MID TERM 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 Low cost, Advanced and Zero Emission first-of-a-kind small-to-medium Biomass CHP. This aim is reached by developing dual bubbling fluidised bed technology integrated with high temperature gas cleaning & conditioning systems and Solid Oxide Fuel Cells. 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 noxious gaseous and PM emissions, projecting electricity production costs below 0.10 €/kWh. This paper shows the midterm project achievements, i.e. the biomass waste gasification and SOFC tests, the overall simulation and the progress on the realisation of 25 kWe SOFC pilot plant.

1 INTRODUCTION

BLAZE project aims at the development of a compact indirectly heated dual bubbling fluidised-bed gasifier (IBFBG: composed of a gasifier within a combustor) integrated wtih primary sorbents and ceramic candle filters filled with Ni catalysts, high temperature fixed bed sorbents reactors and solid oxide fuel cell (SOFC) including first-of-a-kind heat-driven syngas blower (Fig.1).

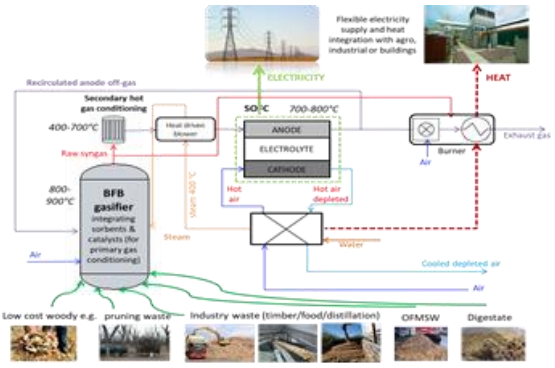

Figure 1: BLAZE SCHEME

The technology is developed for a novel CHP with a capacity range from 25-100 kWe (small scale) to 0.1-5 MWe (medium scale) and is characterised 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 net GHG and PM emissions.

2 OVERALL ACTIVITIES PERFORMED

The project started in March 2019. In the first 24 months the consortium performed:

- biomass feedstock analysis, by screening 10 samples and 5 mixtures of representative biomass wastes, and then by more deeply testing two of the most relevant biomass wastes evaluated;
- gasification tests, without and with primary sorbents to reduce sulphur and chlorine bearing compounds;
- literature review to select bio-syngas representative organic and inorganic contaminants for button cell and short-stack SOFC tests;
- tar catalyst tests in order to select the catalysts to be applied within the filter candles and the secondary tar reformer;
- sorbents tests in order to select the material to be applied in the secondary sulphur and chlorine reactors;
- button cells at ENEA and short stacks at EPFL tests in order to understand SOFC performance (e.g. syngas behaviour and tar, sulfur and chlorine tolerance)
- overall plant simulations and final pilot plant design;
- pilot plant realization, achieving pilot plant gasification with a hydrogen content stable over 30%/v

3 BIOMASS SELECTION AND CHARACTERIZATION

The potential of waste biomass in EU was assessed on the basis of availability, physical properties (low water content and high bulk density), chemical properties (high Calorific Value, high content of volatile substances in order to produce more gas, low ash content, high Carbon to Nitrogen ratio, low Chlorine and Sulphur content), and economic aspects (e.g. cost). Moreover, full characterization of the biomass selected as the representative feedstocks (proximate and ultimate analysis, elements determinations, ignition and burn-out temperatures, ashes characterization) was conducted (see figure below and www.blazeproject.eu/resources). From the analysis of the collected data set all woody and herbaceous biomass feedstocks were usable for gasification with a BFB reactor, since no significant risk of reactor bed defluidisation is expected. However, for most feedstocks, the presence of contents of S and Cl could lead to gaseous products containing S and Cl (e.g. H_2S, HCl and alkali halides),the levels of which are too high for immediate use in a SOFC. A first gas cleaning to reduce their concentrations at levels consistent with the SOFC specification needs to be considered for all these biomass feedstocks [1].

The assessment further revealed that corn cobs, black liquor (BL), MSW and digestate are less attractive for gasification in a BFB reactor. Corn cobs and BL were unsuitable due to their rather low ash melting temperatures compared with the typical values adopted in BFB gasification (i.e. slightly above 600 °C vs 800-850 °C) thus leading to a possible reactor block. MSW and digestate appeared as utilizable feedstocks, although at reduced performance due to the significantly lower heating values compared with all the other considered matrices, and due to the higher ash content. Moreover, their characterization also revealed a rather high content of K, Na, Pb and Zn, which in combination with the high content of Cl could lead to the formation of their respective chlorides, present in the form of vapors in the product gas. KCl and NaCl are known to have a negative effect on SOFC performances; no reference literature is available about $PbCl_2$ and $ZnCl_2$ and their effect on SOFC, however their presence in the producer gas must be considered because of their environmental issues. RDF, MSW and digestate can, on the basis of the ultimate analysis, lead to a producer gas with relatively high contents of H_2S and HCl and therefore their formation should be taken into account and properly addressed, since both species are known to have deleterious effects on the stable and long-term functioning of the SOFCs [1].

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	4,20	21,68	15,60	0,10	1,00	1 250,00
Olive pomace pitted	Secondary residues of industry utilizing agricultural products	36,00	19,79	5,95	0,06	0,00	1 290,00
Sawmill waste	Primary residues from forest	11,20	18,89	0,41	<0,01	<0,01	1 400,00
Multi-essence wood chips	Waste from wood	28,50	17,88	1,45	0,02	<0,01	1 430,00
Olive Prunings	Secondary residues from wood industries	14,90	17,76	1,55	<0,01	<0,01	1 490,00
Almond shells	Secondary residues of industry utilizing agricultural products	10,00	17,68	1,41	<0,01	<0,01	1 000,00
Scarf and sawdust	Secondary residues from wood industries	6,60	17,14	0,48	<0,01	<0,01	>1 465
Wood chips	Primary residues from forest	8,90	16,74	0,54	<0,01	<0,01	>1 465
Corn cobs	Agricultural residues	9,00	16,62	3,04	0,03	0,44	645,00
Arundo Donax	Agricultural residues	10,10	16,25	4,48	0,11	0,29	1 180,00
1- Wheat Straw (pellets 10 mm)	Agricultural residues	7,60	15,98	9,22	0,05	0,12	1 090,00
2- Wheat Straw (pellets 6 mm)	Agricultural residues	7,60	15,40	11,29	0,08	0,21	1 180,00
Rice husks	Secondary residues of industry utilizing agricultural products	5,20	15,19	18,70	0,02	0,03	880,00
Digestate	Digestate from biogas production	71,20	12,69	25,81	0,97	0,10	1 245,00
Black Liquor	Secondary residues from wood industries	20,60	11,20	58,28	0,74	0,12	600,00
Municipal solid waste	Municipal waste	28,00	10,22	37,01	0,20	0,40	1 220,00

Figure 2: Biomass types and technical characteristics

4 GASIFICATION, HOT GAS CLEANING AND CONDITIONING AND SOFC TESTS

Regarding the bio-syngas representative tar to be tested in the lab facilities the project has carried out an open access literature overview (www.blazeproject.eu/resources), analyzing 83 papers (mostly experimental). It was 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: 40% H_2, 22% CO, 15% CO_2, 5% CH_4, 18% H_2O) and 2 organic (toluene between 250 and 750 mg/Nm3, and naphthalene between 25 and 75 mg/Nm3, i.e. 5 and 15 ppm) and 2 inorganic (H_2S between 1 and 3 ppm, KCl between 50 and 200 ppm) representative contaminants levels.

ENEA tested representatives of "good" (i.e. lignocellulosic, e.g. shells) and "bad" (e.g. low-grade corn grit and olive pomace with high content of chlorine and sulfur) feedstock selected in the previous task in the lab scale gasifier. Some hardware modifications were first implemented to the feeding system and head of the reactor in order to allow the feeding to the reactor.

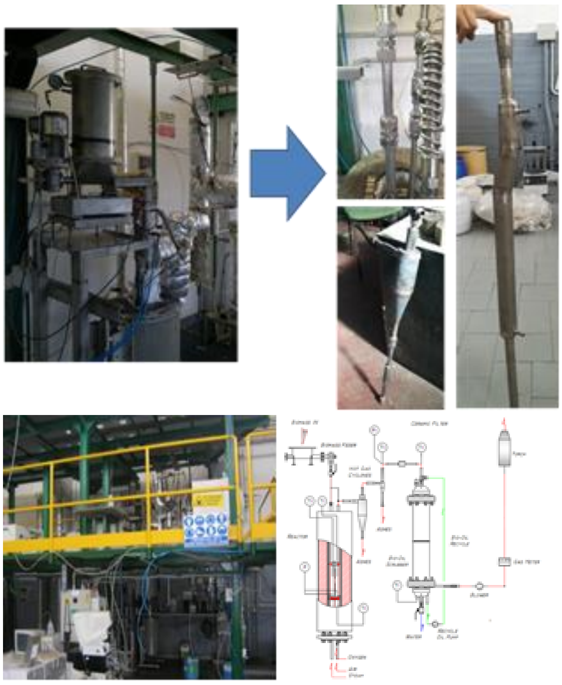

Figure 3: ENEA gasification lab test rig: reactor, facility and scheme

A first gasification campaign was started with the aim to evaluate, according to the purpose of the task, the cleaning effect of in-bed calcined dolomite on the contaminant levels in the producer gas, and the reliability of the upgraded facility were evaluated.

Steam/oxygen gasification tests were then carried out using low grade corn grit as a feedstock and olivine or olivine/dolomite mixture as bed material. The experimental results provided evidence of the efficacy of the calcined dolomite at typical gasification conditions (i.e. ER ≈ 0.25, S/B ≈ 0.5, Tbed ≈ 830 - 850 °C). Specifically, compared with olivine, a mixed bed of olivine and calcined dolomite, 70:30 in percentage by weight, provided a significant reduction (from 23% to 76%) in the contents of both Tar and inorganic contaminants [2,3].

UNIVAQ performed different test campaigns on tar catalysts using the micro-reactor test rig shown in the figure below.

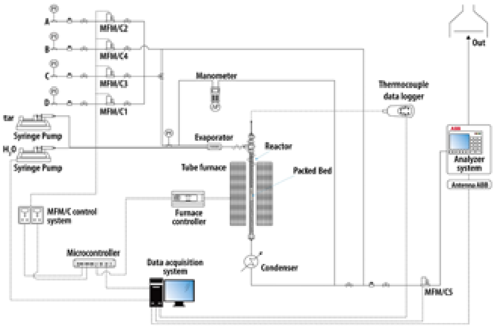

Figure 4: UNIVAQ Micro reactor test rig scheme

First, tests were carried out with a nitrogen flow to get a space velocity similar to that achievable in the candle (5000-6000 gas hourly space velocity, GHSV) with tar as indicated above (toluene and naphthalene as tar representatives). The obtained conversion was in all cases close to 100 %. In order to obtain better discrimination in efficacy, the space velocity was gradually increased till 15000 GHSV. With different inlet tar concentrations the two catalysts tested were similarly active, both converting more than 90 % of tarry carbon to COx, confirming the first order kinetics. A relevant decrease in conversion was observed after lowering the temperature from 800 °C to 700 °C and due to the presence of Sulphur. Gasification tests with catalytic filter were carried out in a bench-scale experimental set-up in the laboratories of the University of Teramo, shown in the figure below together with the sorbents test bench realized in USGM [4-11].

Figure 5: UNIVAQ catalyst and USGM sorbent test-rig

By using almond shells alone, the biomass feedstock selected for the pilot plant, and in mix with Solid Recovery Fuel, in order to add a representative of the problematic feedstock analysed, from the obtained results it was possible to observe that for similar operating conditions (temperature and Steam/Biomass ratio), the test carried out with the mix gave a lower gas yield and extremely high tar content, compared with the tests with simple almond shells. The higher tar content was ascribed to the decomposition of the complex hydrocarbons present in the plastic materials contained in the SRF, that can likely be related to a high production of hydrocarbons, such as lighter tars. Different configurations were tested in order to avoid excessive pressure drops for the gas in the catalytic volume and higher catalytic activity. The best configuration was found to be the one where the catalyst was inserted only in the peripheral part of the cavity of the filter, leaving an internal empty space for the gas to leave the candle, by confining the catalyst in the external part of the candle by means of a ceramic porous tube inserted as boundary between the catalytic volume and the hollow space [4-11].

SP manufactured 30 button cells to be used at ENEA and 4 short stacks to be used at EPFL. Button cells were investigated in order to perform mechanistic studies on the conversion of syngas and on the poisoning effects of contaminants while short stacks were tested in order to investigate the operational window of the SOFC stack. ENEA successfully performed an extensive parametric investigation on button cells samples fed by the following gas mixtures: H2-N2, H2-H2O and CO-CO2, along with a parameterization on the O2 content at the cathode side in order to identify the cathodic processes. Up to six different processes were identified from the DRT plots that were obtained from the impedance spectra, and allowing for quantification of the respective electrochemical processes that take place in the fuel cell. DRT peaks P1 and P2 were both ascribed to the electrochemical oxidation of the fuel occurring at the anode side (e.g. P1 is related to the transport of O2- ions within the YSZ matrix of the anode functional layer) and they showed a prominent dependency on the operating temperature. P2, being unaffected by anodic fuel type and composition, and slightly influenced by the O2 content in the oxidant stream, was ascribed to the charge transfer mechanism for the reduction of O2 to O2- at the cathode side. P4, P5 and P6 were associated, respectively, to mass transport, gas conversion impedance and diffusion of the cathodic gas in the porous structure [12,13].

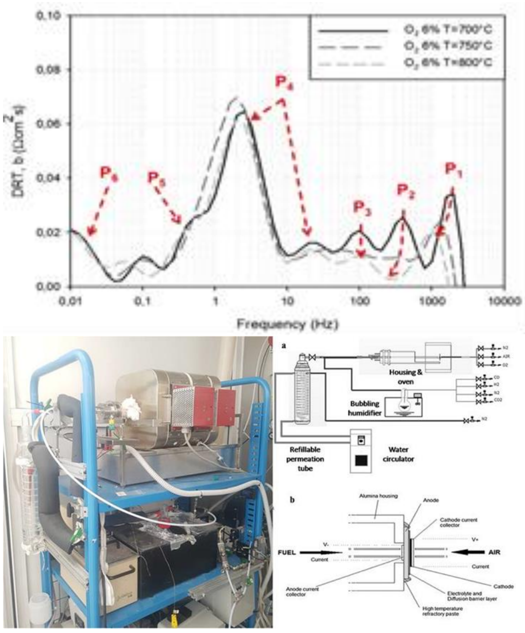

Figure 6: ENEA test rig and DRT plot

EPFL completed the adaptation of the test bench to host the new stack design as showed in figure below. The initial IV curves measured in H2/N2 gas conditions showed good homogeneity of the different repeating units in the short stack.

Figure 7: EPFL test-bench and modification for producing H2S from the decomposition of sulfolane

5 SIMULATIONS AND PILOT PLANT DESIGN

The modeling activities performed 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. For example, CFD Simulations of a 3D Vessel with catalytic candles for validation of the 2D model with experimental data from the bench scale gasifier (Figure 5a) were performed. System simulations were 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 below and www.blazeproject.eu/resources [14].

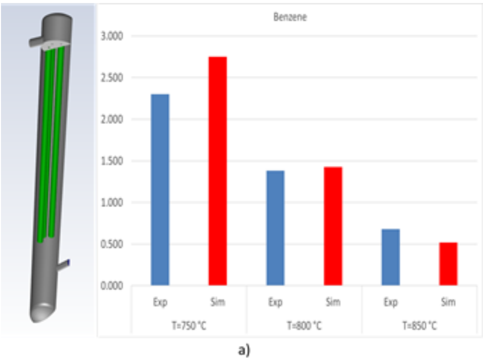

Figure 8: BLAZE modelling: benzene CFD simulations (mg/Nm3)

2 Sorbents and 1 tar reformer were selected as gas cleaning units, and three recirculation points were highlighted and studied for pilot plant implementation: gasification chamber, combustion chamber of the gasifier and fuel inlet of the SOFC unit. The dimensioning of the steam driven gas-bearing supported blower was developed taking into account the results of the optimization and more specific and detailed calculations regarding pressure losses and plant ranges of operation [15,16].
EPFL has simulated potential BLAZE plants by means of the modelling software Aspen Plus, consisting in the allothermal BFB gasifier, gas purification units, SOFC unit (LSM), recirculator and auxiliaries. The cases B, D and F, showed in the table below, were specifically modeled, see related deliverable www.blazeproject.eu/resources [14, 17-21]].

Table I: Cases analysed (AOG: Anode Off-Gas, LSM: Large Stack Module, FU: fuel utilisation,)

Name	**Description**
Case B	Pressurized gasifier. AOG sent to the SOFC LSM inlet stream (RR=0.5) and the rest to the gasifier combustor. The turbo-fan is used in the AOG to LSM stream. FU global = 0.75.
Case D	Pressurized gasifier. AOG sent to the gasifier combustor (without turbo-fan). Case D1 (FU = 0.6) and D2 (FU = 0.75).
Case F	Analogous to B, without a pressurized gasifier but with a suction blower after the tar reformer. FU global = 0.75.

The figure below show the main PFDs analysed

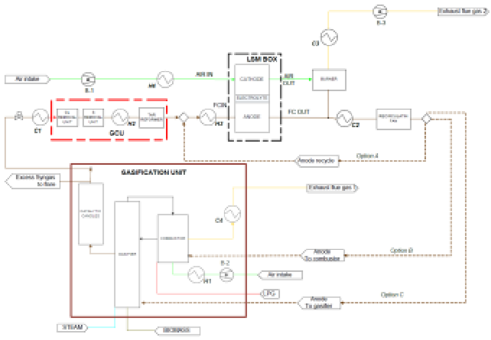

Figure 9: BLAZE modelling: PFD options.

The table below summarises the efficiencies obtained for the 4 PFD's.

Table II: Cases analysed (AOG: Anode Off Gas, LSM: Large Stack Module, FU: fuel utilisation,)

Results	**Case B**	**Case D1**	**Case D2**	**Case 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
Inlet 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

This scenario analysis, together with targeted sensitivity analyses, points out that:

- When recirculating the AOG to the gasifier, there is a larger production of syngas, however with lower calorific value. More LPG needs to be consumed in the combustor, and the performance of the SOFC is penalized due to the syngas dilution.
- There is no clear benefit between Case B and Case D. However, the SOFC performance is penalized, as mentioned before, due to syngas dilution.
- In all cases, the use of the AOG in the combustor of the gasifier decreases the use of LPG and increases the overall efficiency (increasing inlet air/steam temperature to combustor/ gasifier).

For these reasons, Case D was selected for optimization (see in Figure below the specific layout, with the optimization variables in red, and the range of values in the table of the right) [14, 22, 23].

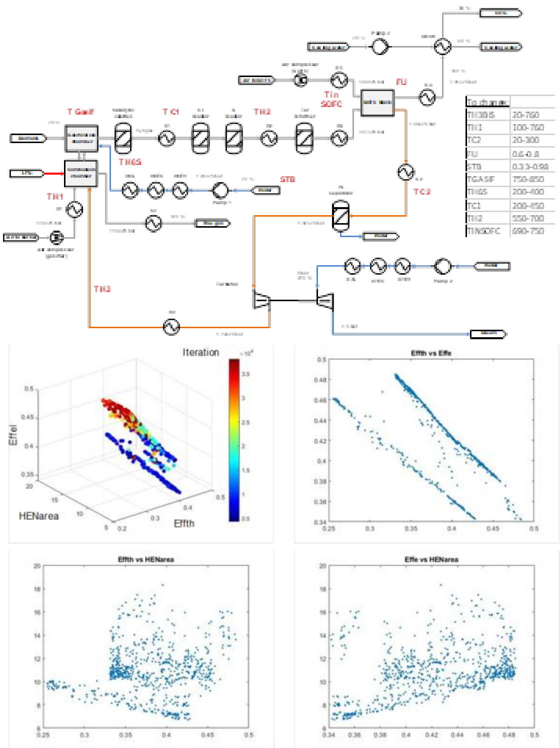

Figure 10: PFD proposed for optimization. In red: optimization variables (range of variation in the table) and Pareto front

The systematic optimization approach used Matlab, Aspen Plus and AMPL. The multi-objective algorithm is Ev-MOGA. The main purpose was to optimize the process design specifications and the heat exchange network (HEN) structure. The results for selected points of the Pareto frontier (maximum Eff elec, maximum Eff th and minimum heat exchanger area) showed that the plant efficiency can reach 80 % and the electrical efficiency can be as high as 49 %. The next steps are to perform the cost analysis of selected scenarios and depict their HEN structure. [14-29]

6 PILOT AND PLANT REALIZATION

Based on the activities carried out in the BLAZE project so far, a pilot plant layout was defined. Although pressurized feeding systems exist for large scale gasifiers, for small systems like the BLAZE pilot gasifier (100 kWth input), a pressurized feeding system is not commercially available. Similarly, for atmospheric operation, a high temperature blower or suction blower is not available. Thus, considering the results of the system simulations and optimization that identified the best use of AOG to the combustor of the gasifier, it was decided to use the steam driven gas-bearing supported blower to push the syngas from the Gas Cleaning Unit to the LSM anode, as described in Figure 1, after having fixed the BLAZE scheme. WT took care of the mechanical design and fabrication of some units, while UNIVAQ together with USGM fixed the detailed layout of the pilot scale gasifier as shown in the figure below.

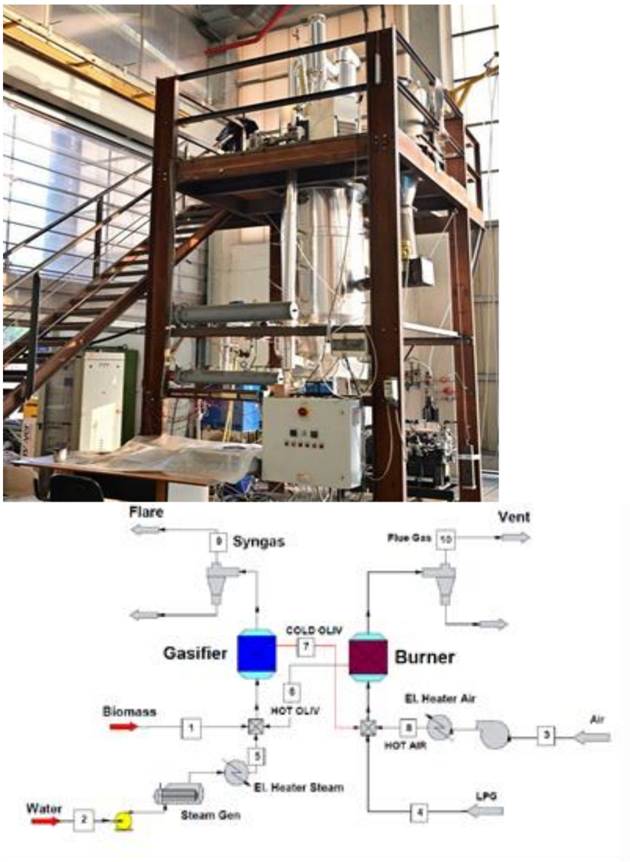

Figure 11: Pilot scale gasifier PFD and photo

The input air to the combustion chamber of the gasifier was pre-heated electrically. The gasifier was insulated with a double layer, in order to minimize the thermal dispersions. A labview control system, reported in the Figure 12, was built in order to measure and control the process.

Figure 12: Display of the control system of the pilot plant

To allow a lower flow of steam for fluidization (i.e. below S/B=1), olivine with a mean particle size of 557 µm was used as bed material. To allow the air injections just over the fluidized bed, in order to increase the temperature locally and thus to guarantee a primary reduction of tar in the freeboard, four inlets were connected around the cylindrical gasifier. Biomass gasification tests were carried out on the gasifier with the operating conditions, the results of which are shown in Table III.

Table III: Gasifier tests: operating conditions and results

	Test #1	**Test #2**	**Test #3**
Biomass	Hazelnut shells		
Biomass feed rate a.r. (kg/h)	10	15	15
Olivine $d_{3,2}$ diameter (µm)	557		
Steam (to gasifier) (kg/h)	~11.5	~11.5	~11.5
S/B	~1	~0.75	~0.75
Air (to combustor) (kg/h)	43		
Air injection (l/min)	-	-	80
LPG (to combustor) (l/min)	16		
T gasifier (°C)	810	830	860
T upper freeboard (°C)	615	680	750
T combustor (°C)	910	930	960
Steam Inlet T (°C)	300		
Air inlet T (°C)	25		
Length of tests (min)		60	
H2 (%vol dry)	36.30	34.34	32.70
CO (%vol dry)	19.03	21.40	19.16
CO2 (%vol dry)	29.08	33.36	33.58
CH4 (%vol dry)	10.25	10.90	7.04
LHV (MJ/Nm3)	9.99	10.31	8.68
Tar (g/Nm3)	8.05	10.57	3.30

Test #2, carried out at a lower S/B ratio and higher temperature compared to test #1, has a slightly higher tar content, probably because of the higher biomass feeding rate. Test #3, in which air injections were added in the freeboard, showed significantly higher temperatures in the gasifier and reduction in the calorific value and tar content. Furthermore, it was noticed that the operating temperatures remained constant during the tests, which is a proof of the effectiveness of the thermal insulation and the validity of the chosen operating conditions, and thus the auto-thermal stability of the process. The results show that the obtained gas composition is close to the one expected, with high contents of H2 and CO. The sum of the volume fractions of the gases is higher than 90%, indicating that the missing fraction, which is assumed to consist of N2, hydrocarbons higher than CH4, and residual moisture, is as low as 10%.

Figure 13: 25 kW Large Stack Module

SOLIDpower manufactured the 25 kWe Large Stack Module (LSM), depicted in the Figure above, with the following specifications: power output 25 kWe, integrating 4 stacks of 6.5 kWe.The LSM was tested under H2-N2 mixture and air, reaching a maximum power of 25 kWe at 85% fuel utilization and a temperature of 700oC. The maximum electrical efficiency was 60%. Furthermore, the main technical, economic, environmental key performance indicators and the main health/safety and legal issues have been identified within the framework of LCA, LCC, Health and Safety studies that are just started. Finally, EUBIA launched the Multi Stakeholder platform BioCogen 2030 and realize the Communication and Dissemination plan (see www.blazeproject.eu/resources and the Figure below) and started the Market Analysis and Business model, in close cooperation with all the partners (in particular WT, ENERECO, HyGear and USGM).

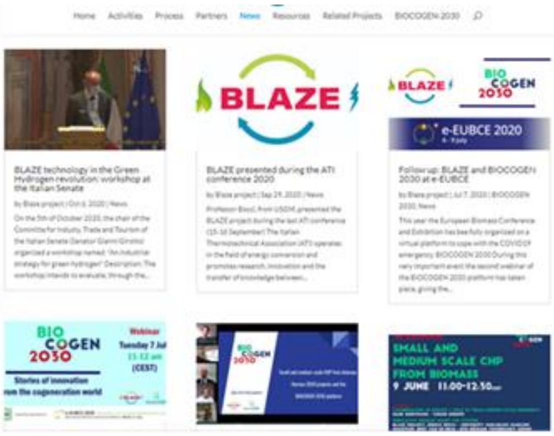

Figure 14: Diss.&Comm. and MSP BioCogen 2030

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7 REFERENCES

[1] https://www.blazeproject.eu/wp-content/uploads/2020/04/D2.1_Biomass_20_12_19_for-Website.pdf

[2] D. Barisano, C. Freda, F. Nanna, E. Fanelli, A. Villone, Biomass gasification and in-bed contaminants removal: Performance of iron enriched Olivine and bauxite in a process of steam/O2 gasification, Bioresour. Technol. 118 (2012) 187–194. doi:10.1016/j.biortech.2012.05.011.

[3] D. Barisano, G. Canneto, F. Nanna, A. Villone, E. Alvino, Production of gaseous carriers via biomass gasification for energy purposes, Energy Procedia, 2014. Volume 45, Pages 2-11

[4] E. Savuto, A. Di Carlo, E. Bocci, A. D'Orazio, M. Villarini, M. Carlini, P.U. Foscolo, Development of a CFD model for the simulation of tar and methane steam reforming through a ceramic catalytic filter, Int. J. Hydrogen Energy. 40 (2015) 7991–8004

[5] E Savuto, A Di Carlo, K Gallucci, S Natali, E Bocci, Characterization and performance analysis of an innovative Ni/Mayenite catalyst for the steam reforming of raw syngas, Fuel 194, 348-356, 2017

[6] V Pallozzi, F Zaza, A Di Carlo, E Bocci, M Carlini, Gas sensors for sustainable and safe integrated gasification-FC system, International Journal of Hydrogen Energy 42 (49), 29606-29619, 2017

[7] V. Pallozzi, A. Di Carlo, E. Bocci, M. Carlini, Combined gas conditioning and cleaning for reduction of tars in biomass gasification, Biomass and Bioenergy 109, pp. 85-90, 2018

[8] E. Savuto, R.M. Navarro, N. Mota, N., A. Di Carlo, E. Bocci, J.L.G. Fierro, Steam reforming of tar model compounds over Ni/Mayenite catalysts: effect of Ce addition, Fuel 224, pp. 676-686, 2018

[9] A. di Carlo, M Moroni, E Savuto, V Pallozzi, E Bocci, P Di Lillo, Cold model testing of an innovative dual bubbling fluidized bed steam gasifier, Chemical Engineering Journal 377, 119689, 2019

[10] V Marcantonio, M De Falco, M Capocelli, E Bocci, A Colantoni, M Villarini, Process analysis of hydrogen production from biomass gasification in fluidized bed reactor with different separation systems, International Journal of Hydrogen Energy 44 (21), 10350-1036, 2019

[11] V Marcantonio, E Bocci, JP Ouweltjes, L Del Zotto, D Monarca, Evaluation of sorbents for high temperature removal of tars, hydrogen sulphide, hydrogen chloride and ammonia from biomass-derived syngas by using Aspen Plus, International Journal of Hydrogen Energy 45 (11), 6651-6662, 2020

[12] Davide Pumiglia, Simone Vaccaro, Andrea Masi, Stephen J. McPhail, Mauro Falconieri, Serena Gagliardi, Livia Della Seta, Maurizio Carlini, Aggravated test of Intermediate temperature solid oxide fuel cells fed with tar-contaminated syngas, Journal of Power Sources, Volume 340, 2017

[13] L Del Zotto, A. Monforti Ferrario, A. Hatunoglu, A. Dell'Era, S. McPhail, E. Bocci Experimental Procedures & First Results of an Innovative Solid Oxide Fuel Cell Test Rig: Parametric Analysis and Stability Test, Energies 14 (8), 2038, 2021

[14] https://www.blazeproject.eu/wp-content/uploads/2021/02/BLAZE-_P4_Task-4.1-EPFL_D4.1-System-models_V231032020.pdf

[15] Patrick Wagner, Jan Van Herle, Jürg Schiffmann, Theoretical and Experimental Investigation of a 34 Watt Radial-Inflow Steam Turbine with Partial-Admission, ASME. J. Eng. Gas Turbines Power. August 2021; 143(8)

[16] Patrick Wagner, Jan Van Herle, Lili Gu, Jürg Schiffmann, Influence of Large Relative Tip Clearances for a Micro Radial Fan and Design Guidelines for Increased Efficiency, Proceedings of the ASME Turbo Expo 2020, Volume 8, September 21–25, 2020. V008T20A025. ASME.

[17] V Marcantonio, E Bocci, D Monarca, Development of a chemical quasi-equilibrium model of biomass waste gasification in a fluidized-bed reactor by using Aspen Plus, Energies 13 (1), 53, 2020

[18] V Marcantonio, A Monforti Ferrario, A Di Carlo, L Del Zotto, D Monarca, E Bocci, Biomass Steam Gasification: A Comparison of Syngas Composition between a 1-D MATLAB Kinetic Model and a 0-D Aspen Plus Quasi-Equilibrium Model, Computation 8 (4), 86, 2020

[19] E. Bocci, M. Sisinni, M. Moneti, L. Vecchione, A. Di Carlo, M. Villarini, State of art of small scale biomass gasification power systems: A review of the different typologies, in: Energy Procedia, Elsevier Ltd, 2014: pp. 247–256.

[20] V. Pallozzi, A. Di Carlo, E. Bocci, M. Villarini, P.U. Foscolo, M. Carlini, Performance evaluation at different process parameters of an innovative prototype of biomass gasification amed to hydrogen production, Energy Convers. Manag. (2016).

[21] M. Moneti, A. Di Carlo, B. Enrico, P.U. Foscolo, M. Villarini, M. Carlini, Influence of the main gasifier parameters on a real system for hydrogen production from biomass, Int. J. Hydrogen Energy. in press (2016).

[22] Ligang Wang, Yumeng Zhang, Chengzhou Li, Mar Pérez-Fortes, Tzu-En Lin, François Maréchal, Jan Van herle, Yongping Yang, Triple-mode grid-balancing plants via biomass gasification and

reversible solid-oxide cell stack: Concept and thermodynamic performance, Applied Energy, Volume 280, 2020

[23] Yumeng Zhang, Ningling Wang, Chengzhou Li, Mar Pérez-Fortes, Liqiang Duan, Jan Van herle, François Maréchal, Tzu-En Lin, Ligang Wang and Yongping Yang, Triple-Mode Grid-Balancing Plants via Biomass Gasification and Reversible Solid-Oxide Cell Stack: Economic Feasibility Evaluation via Plant Capital-Cost Target, Front. Energy Res., 14 April 2021

[24] M Villarini, D Monarca, M Carlini, EM Mosconi, E Bocci, Economic analysis and risk assessment of biomass gasification CHP systems of different sizes through Monte Carlo simulation, Energy Reports 7, 1954-1961, 2021

[25] M Villarini, V Marcantonio, A Colantoni, E Bocci, Sensitivity analysis of different parameters on the performance of a CHP internal combustion engine system fed by a biomass waste gasifier, Energies 12 (4), 688, 2019

[26] Hamedani, Sara Rajabi; Del Zotto, Luca; Bocci, Enrico; Colantoni, Andrea; Villarini, Mauro, Eco-efficiency assessment of bioelectricity production from Iranian vineyard biomass gasification, Biomass and Bioenergy, 127,105271, 2019

[27] Rajabi Hamedani, Sara; Kuppens, Tom; Malina, Robert; Bocci, Enrico; Colantoni, Andrea; Villarini, Mauro, Life Cycle Assessment and Environmental Valuation of Biochar Production: Two Case Studies in Belgium, Energies,12,11,2166, 2019

[28] Monforti Ferrario Andrea, Bocci Enrico, et al., Techno-economic analysis of in-situ production by electrolysis, biomass gasification and delivery systems for Hydrogen Refuelling Stations: Rome case study, Energy Procedia, pp. 82-89, 2018

[29] Hamedani S. R., Villarini M., Colantoni A., Moretti M., Bocci E, Life Cycle Performance of Hydrogen Production via Agro-Industrial Residue Gasification—A Small Scale Power Plant Study, Energies 2018, 6(7), 3167-3181; doi:10.3390/en6073167, 2018