First results of the H2020-LC-SC3-RES-11 BLAZE project: biomass low cost advanced zero emission small-to-medium scale integrated gasifier fuel cell combined heat and power plant

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Abstract. BLAZE aims at developing a Low cost, Advanced and Zero Emission first-of-a-kind small-to-medium Biomass CHP. This aim is reached by developing bubbling fluidised bed technology integrating a high temperature gas cleaning & conditioning system and integration of a 25 kW Solid Oxide Fuel Cell units. The technology is characterised by the widest solid fuel spectrum applicable, high efficiencies (50% electrical versus the actual 20%), low investment (< 4 k€/kWe) and operational (≈ 0.05 €/kWh) costs, as well as almost zero gaseous and PM emissions, projecting electricity production costs below 0.10 €/kWh. This paper shows the first project activities: preliminary economic analysis, selection of 10 samples and 5 mixtures of representative biomass wastes to be tested in the gasification labs; selection of bio-syngas representative tar and contaminants to be tested in the SOFC lab scale facilities; CFD and layout first modelling results.

1 Introduction

At present, installed electricity generation capacity by Combined heat and power (CHP) in the EU-28 is about 120 GWe (ST 62 GWe, CC 30 GWe, ICE 15 GWe, GT 12 GWe), which generates approximately 11% of the EU electricity demand (362 TWh, i.e. on average ≈3000 annual equivalent hours) [1]. The CHP heat capacity is about 300 GWth with a heat production of 775 TWh, i.e. an average of ≈2.5 thermal/electrical power ratio and 2500 annual equivalent hours. Renewables, mainly biomass and in particular low-cost biomass or biomass waste, are becoming increasingly important after having attained 20% of the market. Bioenergy has currently the largest share (88%) of all RES used for heat and cooling with 76 Mtoe, not far from the 2020 Member States plan of 90 Mtoe [2]. CHP systems have a significant penetration in the EU industry, producing approximately 16% of the final industrial heat demand [3]. It is worth noting that cogeneration (CHP) plants account for about 60% of EU-28's bioenergy production from solid biomass [4]. The total EU28 energy demand for Heating and Cooling (H/C) equals 51% of the total final energy demand; the majority of the demand for H/C is due to space heating (52%), followed by process heating (30%) and water heating (10%) with ambitious policy objectives which include, for instance, that all new buildings must be Nearly Zero Energy Buildings (NZEB) from the 31st of December 2020 The European bioenergy potential

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derived from residues is 314 Mtoe; the currently consumed share is less than half of this value [5]. Major limitations of the bioenergy potential relate to the facts that S-o-A small-medium solid biomass power plants currently have an annual operating time of 4000 h, an electrical efficiency of 25%, high local and environmental impacts and a capital cost of 5.000 €/kWe. They cannot compete with the liquid or gaseous fossil fuels CHP where, even if the fuel cost is higher, the CAPEX is lower, the annual operating time is higher and the local emissions are lower [6].

2 BLAZE project

2.1 Aims, goals and objectives

The project aims at the development of an innovative highly efficient and fuel flexible small and medium-scale biomass CHP technology consisting of a compact bubbling fluidised-bed gasifier integrating primary sorbents and ceramic candle filters with Ni catalyst (IBFBG), a high temperature fixed bed sorbents reactor and an integrated solid oxide fuel cell (SOFC) including first-of-a-kind heat-driven gas recirculation (Figure 1).

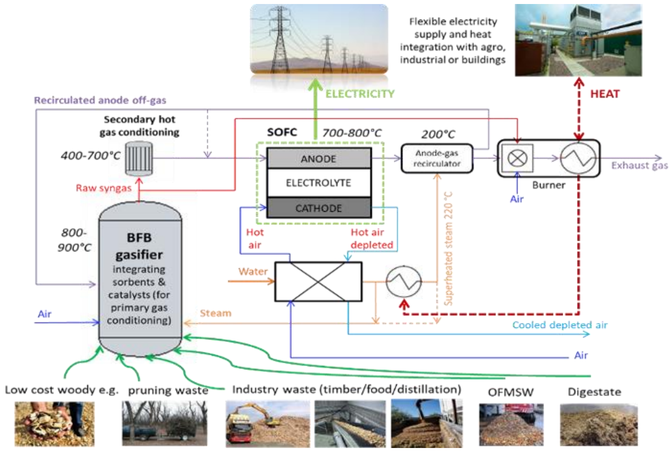


Fig. 1. BLAZE scheme.

The technology is developed for a CHP capacity range from 25-100 kWe (small scale) to 0.1-5 MWe (medium scale) and is characterized by the widest fuel spectrum applicable (forest, agricultural and industrial waste also with high moisture contents, organic fractions of municipal waste, digestate), high net electric (50%) and overall (90%) efficiencies as well as almost zero gaseous and PM emissions; the CO_2 production is neutral, while the other emissions are zero or negligible. In fact, gasification, with respect to other biomass conversions, can convert a greater variety of solid biomass with shorter residence time and higher efficiency into a gaseous fuel that, when converted via fuel cells, can achieve the highest overall (90% versus 65% now, target SET-PLAN 75%) and electrical CHP efficiencies for small and medium scale biomass systems (50% versus 25% now, target SET-PLAN 30%). If in the micro to small scale the fixed bed updraft gasifiers may be well suited (low cost, emissions and space need), within the small to medium scale, bubbling fluidised bed gasifiers also have low cost, are more compact and especially can guarantee better fuel flexibility, efficiency, stable operation and lower emissions, if integrated hot gas cleaning and conditioning measures are applied; this addresses the SET-PLAN challenge "availability and cost of sustainable biomass feedstock is a major barrier for large scale deployment of bioenergy technologies". With the recent advancement and industrialization in gasification, hot gas conditioning and SOFC technologies, capital and operating costs of such biomass CHP plants are reducing. Additionally, they provide flexibility to the energy system. Indeed, the electrical power produced from a renewable storable energy like biomass that maintains higher efficiency at partial load is a solution at system level towards flexibility. Finally, small and medium-scale gasification coupled with fuel cells constitutes a renewable energy breakthrough in the biomass CHP sector that will feed an innovation cycle and lay the basis of the next generation of EU biomass technologies (SET-PLAN challenge "it is necessary to … create the crude energy feedstock basis that could be further refined to final bioenergy products or directly used for high efficient heat and power generation). Regarding the cost, the target is to obtain CAPEX below 4,000 €/kWe (versus the actual 4,000-7,000 €/kWe), and OPEX of ≈ 0.05 €/kWhe (using low cost biomass, i.e. 80 €/t, with respect to the actual greater than 0.10 €/kWhe). As major output of these savings, an electricity production cost below 0.10 €/kWh is projected (versus the actual 0.22 €/kWh, SET-PLAN target of 20% cost reduction by 2020, and 50% by 2030). Such outstanding targets can be achieved by the technology development undertaken in this project that allows to convert with high efficiency low cost fuel, by the currently launched SOFC mass-production (cost projection ≈ 2,000 €/kWe) and by the actual market penetration (and so reduced cost and increased reliability) of small-to-medium scale fluidised bed gasifiers integrating hot gas conditioning and fully automated operation.

2.2 Workplan

The BLAZE proposal is conceived as a holistic approach by identifying the main technological and non-technological barriers/gaps that hamper the spread and exploitation of highly efficient small-to-medium-scale biomass CHP plants as reported in figure 2. The identification of main challenges covers the supply chain from (i) biomass residues and relevant pre-treatment technologies to (ii) sorbents/catalysts and materials for hot cleaning and conditioning (e.g. high temperature ceramic filters) as well as (iii) optimization of a compact integrated system (gasifier/SOFC/auxiliaries), ensuring a significant reduction of electricity production cost.

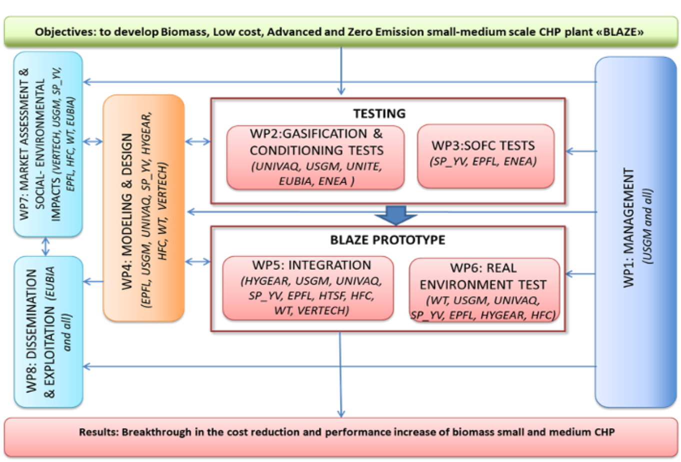


Fig. 2. BLAZE PERT diagram.

In particular, lab scale (3 kWth) and pilot scale (100 kWth) gasification tests and the associated hot gas cleaning & conditioning systems (sorbents and catalysts) are undergoing within WP2. Short and long term tests to determine the gas quality and purification requirements for safe long-term operation of the SOFC stack are undergoing within WP3. Optimised thermally integrated gasifier-fuel cell simulation (WP4) together with specific heat-driven anode gas recirculator, P&ID and control system allowing to operate the integrated system, under varying fuel quality conditions and power/heat demand (WP5) will be developed in 2020. A 100 kWth with 25 kWe SOFC system wil be operated in 2021 (WP6). Regarding the technology assessment part, the following activities will be undertaken: Life Cycle Assessment (LCA), Life Cycle Cost (LCC), Social LCA, Health and Safety Study (HSS) and legal and non-legal barriers (e.g. Restriction of Hazardous Substances Directive, RoHS; Registration Evaluation Authorization restriction of Chemicals, REACH) within WP7. Market Analysis Report, Business Models, IPR and Exploitation plan, Multi-Stakeholder Platform are the dissemination & exploitation results (WP8).

3 BLAZE activities

3.1 First cost estimation

Based on literature data (Cogeneration Report. AEEG, Electricity and Gas Italian Authority, 2010; Report on biomass market segments within the transport, heat & electricity- CHP sectors for EU27 Member States, 2010; Combined Heat and Power: A Clean Energy Solution (2013) and Technology assessment (2017), Department of Energy, USA) it is possible to roughly compare CAPEX (see table 1), OPEX and BLAZE cost of electricity to the conventional biomass CHP systems.

Owing to the normally thermal base load sizing of the CHP, the cost of a gas boiler with burner, flue tubes and accessories is added to the CHP plants cost. To this item, heating civil works, piping, pump, expansion vessel and regulation system have been added. The conventional biomass systems analysed are biomass combustor coupled to organic fluid cycle (ORC) and biomass fixed bed gasifier coupled to internal combustion engine (ICE), because for sizes below 1 MWe, these systems are the mainly applied to the market. The systems are evaluated for the two cogeneration sectors, assuming, for buildings, to give heat (e.g. to a district heating network) at the price of 0.06 €/kWht (considering the average 3000 annual electrical equivalent hours and 2500 annual thermal equivalent hours) and, for industrial, at the price of 0.04 €/kWht [7] (considering 7500 annual electrical and thermal equivalent hours, as usual in industrial plants).

Table 1. BLAZE, ICE and ORC CAPEX comparison.

CAPEX	BLAZE	ICE	ORC
Input kWth	100	100	100
Biomass storage and feeding (spider, hopper, screw) cost €	6,000	6,000	6,000
Gasification (BLAZE or ICE/GT) or Combustion (ORC) cost €	90,000	90,000	70,000
€/kWth	960	960	760
Power generator size kWe	50	25	15
Power generator size kWth	40	50	65
SOFC-ICE/mGT–ORC cost €	100,000	37,500	30,000
€/kWe	2,000	1,500	2,000
System cost €	196,000	127,500	100,00

			0
€/kWe (considering all CAPEX to only electric power)	3,920	5,100	6,667
100 kWth gas boiler with tubes and accessories €	50,000	50,000	50,000
Electric system cost €	170,000	110,000	82,000
€/kWe	3,400	4,400	5,467
Thermal system cost €	76,000	67,500	68,000
€/kWth	1,900	1,350	1,046

The cost analysis has been performed over a period of 20 years as the standard energy power plants lifetime; therefore, the residual value of the plant is not taken into account. Allocation of the CHP plant costs has long been subject for discussion, since several thermodynamic and economic methods are available. Here a simple economic cost allocation based on the market price for the kWht and considering as thermal cost the cost linked only to the heat (therefore, similar to the penalty cost allocation method) is applied. Thus, after having calculated the CAPEX and the other OPEX for the thermal generation, the share of fuel cost attributed to thermal generation is the one that leads to the heat production cost. A price of 60 €/ton (similar to the price of high humidity wood chips) has been used for BLAZE, meanwhile a price of 100 €/ton (similar to the price of low humidity wood chips) has been used for ORC and ICE systems. The more difficult small-scale CHP size is analysed, thus BLAZE 100 (100 kWth biomass IBFBG integrated with 50 kWe SOFC) is compared to a 100 kWth biomass combustor coupled to a 15 kWe ORC and a 100 kWth biomass fixed bed gasifier coupled to a 25 kWe ICE. The table below show the CAPEX for the considered biomass CHP systems.

Because of this small size (i.e. a production from 45 to 150 MWhe) the CAPEXs are generally higher (and the OPEXs have to be low: e.g. no possibility to have dedicated on-site staff, as usual in biomass plants) but the electricity price is also higher. The EU-28 average electricity price for non-household consumers in band IA (<20 MWh annual consumption), all taxes and levies included, is 0.22 €/kWhe, meanwhile in band IB (20-500 MWh) it is 0.17 €/kWhe and in band 1C (500-2000 MWh) 0.14 €/kWhe (Eurostat 2017 data†). A similar comparison can be applied to BLAZE 1000 (using 1 MWth IBFBG and 500 kWe SOFC) and the related solid biomass conventional systems. In this case the CAPEX will be lower, e.g. increasing size, the cost/kW of the gasification/combustion system significantly decreases, thus the economic analysis will have better results. Furthermore, in most cases, the operation of CHP plants is limited by the heat consumption. The high electrical efficiency of an SOFC reduces the heat generated from the combined plant, therefore usually allowing to operate the system efficiently (and with used heat) for larger periods in the year. While for conventional systems 4000 hrs are expected, SOFC systems often operate for 6000 and more hours, reducing thereby the total contribution of CAPEX per kWh electricity produced. On the downside, the slip of the produced gas used directly for heat-only purposes through a burner (see also Fig.1) allows to extend furthermore the SOFC operating hours, with very small additional CAPEX. This enlarges the overall heat and power availability of the system and allows the operation for large periods of the year. This is important, as this minimizes the number of full-start-up/shut-downs of the system that is expected to take (depending on the size) less than 12 hrs from room temperature, while the system can ramp to full load within less than 20 min when in hot stand-by mode. Thus, in BLAZE the costs per kWe produced is less than in the conventional solid biomass cases because, even if the gasification and SOFC CAPEX are

†http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do

higher, the electrical efficiency is double. With the BLAZE system it will be possible to generate twice the kWe produced with conventional Bio-CHP. Finally, we consider here the same conservative gasification costs for ICE systems to BLAZE whereas the BLAZE integrated hot gas conditioning gasification will save equipment cost (conventional low temperature gas cleaning can amount up to a third of the total CAPEX). Thus, BLAZE shows a CAPEX reduction of at least 23% compared to the conventional Bio-CHP systems. Table 2 below shows the global (electric and thermal) OPEXs for the three systems considering 3,000 of electric and 2,500 of thermal equivalent annual hours:

Table 2. BLAZE, ICE and ORC OPEX comparison.

	€/year		
OPEX cost item	**BLAZE**	**ICE**	**ORC**
Personnel (automated operation - 50 h/yr)	1,000	1,000	1,000
Gasifier/Combustor, Gas Cleaning system, Boiler	1,300	1,300	1,000
Power generation (SOFC or ICE)	1,300	1,300	600
Biomass Cost	4,000	7,000	7,000
Ash disposal cost	500	500	500
Other Costs (e.g. insurance, aux. consumptions)	1,000	1,000	1,000
Total OPEX	9,100	12,100	11,100

As expected the higher OPEX costs for traditional CHP with respect to BLAZE are mainly due to the higher biomass cost. We considered here the same conservative gasification OPEX for ICE systems to BLAZE whereas the BLAZE integrated hot gas conditioning gasification (and SOFC for small unit) OPEX are lower than cold gas conditioning (and ICE) OPEX. Thus, BLAZE shows a reduction of at least 18% compared to the conventional Bio-CHP systems.

The evaluation of the costs of the electricity produced is carried out according to the methodology of the "Levelized Cost Of Electricity" (LCOE) or equivalent annual cost (EAC). According to the IEA: "The notion of LCOE is a very easy tool for comparing costs units of different electrical generation technologies". LCOE is the tool generally considered to be more transparent to evaluate the costs of electricity generation and is widely used to compare the costs of different technologies. It was assumed that the investment can be realized in a year, as usual for biomass plants with installed power lower than 1 MWe. The calculation of the LCOE was carried out with the following equation:

$$LCOE = \frac{C_i + \sum_{i=1}^{20} CO_i(1+r)^{-i} + \sum_{i=1}^{20} CC_i(1+r)^{-i}}{\sum_{i=1}^{20} EE_i(1+r)^{-i}} \quad (1)$$

where:

r interest rate; Ci the investment cost incurred (CAPEX); COi the cost of operating and maintenance incurred during the i-th year; EEi electricity (or thermal energy) produced in the i-th year; CCi fuel cost incurred in the i-th year

The OPEX are the sum of CO and CC. The interest rates is assumed equal to 3.00% owing to the actual 0% of ECB, European Central Bank and 3% spread.

Table 3. BLAZE, ICE and ORC OPEX comparison.

	BLAZE		ICE		ORC	
Equivalent annual hours	3000	2500	3000	2500	3000	2500
OPEX €/kWh	0.06	0.03	0.16	0.04	0.20	0.04
CAPEX €/kWh	0.08	0.03	0.11	0.02	0.13	0.02
Tot CAPEX+OPEX €/kWh	0.14	0.06	0.27	0.06	0.33	0.06
Equivalent annual hours	7500	7500	7500	7500	7500	7500
OPEX €/kWh	0.04	0.02	0.12	0.03	0.14	0.03
CAPEX €/kWh	0.06	0.02	0.07	0.01	0.06	0.01
Tot CAPEX+OPEX €/kWh	0.10	0.04	0.19	0.04	0.20	0.04

Table 3 shows that BLAZE is the only system that, in case of lower annual equivalent hours, has a competitive electricity generation cost, and that BLAZE, in case of high annual equivalent hours, can have electricity generation cost of 0.05 €/kWh. As already written before, with increased size, a further cost reduction is foreseen.

3.2 Biomass selection and characterization

Potential waste biomass in Europe of most suitable for gasification considering availability physical (low water content and high bulk density), chemical (high Caloric Value, high volatile substances, low ash, high Carbon to Nitrogen ratio, low Chlorine and Sulphur content), and economic characteristics has been assessed. Moreover characterization of biomass selected as representative (proximate and ultimate analysis, elements determinations, ignition and burn-out temperatures, ashes characterization) has been conducted [8-15] (see figure below and https://www.blazeproject.eu/wp-content/uploads/2020/04/D2.1_Biomass_20_12_19_for-Website.pdf).

Feedstock	CATEGORY	Humidity (%-wt, as received)	LHV MJ/kg	Ash %wt, dry basis	S %wt, dry basis	Cl %wt, dry basis	Ash melting T (DT) (°C)
Subcoal	Municipal waste	3,20	21,68	15,60	0,10	1,00	1250,00
Olive pomace pitted	Secondary residues of industry utilising agricultural products	36,30	19,79	5,95	0,06	0,08	1290,00
Sawmill waste	Primary residues from forest	11,20	18,89	0,41	<0.01	<0.01	1300,00
Multi-essence wood chips	Waste from wood	24,50	17,88	1,45	0,02	<0,01	1370,00
Olive Prunings	Secondary residues from wood industries	14,90	17,76	1,55	<0.01	<0.01	1380,00
Almond shells	Secondary residues of industry utilising agricultural products	10,00	17,68	1,31	<0.01	<0.01	1000,00
Swarf and sawdust	Secondary residues from wood industries	6,60	17,14	0,43	<0.01	<0.01	>1385
Wood chips	Primary residues from forest	8,90	16,74	0,54	<0.01	<0.01	>1385
Corn cobs	Agricultural residues	9,00	16,62	3,04	0,03	0,44	645,00
Arundo Donax	Agricultural residues	10,10	16,25	3,43	0,11	0,29	1185,00
1- Wheat Straw (pellets 10 mm)	Agricultural residues	7,60	15,98	9,22	0,05	0,12	1065,00
2- Wheat Straw (pellets 6 mm)	Agricultural residues	7,60	15,40	13,29	0,08	0,21	1135,00
Rice husks	Secondary residues of industry utilising agricultural products	5,20	15,19	14,70	0,02	0,03	990,00
Digestate	Digestate from biogas production	71,20	12,69	25,81	0,97	0,10	1245,00
Black Liquor	Secondary residues from wood industries	20,60	11,20	48,28	0,74	0,12	680,00
Municipal solid waste	Municipal waste	23,00	10,22	47,01	0,20	0,40	1220,00

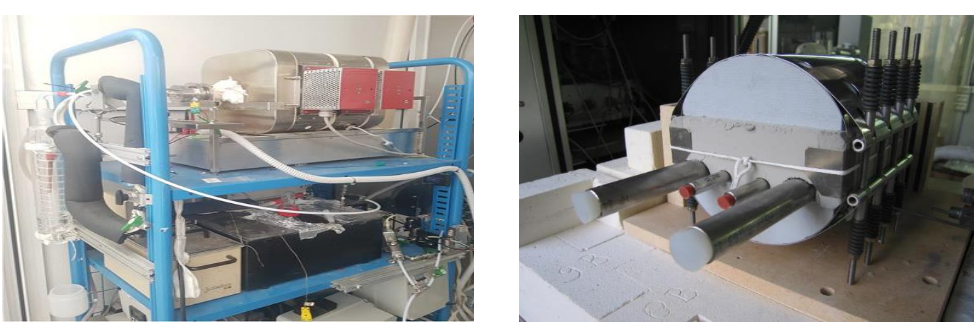
Fig. 3. Biomass types and technical characteristics.

3.3 Gasification, conditioning and SOFC tests

Regarding the bio-syngas representative tar to be tested in the lab facilities the project done an open access literature overview (www.blazeproject.eu/resources) analyzing 83 papers (mostly experimental). It has been decided to focus on 1 representative syngas composition (owing to the decision to focus only on the steam gasification tested at pilot scale, on wet basis: 45% H_2, 24% CO, 11% CO_2, 2% CH_4, 18% H_2O) and 2 organic (toluene and naphthalene) and 2 inorganic (H_2S, KCl) representative contaminants levels [16-19]. In particular, naphthalene has been selected to represent so-called slow tars, i.e. tars with slow conversion kinetics. In order to make meaningful tests, the investigated contaminant levels will be aligned with those reported in literature regarding experimental work on SOFCs, i.e. 25 mg/Nm3 (5 ppm) and 75 mg/Nm3 (15 ppm) naphthalene. Toluene has been selected to represent so-called fast tars, i.e. tars with relatively fast conversion kinetics. Tolerable toluene levels are less clear than for naphthalene, and thus will be aligned with those expected from BFB steam gasifiers with catalytic filters, i.e. 250 mg/Nm3 (to be expected from clean biomass such as almond shells) and 750 mg/Nm3 (feedstock emitting high toluene concentrations). H_2S and KCl have been selected to represent sulfur and both halogens and alkalis compounds respectively. In order to make meaningful tests, the investigated contaminant levels will be aligned with those reported in literature regarding experimental work on SOFCs, i.e. 1 ppm and 3 ppm for and H_2S and 50 ppm and 200 ppm for KCl. In particular button cells have been investigated in order to perform mechanistic studies on the conversion of syngas and on the poisoning effects of contaminants while short stacks are being tested in order to investigate the operational window of the SOFC stack considered in final demonstrator. The following photos show gasification and SOFCs lab scale facilities fitted for the experimental activities [20-28].

a) b)

Fig. 4. a) UNIVAQ catalyst and sorbent test rig, b) ENEA gasification



a) b)

Fig. 5. a) SOFC single cell test rig (ENEA), b) SOFC short stack.

3.4 Modelling

The modelling activities will perform a full process and system design with detailed CFD and process flow diagram (PFD) from the viewpoints of process and system reliability, efficiency, cost and socio-environmental impacts. E.g. CFD Simulations of 3D Vessel with catalytic candles for validation of 2D model with experimental data from the bench scale gasifier (Figure 5a) have been performed.

Global system ASPEN simulations have been already performed [29-32] in order to identify the best layout considering various freedoms of system configurations, e.g., different options of: gas cleaning units, anode off-gas recirculation, heat exchangers, pressurised gasifier/combustor or different fan/blowers; see Figure 5b and https://www.blazeproject.eu/wp-content/uploads/2020/04/BLAZE-D4.1.pdf.

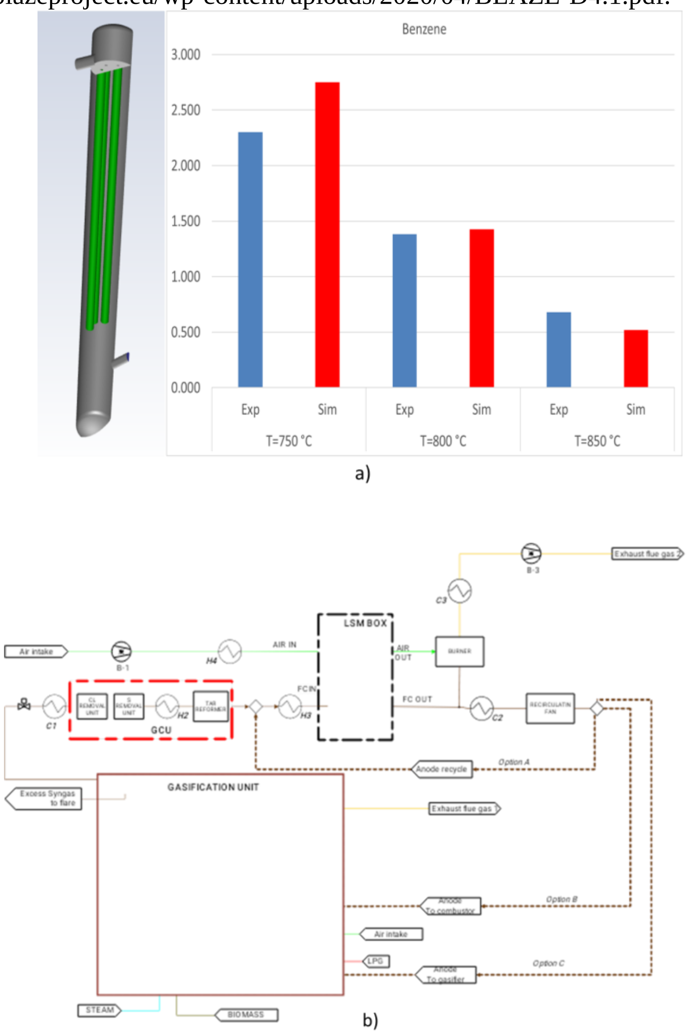


Fig. 6. BLAZE modelling: a) CFD simulations, b) Example of process flow diagram.

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