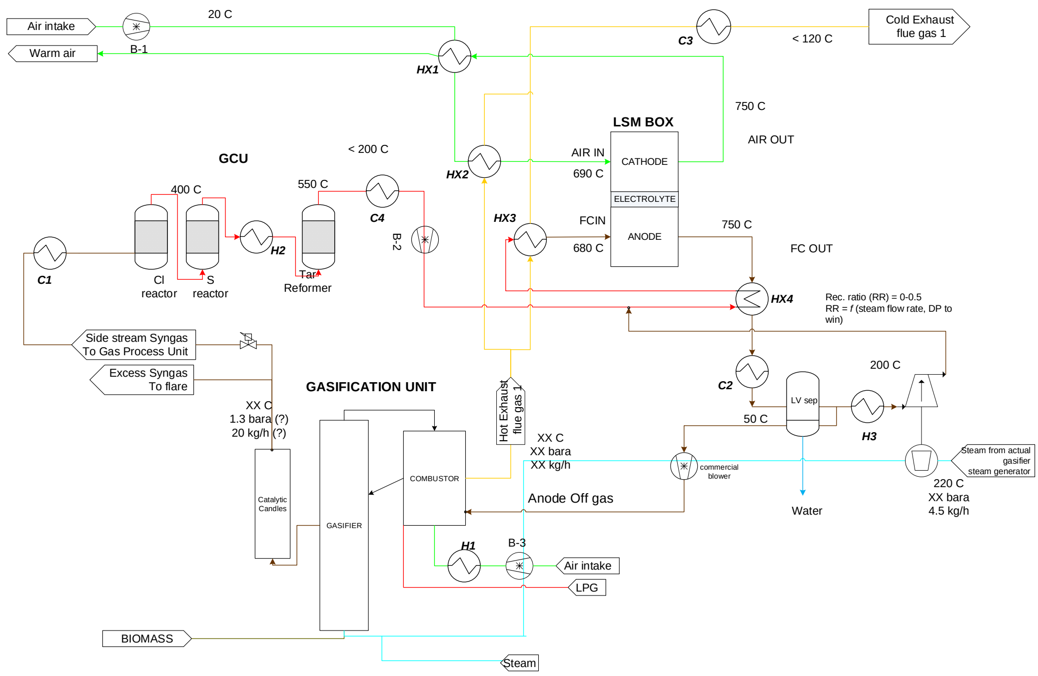

Figure 15. Option F process flow diagram of the BLAZE pilot plant. The AOG is sent to the SOFC LSM inlet stream (RR = 0.5) and the rest is burnt in the gasifier combustor. The recirculator condenses water before recycling. The gasifier is not compressed and the suction blower is placed after the GCU, after the cooler C4 (provided by HyGear, modified by EPFL LAMD and GEM). C: cooler; H: heater.

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Figure 16 represents the heat exchanger system proposed for evaluation (in Section 8), that has as starting point the heat exchanger network described above. It is a preliminary layout to evaluate co-generation efficiency. Exploratory calculations of heating needs (not optimised) show that: HX4 is not needed, C1 (GCU cooling down after the gasifier) can exchange heat with, (i) H2 (placed downstream GCU), (ii) H3 (located between the VL separator and the recirculator fan) and (iii) H1 (for the inlet gasifier combustor air heating up). Heat from C2 and C3 is used to produce steam for plant consumption and to be used by external users. In PFD F, also heat from C4 is sent to produce steam.

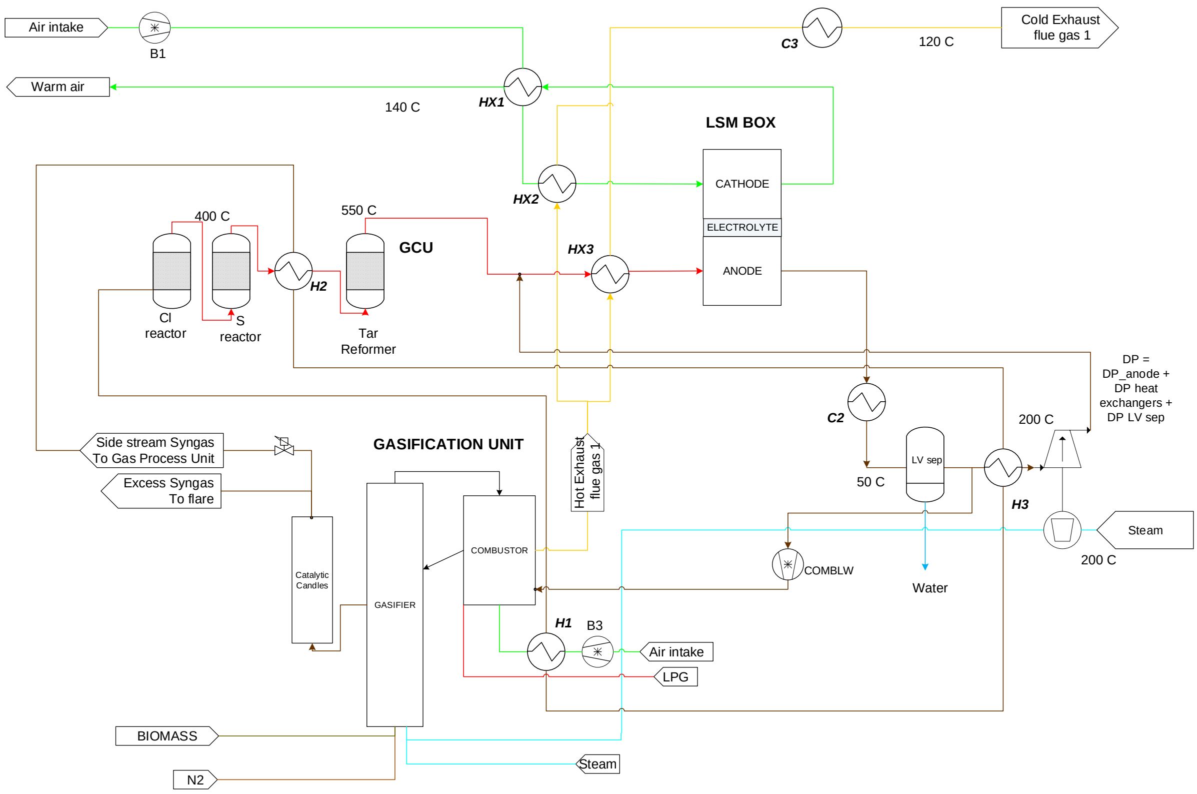

Figure 16. Option B process flow diagram of the BLAZE pilot plant. The AOG is sent to the SOFC LSM inlet stream (RR = 0.5) and the rest is burnt in the gasifier combustor, with heat exchange (same configuration for options D – Figure 14 and F – Figure 15; PFD F has moreover a cooler, C4, downstream the tar reformer) (provided by HyGear, modified by EPFL LAMD and GEM). C: cooler; H: heater.

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Figure 17 summarises the proposed preliminary steam generation system. In the system, water from the outside is consumed, together with condensed water in the VL separator. After its generation at 400 – 410 °C, the steam is separated into two streams: (i) the one that brings steam to the turbine and the excess to the market, and (ii) the one that provides steam to the gasifier (previous mixture with the steam from the turbine expansion). Thus, the temperature of the steam that enters the gasifier depends on the temperature of the steam coming from the turbine, and the temperature of the produced steam. The detailed model is not implemented in the current deliverable (for instance, the pressure modulation for steam use in the turbine is not taken into account).

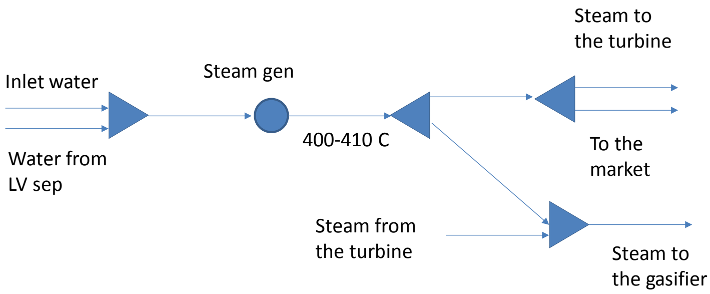

Figure 17. Steam generation system.

6 OPERATING WINDOWS

The values reported in Table 10 to Table 12 summarise the independent variables that can be changed for the different BLAZE plant units; i.e. the operating windows. The constraints in the tables are control parameters that should be checked during experimental work / modelling to secure the correct functioning of the units.

The gasifier and fuel cell counts with a range of temperature, flow and operating variables. The GCU, burners and the recirculator variables are mainly temperature ranges.

Independent variables and constraints	Value range
Biomass type	Hazelnut shell*
Biomass flow	10-30 kg/h
Biomass power input	50-150 kW_{th}
T gasification (gasifier chamber)	750 - 850 °C
S/B (steam to biomass ratio)	0.33 - 0.98
Delta T between combustion chamber and gasification chamber	50 – 100 °C
T steam inlet in gasification chamber (at the moment preheated by evaporator + electric heater)	200 - 400 °C
Total flow steam injected in the gasification chamber	11.6 kg/h (1)
Steam required in the gasification chamber for fluidization and gasification	9.77 kg/h (2)
Flow steam in the combustor. This is the steam flow due to the recirculation of the olivine between the chambers; this steam pass from gasifier to the combustor and leave it with the flue gas and it is the difference between (1) - (2)	1.83
T inlet air ONLY in combustion chamber (preheated with electric heater)	300 - 400 °C
Flow air in combustion chamber (aprox.)	43 kg/h
LPG for the combustion chamber (aprox.)	20 l/min
T outlet syngas BEFORE filter candles (estimated)	700 - 750 °C
T outlet syngas AFTER filter candles (estimated)	650 - 700 °C
P inside gasifier and combustor chamber	little more ambient pressure (3)

Table 10. Independent variables and constraints for the DBFBG. Range for the pilot plant using olivine with diameter 400 um.*Hazelnut shell is the nominal biomass type; other biomass types will be also tested and modelled. (1) and (2) are indicative values calculated for hazelnut shells. (3) will depend on the pressurisation technique.

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Independent variables and constraints	Value range
Anode inlet temperature	690 - 750 °C
Cathode inlet temperature	690 - 750 °C
Air flow rate to SOFC	~ 5600 Nl/min
FU	0.6 - 0.8
DT in the stack	0 - 100 °C
SOFC outlet temperature	790 °C
Cell voltage	above 0.7 V

Table 11. Independent variables and constraints for the SOFC LSM.

Independent variables and constraints	Value range (°C)
Cl removal unit, operating T	200 - 500
S removal unit, operating T	200 - 450
Tar reformer, operating T	550 - 750
T recirculation / syngas	(200-300) – (600-700)
Flue gas outlet T	140
Steam T for the recirculator	140 - 220

Table 12. Independent variables and constraints for the GCU, recirculator and burner.

7 OPERATING SCENARIOS

As described in Section 5.3, the primary selection of the PFD's options derived into two recirculation points in the pilot plant:

- Recirculation towards the anode inlet and,
- Recirculation towards the gasifier combustor.

The operating scenarios in the BLAZE optimisation task, are three; also including:

- Recirculation towards the gasifier gasification chamber.

The main objective of the project is to increase energy efficiency. Thus heat integration (and particularly, steam generation) is important.

In the operating scenarios of the BLAZE pilot plant, different biomass types and operating conditions will be considered, based on the operating windows.

The following expressions are used in the evaluation of the BLAZE preliminary pilot plant performance in Section 8. All streams and their LHV's are considered in as-received (ar) basis. The pursued target is "*to obtain a biomass CHP (within the small-to-medium scale 25-5,000 kW$_e$) with high electric (50 % versus the actual 25 %) and overall (90 % versus the actual 65 %) efficiencies*". *CGE* stands for cold gas efficiency of the gasifier (with the syngas considered after the candle filters); *Eff_SOFC* only takes into account the SOFC LSM power produced, considering the recirculation; *Eff_elec* considers the net electrical efficiency and *Eff_total* considers as well the heat sent to produce steam that will be destined to external users.

$$CGE = \frac{\dot{m}_{syngas,ar} \cdot LHV_{syngas,ar}}{\dot{m}_{biomass,ar} . LHV_{biomass,ar} + \dot{m}_{LPGs,ar} . LHV_{LPG,ar} + \dot{m}_{AOG,ar} . LHV_{AOG,ar}} \quad (1)$$

$$Eff\_SOFC = \frac{P_{prod}}{\dot{m}_{syngas,ar} . LHV_{syngas,ar}} \quad (2)$$

$$Eff\_elec = \frac{P_{prod} - (P_{B1} + P_{B3} + P_{COMBLW})}{\dot{m}_{biomass,ar} . LHV_{biomass,ar} + \dot{m}_{LPGs,ar} . LHV_{LPG,ar}} \quad (3)$$

$$Eff\_tot = \frac{P_{prod} - (P_{B1} + P_{B3} + P_{COMBLW}) + P_{steam}}{\dot{m}_{biomass,ar} . LHV_{biomass,ar} + \dot{m}_{LPGs,ar} . LHV_{LPG,ar}} \quad (4)$$

7.1 Decision variables

The decision variables are used in the optimisation problem to select the most suitable conditions based on the objective function. In the BLAZE plant, at nominal conditions (or other specific conditions of biomass type, gasification temperature, S/B and FU), the decision variables are: (i)the recirculation option, (ii) the recirculation ratio, (iii) the recirculation temperature, (iv) S and Cl separation unit's temperature, (v) tars reforming unit temperature, (vi) cathode inlet temperature, (vii) anode inlet temperature, (viii) air to gasification temperature and (ix) gasification steam temperature.

7.2 Heat management

The heat integration problem determines the structure and the design values (inlet/outlet temperatures, mass flowrates) of the heat exchanger network (HEN), and the selection, structure and design variables of the utility system(s). Table 13 summarises the heat exchangers, modelled as simple heating and cooling needs, in the BLAZE plant (Figure 16) with selected operating temperatures (see Table 16).

Heat exchanger (cooler or heater)	Temperature range (°C)	Type of stream
C1	(750-850) – 400	Syngas
C2	790 – 50	AOG
C3	(960-600) - 120	Flue gas
C4	(550-750) - 190	Syngas
H1	25 – (750-850)	Air
H2	(200-450) – (550-750)	Syngas
H3	(550-750) – (690-750)	Syngas
HX1 -Cold	30 – (680-690)	Air
HX1 -Hot	790 – 140	Air
HX2 -Cold	~680 - 700	Air
HX2 -Hot	960 – 700	Flue gas
HX3 -Cold	(415-550) - 700	Syngas
HX3 -Hot	960 – (530-880)	Flue gas
Steam generation	Steam at 400-410 °C	Water

Table 13. List of all the heating and cooling needs of the BLAZE plant, and their approximate temperature range. –Cold and –Hot stand for cold and hot sides of the heat exchanger.

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8 PRELIMINARY MODELS

The BLAZE plant model is needed in T4.2 Process modelling and validation, T4.5 Techno-economic optimisation of the conceptual CHP plant designs and T4.6 Final CHP system design. In the next paragraphs an overview of the modelling strategy of the principal units is given. The software selected for modelling is Aspen Plus V10. The plant model is implemented in Aspen Plus using the in-built library models within the software, and are considered zero-dimensional. The Peng-Robinson Boston-Mathias property methods is used. The models (mainly the gasifier and the SOFC LSM) will be further validated before starting Task 4.5.

8.1 Fluidised bed gasifier

The model considers Gibbs free energy minimisation applying the restricted quasi-equilibrium approach via Data-Fit from experimental data. The biomass is modelled as an unconventional stream, which is converted into C, H, O, S, N, Cl, S and ash in an RYield reactor using the ultimate analysis of the considered biomass (simulating the pyrolysis step of the gasification process). Then, the stream goes to an RStoic reactor to simulate the production of H_2S, HCl and NH_3. Afterwards, the volatiles, char (divided into two streams) and inorganics are separated. An 11% of char is separated and sent towards the gasifier combustor. The volatile stream is divided into two streams; one goes to the gasification block (RGibbs with Data-Fit), and the other one is used to simulate tar production (RYield), considering toluene, benzene and naphthalene productions. Afterwards, all separated streams are mixed [2].

The gasifier combustor is modelled as an isothermal reactor with complete stoichiometric combustion. The inlet air is compressed and heated up before entering the unit. The amount of air is calculated as 1.12 the stoichiometric amount. The combustor burns LPG, recycled AOG and char. The temperature of the gasification process is an input of the model. It is assumed that combustion takes place at 110 °C higher than gasification. The heat balance in the combustor determines the amount of extra LPG needed to have a perfectly integrated gasification process. This balance takes into account the heats released and absorbed in: the RYield that simulates the initial conversion of biomass, the RGibbs that simulates the gasification step, the RYield and RStoic that simulate contaminants production and the RStoic that simulates the reactions in the candle filter.

The candle filters step (even though described in the next Section) belongs to the gasifier. The temperature of the syngas going out of the gasifier takes into account this step; it is considered to decrease the gasification temperature in 70 °C.

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8.2 Gas cleaning units

The gas cleaning units in the BLAZE plant include [3]: the in-bed gas cleaning by a calcined dolomite bed, the catalytic filter candles, the sorbent reactor that separates S compounds, the alkali-based sorbent reactor that separates Cl compounds, and the tar reformer.

As a simplification, in the BLAZE plant model, the syngas cleaning units are considered as:

- A RStoic reactor simulating the catalytic filter candles, where methane, toluene, benzene and naphthalene react with water to produce CO and H_2. These reactions are considered to take place at a temperature that is 70 °C lower than the gasification temperature.
- Two heat exchangers that adapt the temperature to 400 °C and 550 °C; the two selected operating temperatures for S and Cl separation, and for the tar reforming, respectively.
- A component separator that separates all the contaminants from the syngas.

8.3 SOFC LSM

The SOFC LSM (0D) model takes into account the following hypotheses: the electrochemical and chemical reactions occur at an average reactor temperature (740 °C); the outlet gas composition is at equilibrium; the fuel cell is non-isothermal, and it is assumed that the outlet temperatures of the anode and cathode gases are the same (790 °C) [4]. The inlet gases are preheated close to the reaction temperature (700 °C). The model, given a local FU, calculates the current density and voltage, this last calculating the reversible voltage and subtracting the area specific resistance (ASR) (composed by its activation, ohmic and concentration losses terms). The is therefore calculated. The anode block is modelled by an internal reformer (RGibbs) and a final RGibbs which considers the introduction of oxygen. The cathode block is a component separator, which splits the O_2 required for the electrochemical reaction. The heat loss for the LSM is approximated by experimental data.

8.4 AOG recirculator

This unit is modelled using the compressor and turbine units from Aspen Plus. The connecting condition implies that the turbine has to provide all the power needed by the recirculator, which indeed depends on the RR and the composition of the recirculated stream. Depending on the density of the recirculated stream, the needs of the recirculator vary, and thus the steam expanded in the turbine vary accordingly.

It is assumed that the turbine has an overall efficiency of 0.4, and the inlet steam is at 5 bar and 220 °C. The pressure ratio is 2. The turbo-fan is assumed to work with an isentropic efficiency of 0.6 and a mechanical efficiency of 0.8.

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8.5 Compressors, heaters and coolers

The balance of plant (BoP) components such as blowers for air supply and gas circulation, heaters and coolers, are modelled using standard Aspen Plus library components. The performance of the blowers is determined based on the isentropic efficiencies (0.6, and mechanical efficiencies 0.8). Simple coolers and heaters are usually modelled without pressure loss (except for H3).

8.6 Preliminary analysis of PFD options

The following Table 14 to Table 17 summarise the main inputs (specific values to variables and constraints from Section 6) and results (see formulae 1 to 4) of the analysis of PFD's B, D and F (see Section 5.3). Note that PFD D has two parts: D1, where the global FU value is 0.6, and D2, where the global FU is 0.75. The purpose is to fairly compare the use of the recirculator (PFD B or F) with (i) not using it, at the specified local FU (0.6) (PFD D1), and with (ii) not using it, at the global FU obtained with recirculation (0.75) (PFD D2). This preliminary analysis has some shortcuts; it does not include the modelling of N_2 in the pressurised gasifier configuration (PFD's B, D1 and D2), nor the compression of steam. A HEN is considered based on practical purposes, as described in Section 5.3; the results presented here are not the result of an optimisation. Note that the HEN proposed, is the same in all the studied PFD's.

Looking at Table 14, all PFD's have in common the inlet gasifier conditions. As a result of not using the recirculator, PFD's D1 and D2 have air and steam streams going to the gasifier at a higher temperature than in cases B and F. The reason for (i) a higher air temperature is that H3 is not used (no need to heat up the AOG), (ii) a higher steam temperature is that there is no mixture of turbine and raw steam (see Figure 17). The inlet amount of biomass, 11.2 kg/h of hazelnut shell, is the specific amount of biomass needed that produces a syngas that requires the maximum possible amount of air in the SOFC LSM, for PFD's B and F. As a result of the gasifier heat balance, the amount of LPG needed to close the balance, is calculated. Note that the amount of LPG is notably less in D1, compared with B and F. The reason is that more AOG is injected in the gasifier combustor. In case D2, the need of LPG is higher: note that in this case, since the local FU is 0.75, the calorific value of the AOG is lower than in D1 (14 vs 22 kW). There is also the effect of the temperature of the steam going to the gasifier: the higher the temperature, the lower the need of LPG. However, in case D2, this effect is tempered by the lower LHV of the AOG. The higher the air needs in the gasifier combustor, the higher the compression needs.

According to Table 15, the highest voltage belongs to PFD D1. Analogously, the lowest current density value belongs to PFD D1, while for the rest of the cases the value is similar. The reason is a similar global FU. Note that in case D1, less air is needed in the cathode (to refrigerate the SOFC LSM), compared with a larger amount needed in case D2 (with a higher local FU).

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Independent variables and constraints	B	D1	D2	F
Biomass type	Hazelnut shell	Hazelnut shell	Hazelnut shell	Hazelnut shell
Biomass flow	11.2 kg/h	11.2 kg/h	11.2 kg/h	11.2 kg/h
T gasification (gasifier chamber)	850 °C	850 °C	850 °C	850 °C
S/B (steam to biomass ratio)	0.5	0.5	0.5	0.5
Delta T between combustion chamber and gasification chamber	110 °C	110 °C	110 °C	110 °C
Delta T between gasifier bed and candle filters	70 °C	70 °C	70 °C	70 °C
T steam inlet in gasification chamber	265 °C	400 °C	400 °C	265 °C
Total flow steam injected in the gasifier chamber	5.6 kg/h	5.6 kg/h	5.6 kg/h	5.6 kg/h
T inlet air ONLY in combustion chamber	197 °C	268 °C	240 °C	152 °C
Flow air in combustion chamber (1.12 excess)	38.4 kg/h	39.22 kg/h	45.33 kg/h	41.5 kg/h
LPG for the combustion chamber	0.9 kg/h	0.5 kg/h	1.3 kg/h	1.1 kg/h
T gasification	850 °C	850 °C	850 °C	850 °C
T syngas after filter candles	780 °C	780 °C	780 °C	780 °C
P inside gasifier and combustor chamber	1.29325 bar	1.29325 bar	1.29325 bar	1.01325 bar

Table 14 Selected values for independent variables and constraints for the DBFBG and results.

Independent variables and constraints	B	D1	D2	F
Anode inlet temperature	700 °C	700 °C	700 °C	700 °C
Cathode inlet temperature	700 °C	700 °C	700 °C	700 °C
T inside SOFC	740 °C	740 °C	740 °C	740 °C
Air flow rate to SOFC	5668 Nl/min	4320 Nl/min	6045 Nl/min	5714 Nl/min
FU global / local	0.75 / 0.6	0.6	0.75	0.75 / 0.6
DT in the stack	90 °C	90 °C	90 °C	90 °C
SOFC outlet temperature	790 °C	790 °C	790 °C	790 °C
Cell voltage	0.863 V	0.896 V	0.864 V	0.863 V
Current density	0.387 A/cm2	0.310 A/cm2	0.387 A/cm2	0.387 A/cm2

Table 15. Independent variables and constraints for the SOFC LSM.

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See in Table 16 a summary of the selected temperatures and the DP value that the recirculator has to overcome.

Independent variables and constraints	All
Cl removal unit, operating T (°C)	400
S removal unit, operating T (°C)	400
Tar reformer, operating T (°C)	550
T recirculation / syngas (°C)	50
Flue gas T (°C)	120
Steam T for the recirculator (°C)	220
Steam P for the recirculator (bar)	5
Delta P recirculator (mbar)	60

Table 16. Independent variables and constraints for the GCU, recirculator and burner.

Results	B	D1	D2	F
Power SOFC (kW)	27	22.4	27	27
Wnet (kW)	25.4	20.7	25	25.2
Syngas LHV (ar) (MJ/kg)	12.47	12.47	12.47	12.47
Syngas flow (kg/h)	15.9	15.9	15.9	15.9
Syngas composition (mole fraction)				
H2	0.49	0.49	0.49	0.49
CO	0.25	0.25	0.25	0.25
CO2	0.11	0.11	0.11	0.11
H2O	0.15	0.15	0.15	0.15
CH4	0.004	0.004	0.004	0.004
In biomass (kW)	58.6	58.6	58.6	58.6
CGE	0.67	0.65	0.63	0.65
Eff_SOFC	0.49	0.41	0.5	0.49
Eff_elec	0.36	0.32	0.33	0.34
Eff_total	0.7	0.63	0.63	0.66
Steam to sell	25.5 kg/h	20.1 kg/h	22.7 kg/h	27.2 kg/h

Table 17. Summary of main results.

Table 17 summarises the syngas characteristics (the same for all the cases, as the operating variables of the gasifier are fixed for all of them) and the power and efficiency values for the 4 PFD's. The power produced by PFD's B, D2 and F are similar (27 kW) as the global FU is 0.75 for all. Notably less power is produced in PFD D1 (22.4 kW) as the FU is 0.6. The net efficiency is analogously higher in cases B, D2 and F. Note that more power is consumed in case F, as the gasifier is pressurised, and in case D2, as more air is needed in the SOFC LSM. There is also more compression needed in the COMBLW in cases D, as the amount of AOG that goes to the gasifier combustor is larger.

The *CGE* is similar in all 4 cases. It is slightly higher for PFD B (lower LPG needed), and lower for PFD D2 (more LPG needed). The case with less LPG needed is PFD D1; but it is not the case with the largest CGE. The reason is because the inlet AOG is larger than for PFD B. In the current simulation, the effect of air and steam inlet temperature on the CGE is minimal.

The *Eff_SOFC* is pretty much the same (0.5) in all PFD's with equal global FU (PFD's B, D2 and F), while the *Eff_SOFC* is lower when the FU is 0.6 (0.39). The *Eff_elec* is higher in PFD B (0.36), and lower in PFD D1 (0.32). *Eff_tot* is higher in PFD B (0.7) and lower in PFD's D1 and D2 (0.63). Note that *Eff_elec* varies 4 percentual points, while *Eff_tot* varies 7 percentual points. At system level, under the current hypotheses and pre-determined HEN, the best option is PFD B (not only in terms of efficiency, but also in terms of layout simplicity compared to PFD F). However, note that the final results do not point out a "much better" and a "much worst" solution but, it can be said that, due to the trade-offs identified in terms of auxiliaries' consumption, final temperatures, and heating and cooling needs, the results of PFD's B, D2 and F do not differ too much (except for the layout and operating conditions differences). The selection of the PFD for the pilot plant, should take into account the individual favourable operating and layout options of the gasifier (pressurised vs. downstream fan) and the SOFC LSM (recirculation vs. not recirculation). These will be further analysed in D4.4.

Also in D4.4 we will include:

- Further validation of the gasifier and the SOFC LSM models.
- HEN optimisation for selected options.
- Techno-economic optimisation of the plant design.

9 CONCLUSIONS

The objective of this deliverable is twofold: (i) to compile the information shared among the partners to set the basis of the BLAZE plant, and (ii) to provide the preliminary models and results, as basis for D4.3 and D4.4. The extent of the exchange of information between the partners is illustrated by the number of PFD's described in Section 5. The plant layouts for evaluation in the current deliverable count with different options for the gasifier (pressurised vs. downstream compression) and the SOFC LSM (recirculation vs. no recirculation) at a fixed local FU of 0.6 (PFD's B, D1 and F), or at a global FU of 0.75 (PFD's B, D2 and F). The results show that the combined heat and power efficiency can go up to 70 % within the selected working conditions and layouts. The importance of selecting the most favourable operating conditions and layout for the (i) gasifier and the (ii) SOFC LSM individually is pointed out, as the system evaluation of different plant layouts show in fact similar final results (i.e. similar efficiency values). The BLAZE partners are currently discussing the role of the recirculator in the experimental pilot plant.

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