Results from oxy-fuel CFBC process simulations

Author: Joseba Moreno, Max Schmid

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WP Leader or co-leader	Camilla Thomson	Camilla Thomson	6th June 2022
Project Coordinator	Mathieu Lucquiaud		

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Executive Summary

Within the NEWEST-CCUS project (Project-Nr.: 299683), different carbon capture, usage, and storage (CCUS) technologies are to be investigated in the context of Waste-to-Energy (WtE) plants, aiming at achieving net-negative CO_2 emissions.

The deployment of oxy-fuel combustion in the waste management sector can make municipal and industrial waste a strategic resource for climate change mitigation. This approach is often referred to as bioenergy with carbon capture and storage (BECCS) since biogenic carbon in waste becomes a domestic source of negative emissions.

At the Institute of Combustion and Power Plant Technology (IFK) of the University of Stuttgart, experimental tests with solid recovered fuel (SRF) were performed using a pilot-scale circulating fluidized bed oxy-combustor (oxy-CFBC). In parallel, a full-scale oxy-CFBC waste-to-energy (WtE) plant was designed using Aspen Plus®. The model was subsequently validated to serve as a computer tool to predict the oxy-combustion process' behavior under various operational conditions. In this deliverable, the performance of the full-scale model is evaluated upon changes in (i) fuel composition, (ii) oxygen concentration in oxidizer and flue gas, and (iii) extent of gas pollutant treatment. Fuel selection has shown not to affect gaseous emissions significantly. However, caution is advised when interpreting NO_x results, as the simulation work does not consider side-effects caused by fuel inhomogeneity or dosing feasibility (e.g., localized hot spots).

The results included in this study contribute to a better understanding of the fundamental oxy-fuel knowledge with alternative fuels and may serve to guide future process design and scale-up.

Table of Contents

List of abbreviations

Acronym	Description
ad	air dried
ASU	Air Separation Unit
BFD	Block Flow Diagram
CFB	Circulating Fluidized Bed
CFBC	Circulating Fluidized Bed Combustion
CPU	CO_2 Processing Unit / CO_2 Compression and Purification Unit
FGD	Flue Gas Desulfurization
HP	High Pressure
HPC	High Pressure Column
in	inlet
LP	Low Pressure
LPC	Low Pressure Column
NIR	Near-Infrared
OLE	Object Linking and Embedding
out	outlet
PFD	Process Flow Diagram
PM	Particulate Matter
SNCR	Selective Non-Catalytic Reduction
SRF	Solid Recovered Fuel
th	thermal
waf	water and ash free
wf	water free
WtE	Waste-to-Energy

List of symbols

Symbol	Description
Ca/S	Calcium to sulfur molar ratio
ξ_i	Molar fraction of component “i” (mol%)
$\dot{N}_\iota$	Molar flow of component “i” (kmol/h)
T	Temperature (°C)
$v_{recycled}$	Flue gas recirculation ratio (%)
y_i	Volume fraction of component “i” in gas (vol% or ppmv)
γ_i	Mass fraction of component “i” in fuel (kg/kg)

1 Introduction

Climate change mitigation and sustainable waste management are among the most important societal challenges recognized by the 2015 Paris Climate Agreement [14] and the European Union Action Plan for a Circular Economy Package [3]. Incineration and co-combustion are well-established strategies for the valorization of refuse waste materials. The thermal utilization of waste-derived fuels allows reducing the volume of solids dumped in landfills, thereby decreasing greenhouse gas emissions and adverse health and environmental impacts. However, because of the challenges resulting from the intrinsic fuel characteristics (e.g., form and particle size, ash and moisture content), combustion systems need to be carefully designed to guarantee reliable plant operation and effective emissions control.

The present deliverable offers a performance assessment of a full-scale oxy-fuel circulating fluidized bed combustion (CFBC) waste-to-energy (WtE) plant by Aspen Plus®. The model has been validated using data from the IFK's 200 kW_{th} CFBC pilot facility, powered by oxy-fuel combustion of solid recovered fuel (SRF) at semi-industrial conditions (i.e., recirculated flue gas and technically pure oxygen). Within the scope of this report, the influence of (i) fuel composition, (ii) inlet and outlet oxygen concentration, and (iii) gas pollutant emission is evaluated.

2 The Aspen Plus® simulation software

The following sub-section gives a first impression of Aspen Plus®. For a detailed description of the simulation tool please refer elsewhere [1,2].

Aspen Plus is a process simulator that predicts the behavior of chemical reactions and steps using standard engineering relationships, such as mass and energy balances, rate correlations, as well as phase and chemical equilibrium data. The tool can interactively change specifications, such as the flowsheet configuration, operating conditions, and feed compositions, to predict new cases and analyze alternatives. The software can analyze results, and generate plots, reports, process flow diagram (PFD)-style drawings, and spreadsheet files. Aspen Plus® predicts the cycle performance and performs a wide range of additional tasks such as:

- Perform sensitivity analyses and case studies;
- Generate custom graphical and tabular output;
- Estimate and regress physical properties;
- Fit simulation models to plant data;
- Optimize processes;
- Interface results to spreadsheets and other compatible packages;
- Share input and results among other Windows applications using object linking and embedding (OLE).

Aspen Plus® contains data, properties, unit operation models, built-in defaults, reports, and other features and capabilities developed for specific industrial applications. The software incorporates a comprehensive library of solids unit operations (such as dryers, granulators, crystallizers, fluidized beds, crushers, gas/solid and liquid/solid separators, classifiers, and conveying systems).

3 The full-scale oxy-CFBC WtE facility

Similar to a grate incinerator, a WtE oxy-fuel CFBC facility may consist of the following process steps:

- Incoming waste reception
- Storage of waste and raw materials
- Fuel preparation/conditioning
- Fuel loading into the process
- Cryogenic oxygen production (in an air separation unit, ASU)
- Thermal treatment of the waste
- Energy recovery and conversion
- Flue gas cleaning system
- Flue gas discharge
- CO_2 compression and purification (CPU)
- Emissions monitoring and control

The latter steps can be summarized into four major process blocks according to Figure 1:

- Waste delivery and storage
- Thermal management and energy generation
- Flue gas cleaning
- Preparation of combustion gas and conditioning of combustion flue gas

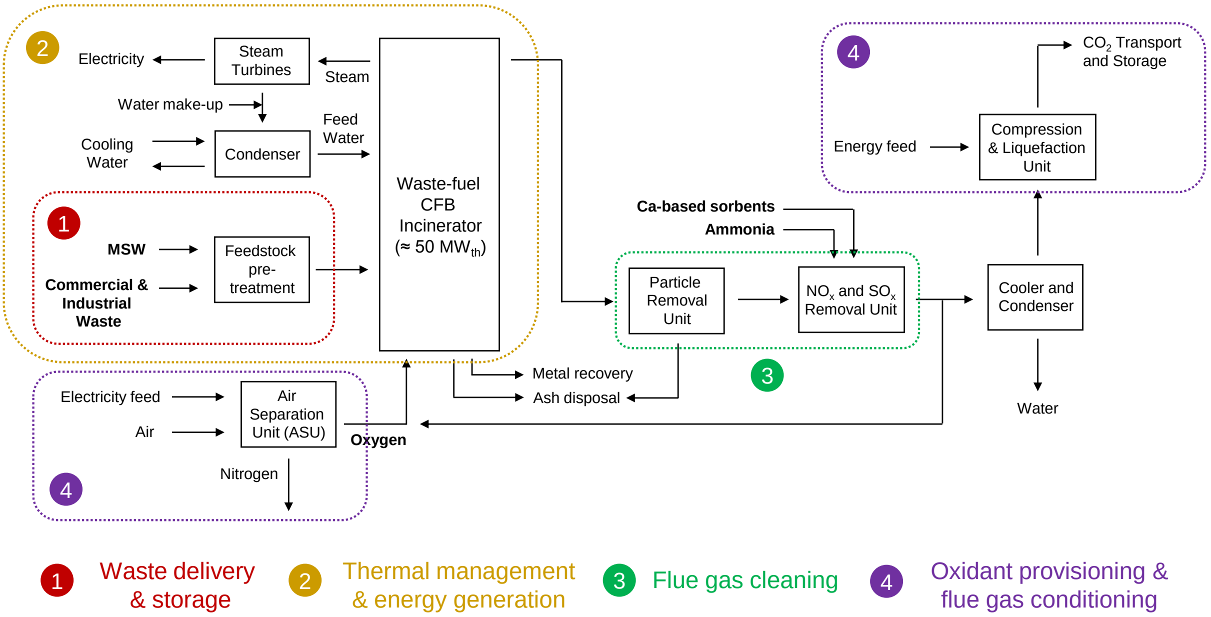

Figure 1. Block flow diagram of the reference oxy-fuel WtE plant with a CFB boiler

4.1 Waste delivery and storage

Compared to grate furnaces, circulating fluidized bed (CFB) units require fuel preparation. Fuel conditioning may be regarded as an economic disadvantage, but it facilitates combustion and ash handling in the furnace. Similarly, the addition of bed material is a cost for CFB systems, although active materials can bring an added value to the process, such as the reduction of acidic gas species using limestone. Also, a great advantage of CFB boilers is their ability to handle short and long-term variations in the fuel composition, which concurrently enables a wider choice of fuels for co-combustion.

Fuel preparation becomes particularly important when considering municipal solid waste, bulky waste and blend industrial waste similar to municipal waste. The process comprises separation of high calorific fractions and a selective reduction especially of chlorine. Near-Infrared (NIR) system sorting can be employed to reduce chlorine and heavy metals in high calorific fractions [5]. The separation of high calorific fractions is followed by the actual production of secondary fuels according to certain quality criteria. The process of producing an SRF is made up of multiple steps; two size reducing steps [6], two wind-shifters for separation of heavy parts (i.e., inerts and metals), and several steps of iron/ non-iron separation. The result is a fluffy SRF with the requested grain size (e.g., $d_{95} > 25$ mm) and a large surface. The residues from the separation of the high calorific fractions from municipal waste are dried in a biological process first and then burnt in waste-to-energy plants to produce heat, steam and power.

4.2 Thermal management and energy generation

3.2.1 The CFB combustion unit

The full-scale oxy-fuel CFBC WtE facility is simulated using Aspen Plus®. The combustion model is constructed and validated using experimental data from the 200 kW_{th} CFB pilot facility located at the University of Stuttgart.

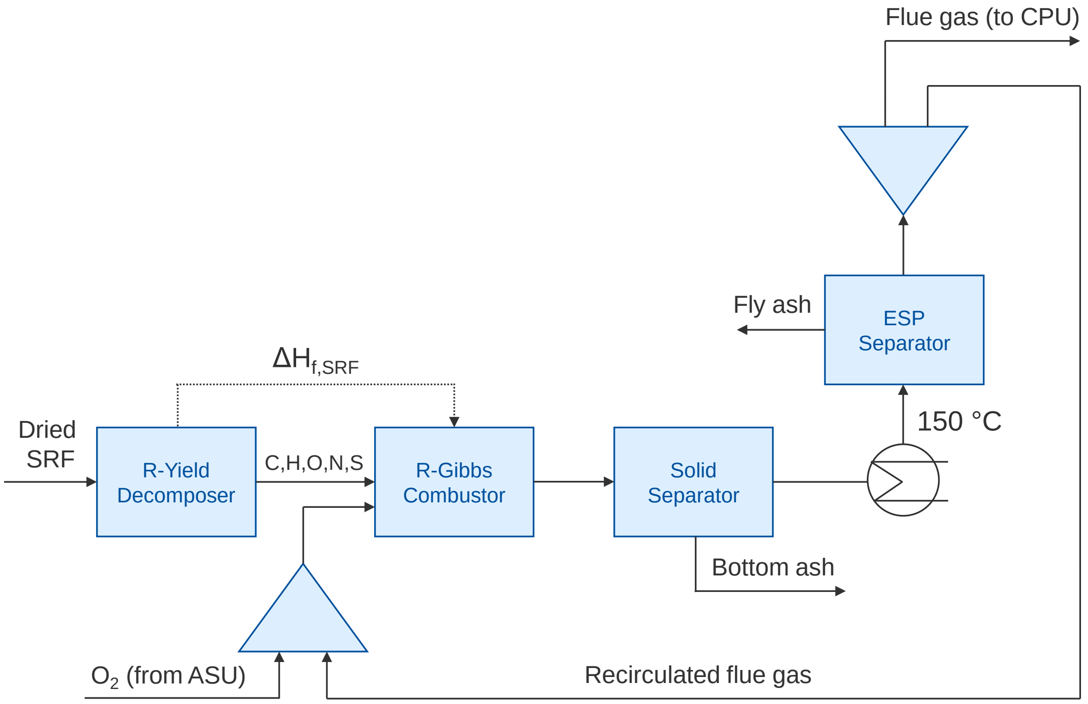

Figure 2. Block flow diagram of the reference combustion model

The block flow diagram (BFD) of the reference combustion model is introduced in Figure 2. The model is based on the following assumptions: (i) the combustion process is divided into four sequential steps: fuel drying, decomposing, burning, and flue gas cleaning; (ii) all blocks are in stable operation states; the parameters cannot be changed with time; (iii) oxidant staging is not considered; (iv) fuel and oxidizer are homogeneously mixed in the reactor; (v) ash does not take part in the chemical reactions during the combustion process; (vi) the unburnt part of C is assumed being ejected to the ash.

The modelled combustion unit works as follows: a dried stream of SRF enters first a R-Yield that decomposes the material into simple components and ash. At the same time, the heat of fuel decomposition is carried to a R-Gibbs unit labeled as combustor. The combustor is used to model reactions that come to chemical equilibrium by minimizing the Gibbs free energy of the system. A mixture of O_2 and recirculated flue gas is used as oxidant. The flue gas is then passed through a solid separator to discharge bottom ash and is cooled down to 150 °C to ensure proper functioning of the ESP separation unit. In the following, the non-recirculated flue gas is directed to the CPU unit.

3.2.2 The steam cycle

The WtE facility considered in this study consists of a power plant with a total thermal input of roughly 50 MW. In the following, the main operating units of the steam cycle are briefly introduced.

- Deaerator (DEA-1)
  A feedwater preheating system with a deaerator is used to preheat the boiler feedwater up to 140 °C. Contrary to a grate boiler, in an oxy-fuel CFB furnace there is no need to preheat the oxidant stream before injection to the chamber, as the flue gas is already recirculated in hot conditions (approx. 150 °C).
- Steam turbines
  Operating experiences from reference boilers have proven to be both efficient and reliable in commercial WtE CFB plants (e.g., Mälarenergie AB or E.ON Värme). Typical steam values for the latter plants are of 450-475 °C and 60-74 bar before turbine expansion. For the sake of simplicity, the reference case included in this study considers steam parameters typical of conventional grate incinerators, namely (i) live steam conditions of 400 °C and 59 bar before turbine expansion, and (ii) 140 °C and 3.5 bar after reheat. Nevertheless, owing to the continuous and extensive development work in CFB technology, WtE with advanced steam conditions are also available. Taking the WtE facility operated by Zibo Green New Energy Co., Ltd. In Linzi (China) steam parameters as high as 520 °C and 90 bar are now possible. Besides, the turbine island consists of a high-pressure (HP) turbine and a low-pressure (LP) turbine. Also, steam bleed streams are considered. The steam bleeding of the HP turbine feeds the deaerator unit at 3.5 bar, whereas the LP turbine steam bleeding feeds the condenser and the feedwater heater at 1.5 bar.
- Condenser
  The condenser is fed by the LP turbine and the recirculated feedwater stream. The condenser consists of a once-through cooling system with a cooling water supply of 18.2 °C and a cooling water temperature rise of 14 °C.
- Specification of other process units
  For the simulation of other process units such as heat exchangers, separators, pumps, fans, compressor or expanders the reference values given in Table 1 are considered. Here as well, the exact efficiencies will depend on the exact type of unit, the size, and on the operating conditions.

Table 1. Efficiencies for pumps, fans, compressors, and expanders

Parameter	Unit	Value
Pump efficiency	%	80
Isentropic efficiency compressor	%	85
Isentropic efficiency expanders	%	85
Fan efficiency	%	85

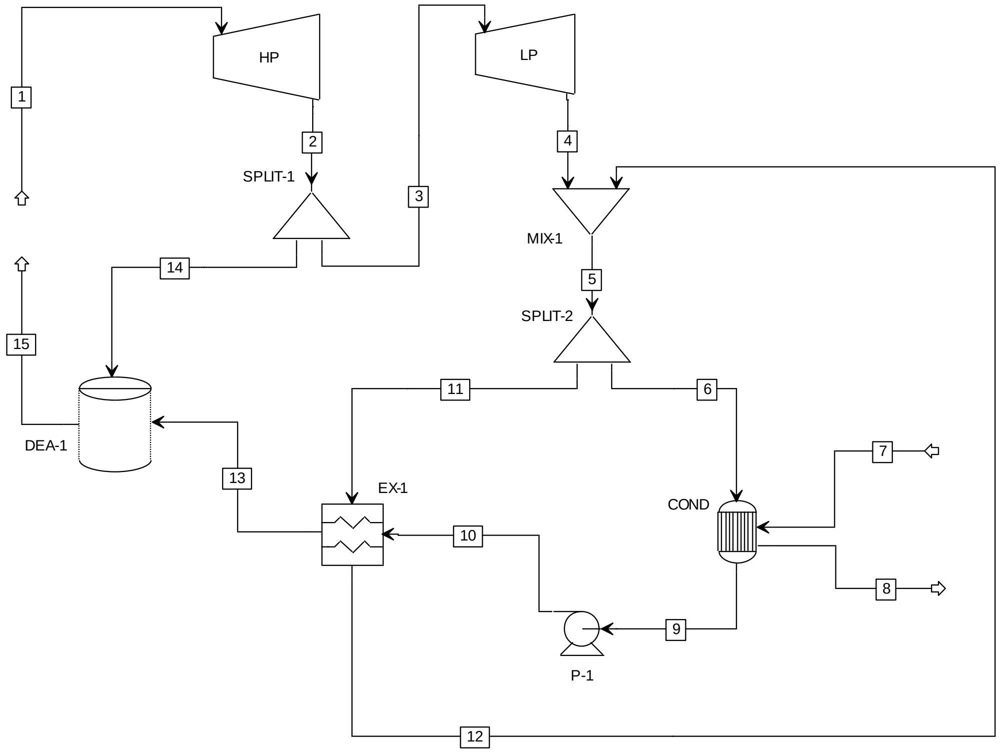

Figure 3. Flowsheet of the WtE oxy-CFBC plant's steam cycle

4.3 Flue gas cleaning

Refuse waste incinerators require effective flue gas treatment to meet stringent environmental regulations. Removal of particulate matter (PM), acidic gases and nitrogen oxides constitutes a major aspect in this regard. The simulation activities included in this deliverable will consider (i) an electrostatic precipitator for removal of PM, (ii) selective non-catalytic reduction of NO_x, and (iii) SO_2 removal by in-situ desulphurization.

Figure 4 shows the combustion model flowsheet of the BFD depicted in Figure 2, which includes corresponding units for the removal of PM (ESP), NO_x (DENOX), and SO_2 (DESOX). ESP corresponds to a built-in electrostatic precipitator, whereas DENOX and DESOX consist of a stoichiometric reactor (RSTOIC).

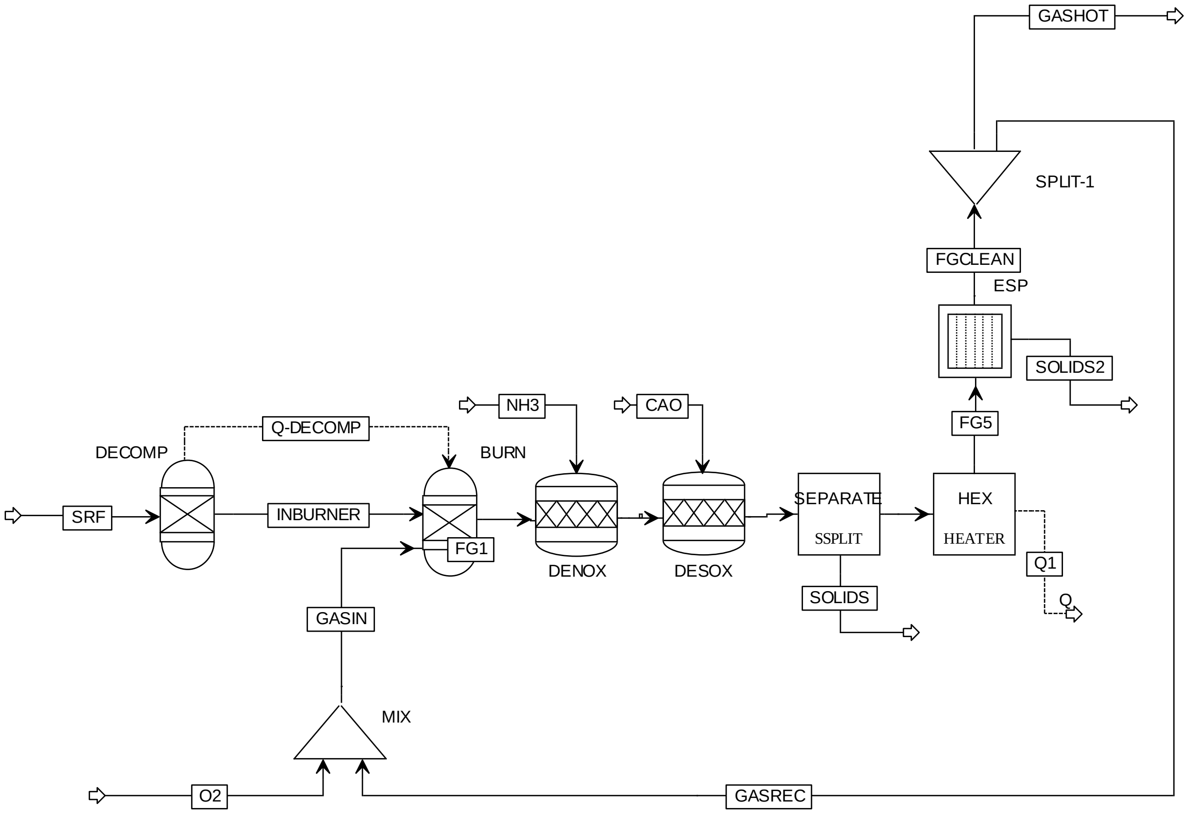

Figure 4. Flowsheet of the modelled combustion unit with corresponding units for flue gas cleaning (ESP, DENOX, and DESOX)

4.4 Provisioning of combustion gas / Conditioning of combustion flue gas

3.4.1 Air separation unit (ASU)

The conventional setting of an oxy-fuel power plant uses the mixture of oxygen and recycled flue gas to replace air to combust with fuel. Different separation methods are available for oxygen production, although high purities and commercial scale of oxygen is produced by cryogenic air separation approach.

The ASU model considered in our simulation activities consists of the double-column cryogenic distillation of air [9]. The air is compressed to 5.5 bar from atmospheric pressure by a three-stage compression procedure and cooled between each stage to 30 °C (see Figure 5). The main heat exchanger cools down the compressed steam to -175 °C. The cooled stream is introduced to the bottom stage of a high-pressure distillation column (HPC) that separates air into oxygen, nitrogen, and argon. The oxygen, from the bottom, and the nitrogen, from the top, are passed through a heat exchanger before being depressurized and supplied to a low-pressure distillation column (LPC). The two columns are thermally coupled by a reboiler (LPC) and a condenser (HPC). The HPC and LPC contain 20 and 50 stages, respectively.

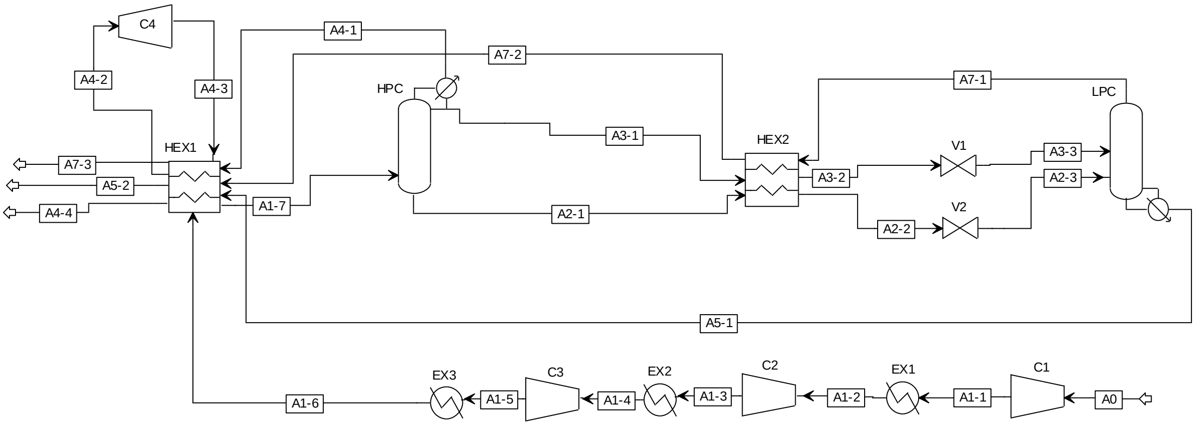

Figure 5. Flowsheet of the simulated double-column cryogenic air separation unit

3.4.2 CO_2 compression and purification (CPU)

Besides, the CO_2 capture from the oxy-fuel process is subjected to a final conditioning step to meet the requirements for CO_2 transport, utilization or storage processes. In our simulation activities the CO_2 derived from oxy-fuel combustion of SRF is compressed to 68 bar by a three-stage compression procedure, in which inter-coolers and flash tanks are used to cool the stream and draw of water (see Figure 6). The stage-by-stage conditions for the CO_2 compression process are given in Table 2.

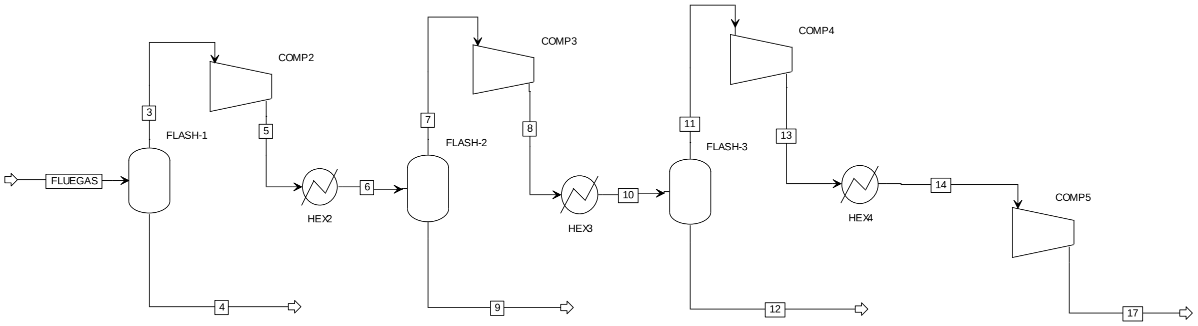

Figure 6. Flowsheet of the simulated three-stage CO_2 compression process

Table 2. Stage-by-stage conditions applied during the CO_2 compression process

	Inlet pressure (bar)	Discharge pressure (bar)	Pressure ratio (-)	Isentropic efficiency (%)
Stage 1	Varies	4.3	4.3	85
Stage 2		18.6	4.3	85
Stage 3		73	3.7	85

Due to the relative high fraction of O_2 contained in the flue gas (ca. 20 mol%), additional treatment is required so as to enhance the purity of the compressed CO_2 stream. In this deliverable, we propose a cryogenic separation and liquefaction process as depicted in Figure 7. On the basis of Ref. [15], the dehydrated flue gas is first subjected to a three-staged separation and liquefaction process. The crude liquid CO_2 separated from the cryogenic separation subsystem is further purified in a distillation subsystem to improve its CO_2 purity.

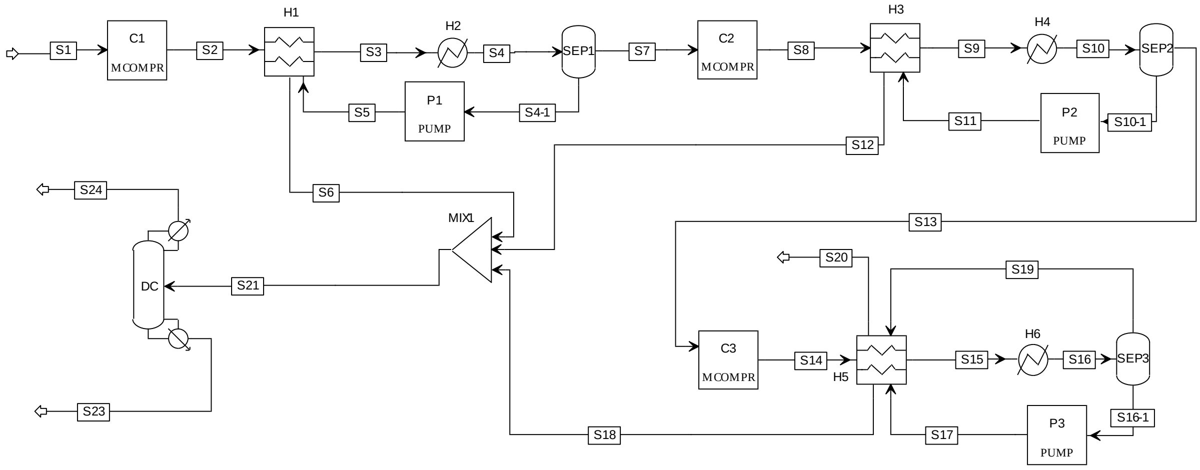

Figure 7. Flowsheet of the simulated CO_2 purification process

4 Results and discussion

4.1 Full-scale model simulation at reference conditions

Table 3 summarizes the thermal management and energy recovery data of the oxy-CFBC facililty when operated at reference conditions. Moreover, the design parameters and results of the air separation unit, H_2O condensation unit, and CO_2 compression and purification unit, also at reference conditions, are given in Table 4.

Table 3. Thermal management and energy recovery data for the full-scale oxy-CFBC WtE model at reference conditions. Fuel: SBS®1

Steam turbine data		
Steam mass flow rate	kg/s	18.5
Turbine inlet temperature	°C	400
Turbine inlet pressure	bar	59
Turbine isentropic efficiency	%	90
Steam turbine high pressure bleed	bar	3.5
Steam turbine low pressure bleed	bar	1.5
Condenser pressure	bar	0.1
WtE boiler data		
Evaporation pressure	bar	60
Steam-superheated temperature	°C	400
Oxidant inlet temperature	°C	150
Oxygen vol. dry fraction in exhaust gases		11.1
Feed water outlet temperature	°C	140
Exhaust gas temperature exist the boiler	°C	130
Boiler efficiency	%	86.5
Energy data		
Fuel feed rate	kg/s	2.8
Thermal input	MW	53.5
Electric output	MW	13.5
Electricity generation efficiency	%	25.2

Table 4. Design data and results for the air separation unit, H_2O condensation unit, and CO_2 compression and purification unit at reference conditions. Fuel: SBS®1

Air separation unit (ASU)		
Molar air inflow	kmol/h	35926
Molar O_2 outlow	kmol/h	1013
O_2 fraction in the outflow stream	mol%	98.7
H_2O condensation unit		
Molar flue gas inflow	kmol/h	1601
O_2 fraction in the inlet stream	mol%	12.0
H_2O fraction in the inlet stream	mol%	41.8
Molar flue gas outflow	kmol/h	926
O_2 fraction in the outlet stream (to CPU)	mol%	20.7
H_2O fraction in the outlet stream (to CPU)	mol%	0.3
CO_2 purification and compression unit (CPU)		
Molar flue gas outflow (to utilization/storage)	kmol/h	677
CO_2 fraction in the outlet stream	mol%	98.6
O_2 fraction in the outlet stream	mol%	0.6
Total amount of CO_2 captured per year	kton/year	133

4.2 Full-scale model validation and evaluation through sensitivity analysis

The chemical composition of the fuels evaluated in this work is introduced in Table 5. SBS®1 and SBS®2 were obtained from REMONDIS GmbH & Co. KG, Region Rheinland (Germany). While SBS®1 is produced from high calorific fractions separated from bulky and household waste, SBS®2 is mainly composed of plastic-enriched waste (i.e., sorting residues of light fraction packaging materials). Both fuels have the quality award RAL-GZ 724 [13] and have been investigated for co-combustion issues within the framework of two European projects (i.e., RECOFUEL and RECOMBIO) [4,10]. Besides, Chemnitz was obtained from the Chemnitz AWVC (Germany) and consisted of non-hazardous municipal solid waste. In addition, pelletized steam-treated municipal solid waste from ECONWARD® (Spain) was obtained. All four SRFs were intentionally prepared for quality criteria such as calorific value and mercury or chlorine content [8]. Under air-dried conditions, the net calorific value of SBS®1, SBS®2, Chemnitz, and ECONWARD® accounted for 19.1, 29.5, 14.7, and 14.3 MJ/kg, respectively. In parallel, the volatile matter content for each of these fuels yielded respective values of 85.3, 94.9, 87.8, and 88.2 wt% on a water and ash-free basis.

Table 5. Chemical composition of the solid recovered fuels considered for the simulation activities (waf: water-ash-free, wf: water-free, ad: air-dried)

	γ_C	γ_H	γ_O	γ_N	γ_S	γ_{Cl}	γ_{ash}	γ_{H_2O}
	kg/kg, waf						kg/kg, wf	kg/kg, ad
Remondis SBS®1	0.559	0.072	0.334	0.025	0.003	0.006	0.125	0.009
Remondis SBS®2	0.706	0.104	0.164	0.012	0.002	0.012	0.065	0.015
Chemnitz	0.569	0.079	0.314	0.023	0.006	0.009	0.338	0.028
ECONWARD®	0.538	0.087	0.337	0.024	0.004	0.010	0.207	0.100

In this deliverable, the model's performance is evaluated using three different variables, namely: (i) fuel composition, (ii) oxygen concentration in oxidizer and flue gas, and (iii) extent of gas pollutant treatment.

Table 6 gives the boiler off-gas composition that arises from the combustion of the fuels presented in Table 5. Please recall that the moisture content of each fuel was corrected for the simulation activities, adopting the same value measured in SBS®1 during the pilot plant experiments ($\gamma_{H_2O,2}$ = 0.114 kg/kg). The net calorific value of each fuel was accordingly re-calculated. Under same temperature, oxy-fuel level, and excess-oxygen conditions (T = 880 °C, $y_{O_2,in}$ = 30 vol%, $y_{O_2,out}$ = 12 vol%) all four fuels introduced a similar behavior with regard to the CO_2 and H_2O concentrations. Regarding SO_2, the calculated volume fractions showed that almost all fuel-S was converted to SO_2, indicating a negligible effect of sulfur self-retention in the ash minerals. Please recall that fuel combustion was carried out in a Gibbs reactor, reaching chemical equilibria and neglecting side reactions ocurring with fuel ash. The conversion of fuel-N to NO_x with SBS®1 yielded values close to 5%, leading to NO_x volume concentrations similar to those measured at the 200 kW_{th} oxy-CFBC facility [12]. As excess oxygen and temperature were maintained for all simulation tasks, the differences in NO_x concentration calculated for SBS®2, Chemnitz, and ECONWARD® can be ascribed to the fuel-N content in combination with the catalytic activity of the minerals in the fuel ash and the bed material. Furthermore, it should be noted that industrial plants operated under SRF oxy-fuel combustion conditions might expect increased NO_x values due to the challenges arising from fuel inhomogeneity and feeding behavior (e.g., localized hot spots).

Table 6. Influence of waste fuel composition on flue gas components

Parameter	**Unit**	**Value**			
		SBS®1	*SBS®2*	*Chemnitz*	*ECONWARD®*
Outlet CO_2 concentration ($y_{CO_2,out}$)	vol%	44.1	43.2	42.8	39.6
Outlet O_2 concentration ($y_{O_2,out}$)	vol%	12.0	12.0	12.0	12.0
Outlet H_2O concentration ($y_{H_2O,out}$)	vol%	41.7	43.0	43.0	46.2
Outlet SO_2 concentration ($y_{SO_2,out}$)	ppmv	256	127	498	328
Outlet NO_x concentration ($y_{NO_x,out}$)	ppmv	233	246	207	69

From the operational standpoint, increased oxy-fuel levels are desirable to reduce the heat demand in the CFB boiler, thus enhancing the system's efficiency while reducing investment costs. As shown in Figure 8a, the achievement of high oxygen inlet concentrations required a reduction in the recirculated flue gas volume flow to avoid the dilution of oxygen. $y_{O_2,in}$ introduced a linear behavior with $v_{recycled}$ both for the calculated and measured data, in line with the conclusions drawn in previous works [7,11]. Moreover, an increase in excess oxygen from 4 vol% to 12 vol% resulted in a dilution of $y_{CO_2,out}$ and $y_{H_2O,out}$ (see Figure 8b). According to the illustration, the simulation model tended to slightly overpredict the concentration of H_2O in the flue gas, while simultaneously underestimating the volume fraction of CO_2. In any case, the attained differences between the model and the pilot plant data can be regarded as minimal and introduce a similar behavior at increased excess oxygen conditions.

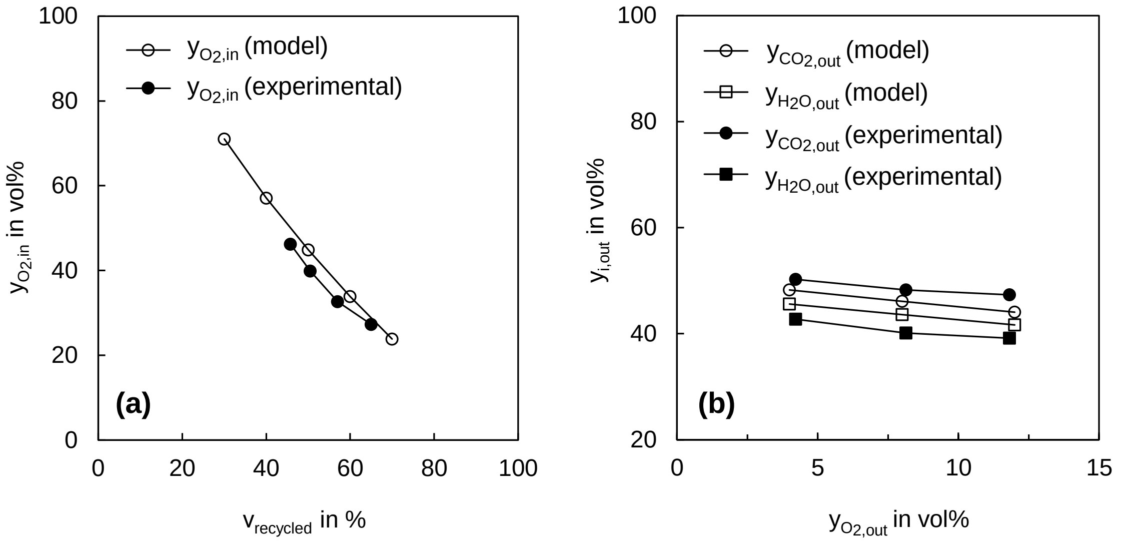

Figure 8. (a) Inlet oxygen concentration vs amount of recirculated flue gas. (b) Influence of excess oxygen on boiler off-gas composition. Fuel: SBS®1

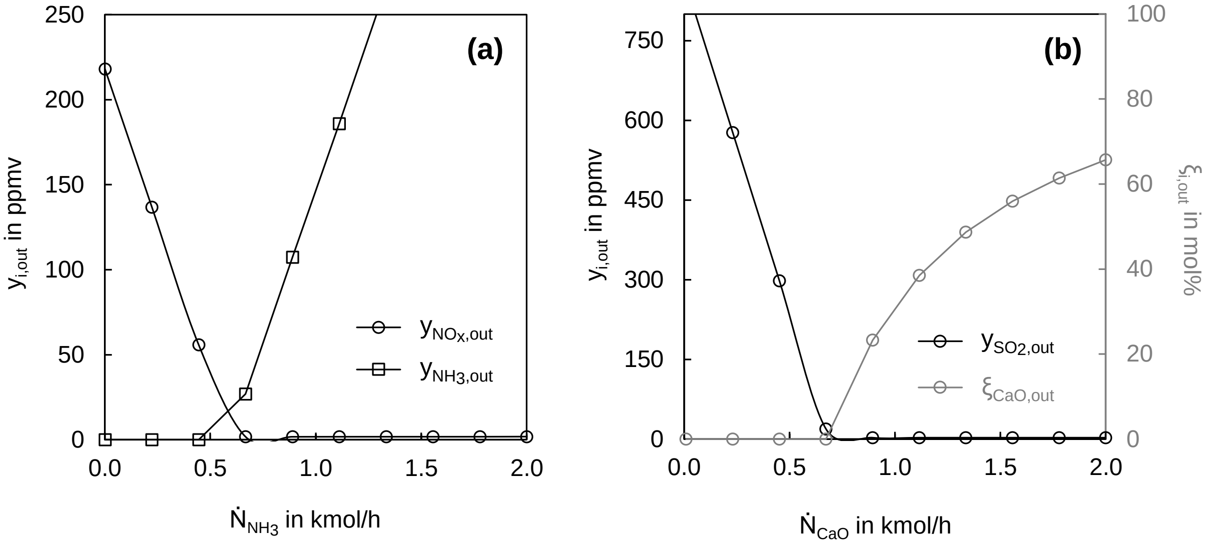

Figure 9. (a) NO_x and NH_3 volume concentration vs ammonia molar flow. (b) SO_2 and CaO volume and molar concentration, respectively, vs CaO molar flow. Fuel: SBS®1

Despite the notable advantages of oxy-fuel combustion, there is still a need to control both the emission of nitrogen and sulfur oxides to the atmosphere and their content in the captured carbon dioxide. In this work, the relatively high calculated NO_x concentrations will most certainly require additional treatment (e.g., selective non-catalytic reduction, SNCR). Figure 9a shows that the calculated $y_{NO_x,out}$ values required around 0.6 kmol/h of ammonia to maximize the reduction of NO_x to N_2 after the boiler. In addition, the SO_2 emissions generated during CFB combustion can be effectively controlled by dry flue gas desulfurization (FGD) methods (e.g., adsorption with lime). According to Figure 9b, the calculated SO_2 volume concentrations could be reduced by more than 99% when a CaO molar flow of 0.6 kmol/h was applied. While the latter conditions represent a molar Ca/S ratio of roughly 1.1, it should be considered that complete flue gas desulfurization can be detrimental in terms of acid-chloride crevice corrosion. Hence, the implications of FGD with chlorine-rich fuels (e.g., waste-derived) should be revised with more detail.

5 Conclusions

This deliverable has evaluated the performance of a full-scale oxy-CFBC WtE model constructed by Aspen Plus®. The model has been validated using experimental data from a 200 kW_{th} oxy-CFBC facility, powered with SRF under semi-industrial conditions. Under the scope of this report, three variables have been assessed, namely: (i) fuel composition, (ii) oxygen concentration in oxidizer and flue gas, and (iii) extent of gas pollutant treatment. While almost all fuel-S was converted to SO_2, $y_{NO_x,out}$ was found to be mostly dependent on the fuel-N content and catalytic activity of ash minerals and bed material. Please recall that fuel combustion was carried out in a Gibbs reactor, reaching chemical equilibria and neglecting side reactions ocurring with fuel ash. The achievement of high inlet O_2 concentrations entailed a substantial reduction in the gas recirculation rate to avoid dilution of O_2, describing a linear behavior comparable for both simulation and experimental data. In addition, excess oxygen in the flue gas was found to pose a significant dilution on major gas components such as $y_{H_2O,out}$ and $y_{CO_2,out}$. During the flue gas treatment step, an ammonia flow of 0.6 kmol/h was calculated as necessary to convert 98% of the attained NO_x concentrations. Concerning SO_2, a molar Ca/S ratio of 1.1 was required to maximize sulfur retention in the boiler.

Acknowledgements

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Annex

A1 Flowsheet of the full-scale oxy-CFBC WtE simulation model