13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

Reference case and test case for benchmarking of HiPerCap technologies

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Abstract

HiPerCap aims to develop high-potential novel and environmentally benign technologies and processes for post-combustion CO_2 capture leading to real breakthroughs. The project includes all the main separation categories for post-combustion CO_2 capture, absorption, adsorption and membranes. Each technology category is focused on several promising concepts and a key focus in the project is to demonstrate the potential of these various capture technologies. A methodology has been developed for assessment and fair comparison of the various technologies and benchmarking against a state-of-the art capture technology demonstrated in the CESAR project. In the present paper, this methodology is demonstrated for two of the absorption-based concepts involving precipitating solvent systems. Here, the assessment is based on energy efficiency penalty for the total integrated power plant and capture plant process. Though there is a slight improvement compared to the reference plant (0.5 and 7%, respectively) neither of the two precipitating solvent systems assessed here meet the project target of 25% improvement. However, the uncertainty level in the numbers is higher for these two systems compared to the reference case and the models used for the capture process should be improved before a conclusion can be made. The HiPerCap project is just starting the assessment phase and it must be emphasized that additional assessment criteria will be used and other types of technologies will be assessed before completion at the end of 2017.

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1. Introduction

Substantial research on CO_2 capture technologies has been carried out in recent years. Many different process concepts have been proposed and there is often a great variation of chemicals and materials for each concept. However, it can be very difficult to assess the relative performance and potential of different capture technologies. Claims made concerning the performance and potential of a given technology often rely on many assumptions, which may not be comparable assumptions reported by others. When claims are made concerning future potential of a technology, it is not always clear if thermodynamic and process limitations of the technology are considered and some numbers may be unrealistic. The EU funded project HiPerCap is addressing these concerns through development of both various types of technologies as well as a unique assessment process.

HiPerCap aims to develop high-potential novel and environmentally benign technologies and processes for post-combustion CO_2 capture leading to real breakthroughs. The project includes all the main separation categories for post-combustion CO_2 capture: absorption, adsorption and membranes. Each technology category is focused on several promising concepts (four for absorption, two for adsorption and two for membranes) and a key focus in the project is to demonstrate the potential of these various capture technologies. This means showing that all key aspects of a technology are feasible and that the technology can provide a real breakthrough in terms of energy use. In terms of the latter, a target of 25% reduction in efficiency penalty compared to a demonstrated state-of-the-art capture process has been set. The conventional absorption/desorption process with 30wt% MEA as solvent system is still used as a reference, but the research over the last 15 year has led to development of more energy efficient solvents and processes. Thus, to prove the progress in the HiPerCap project it was decided to use a benchmark concept demonstrated at pilot scale within the CESAR project (Knudsen et al. [1]).

Though the materials required for the three types of separation technologies studied in this project are different, a synergy between them is the need for development of feasible process concepts based on a similar set of assumptions. This ensures that a fair comparison can be made between the various technologies. In doing so, the results of the assessment will identify the priorities for the future development of these technologies. The time and budget does not allow for studying the large variation of possible CO_2 sources within HiPerCap. Therefore, a large-scale coal fired power plant (800 MWe (gross) Advanced Supercritical (ASC) pulverized coal-fired power plant) has been chosen as the source for CO_2. This may not be regarded as fair for some technologies, which may turn out to be better suitable for other sources of CO_2. However, the idea has been to develop a methodology that can be used for similar technology assessment and benchmarking studies and the case chosen here is for demonstrating the methodology using a well-documented source of CO_2. The specific coal fired power plant is based on the European Benchmarking Taskforce (EBTF) project established through common activities in the three previous projects CESAR (2011), CAESAR (2011) and DECARBit (2011). More information about this work is reported e.g. by Booth et al. [2].

In the present paper, the focus is on the proof-of-concept assessment and benchmarking methodology demonstrated for one of the absorption based technologies. This technology involves amino acid based precipitation solvent systems and in HiPerCap, two different amino acids are studied [3]. The proof-of-concept assessment and verification of the data is designed to be in line with the principles of the technology qualification [4]. Although a full technology qualification assessment is beyond the scope of the HiPerCap project, the principles are applied to assess the scale up risks and uncertainties. Three Key Performance Indicators (KPI), Energy, Cost, and Environment, will be used for the assessment and benchmarking in the project. In this paper, the main focus is on energy.

2. Basis for the study

2.1. The Coal power plant reference case

    As mentioned previously the power plant is adopted from the EBTF [2] guidelines and is based on an Advanced-supercritical pulverized single unit coal boiler. The fuel is bituminous Douglas Premium Coal with an ultimate analysis of 66.5% carbon, 5.46% oxygen, 3.78% hydrogen, 1.62% nitrogen, 0.52% sulphur, 14.1% ash and 8.0 % moisture and related boiler efficiency of 94%. The steam cycle is based on supercritical pressure level (270bar, 600°C) with simple reheat of intermediate pressure steam (60 bar, 620°C). It was modelled using PROATES®. A sketch of the model is given in Fig. 1. The gross power output is 820 MWe. With an auxiliary power consumption of 69.6 MWe, the net power output is 750.4 MWe. Thus, the net cycle efficiency at full load operation and condenser pressure of 52 mbar is 44.0 % related to Lower Heating Value (LHV). The specific CO_2 emission is 805 g/kWh$_{net}$ without CO_2 capture.
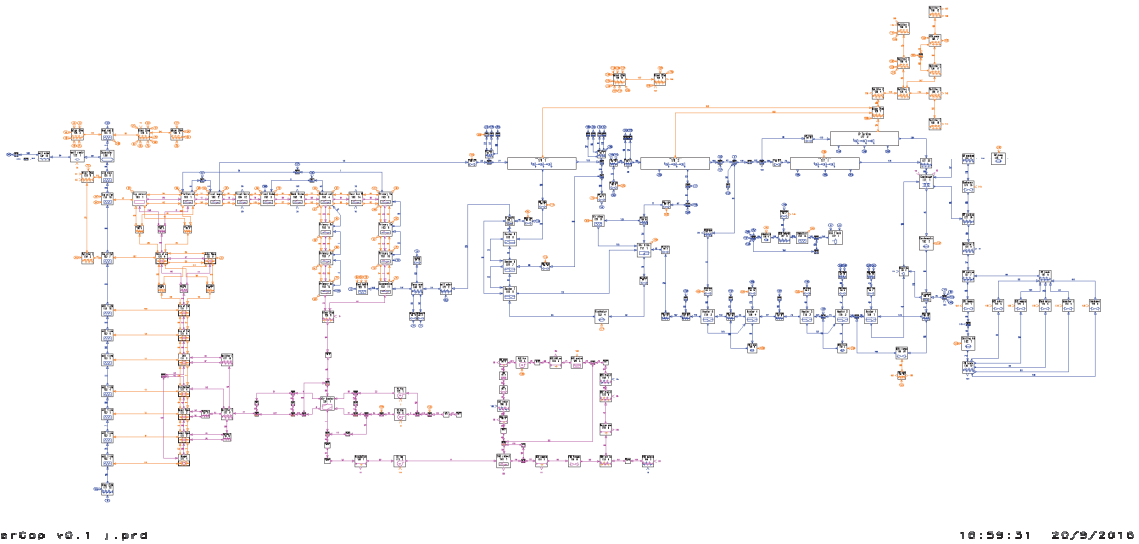

Fig. 1. PROATES® model of the ASC power plant

2.2. Capture plant interfaces

    Since within HiPerCap various technologies for post-combustion capture are considered, it is essential to identify potential integration points for treatment of the flue gas in the capture process as well as to identify the utilities available for this process.

    Flue gas

The flue gas path within the reference power plant consists of standard coal-fired flue gas clean-up technologies, including SCR for NOx control, ESP for particulate removal and FGD for SOx removal. A gas-gas heater has been included in the design, providing additional flue gas conditions, which may better suit the requirements of the different CO_2 capture processes. The potential flue gas extraction points are shown in Fig. 2 while the corresponding flue gas composition and conditions at these points are given in Table 1.
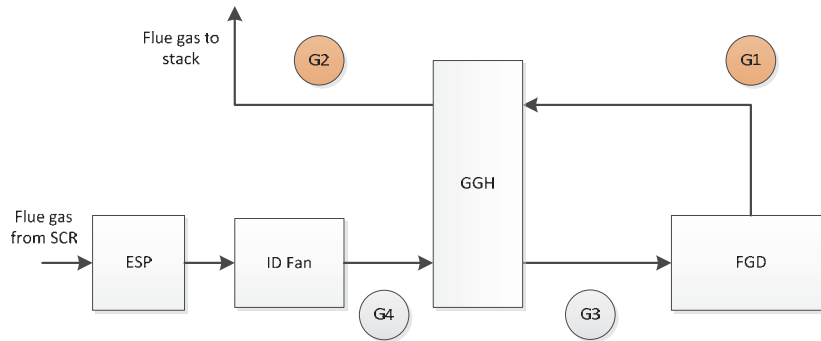

Fig. 2. Potential flue gas extraction points

Table 1. Flue gas composition and conditions of the flue gas at the extraction points shown in Figure 2 based on simulation of an ASC power plant in PROATES

Description		G1 Desulphurized, Cold	G2 Desulphurized Hot	G3 Sulphur Contaminated (Cold)	G4 Sulphur Contaminated (Hot)
Temperature (°C)		47	79	100	132
Pressure (bar a)		1.05	1.05	1.05	1.05
Mass Flowrate (kg/s)		801.09	801.09	784.45	784.45
Density (kg/m^3)		1.161	1.053	1.009	0.927
Composition (vol. %)					
	N_2	71.694	71.694	74.284	74.284
	O_2	3.687	3.687	3.820	3.820
	CO_2	13.597	13.597	14.089	14.089
	H_2O	10.160	10.160	6.875	6.875
	Ar	0.857	0.857	0.888	0.888
	SO_2	0.0025	0.0025	0.042	0.042

Steam

With the expectation that most of the investigated capture processes will consume the majority of their energy as steam (except for the membranes), it was necessary to fully define a realistic steam cycle. The steam extraction points considered suitable for partial or full provision of steam to a capture process is shown in Fig. 3, while the corresponding steam conditions at these points are given in Table 2.
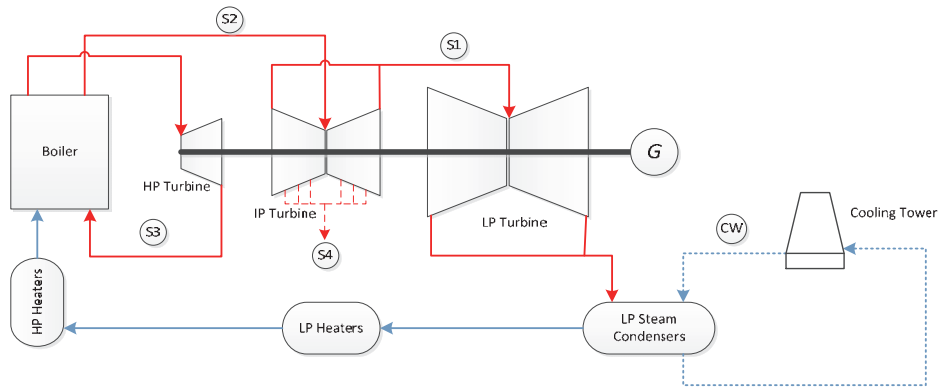
Fig. 3. The potential steam extraction points in the steam cycle for the reference power plant.

Table 2. Steam conditions (for the power plant without capture) for the various steam extraction points as shown in Fig. 3

	S1	S2	S3	S4
Description	*IP/LP Crossover*	*Hot Reheat*	*Cold Reheat*	*IP Extraction Steam*
Temperature (°C)	286.47	620.08	361.74	286-512
Pressure (bara)	5.758	59.120	64.011	5.9-29.6
Mass Flowrate (kg/s)	429.08	507.03	571.88	15.9-38.9
Enthalpy	3 034.6	3 706.6	3 067	3 034.6-3 483.7

Conventional amine scrubbing processes typically target the use of IP/LP crossover steam (S1) as governed by the pressure and corresponding temperature (at saturated conditions) at the capture plant battery limit. As such, some degree of desuperheating is required in order to ensure saturated steam is available for condensing/heating processes. This is considered when optimizing the integration of the capture plant into the power plant. The effect of decreasing IP/LP crossover pressure due to steam bleeding is also considered and pressure reduction valve is planned to be installed downstream the bleeding point and upstream LP turbine block to block the pressure decrease allowing normal operation of IP turbine block.

The IP/LP crossover conditions also represent the least penalizing method of extracting steam from the power cycle due to the low quality (low pressure and temperature) of the steam and its potential to do work within the power cycle. Cold and hot-reheat steam (S3 and S2) holds greater value due to its ability to do work within, both, the IP and LP turbines.

For the same capture plant heat duty, extraction from either S3 or S2 will result in a notably greater impact on the power plant's net output and efficiency in comparison to using S1 steam. Opportunities to tie into some of the power plant's steam bleeds are also shown (S4) as there may be certain scenarios where lower a combination of steam quality may be of interest to the capture process. Extraction of steam from S4 will result in changes to the heating profile throughout the feed-water pre-heaters resulting in additional steam being bled from the cycle.

Cooling water
Cooling water is available at 20.78 °C and is pressurized to approximately 3.67 bar with a 6.66 MW pump. Without operation of CCS, the power plant currently returns cooling water to the cooling towers at 30.53 °C and at atmospheric pressure.

2.3. Reference Capture plant

As mentioned in Section 1, the applied benchmark solvent system is the best performing solvent system demonstrated at pilot scale within the CESAR project. This solvent system is a mixture of AMP and Piperazine, hereinafter referred as the CESAR1 solvent system. This solvent system and associated process concept was optimized within the OCTAVIUS project (see [5] for further details) and used as basis for the reference capture

plant in HiPerCap. It should be noticed that both absorber intercooling and lean vapour recompression as a mean for further energy penalty reduction were considered in that work. However, it was concluded that the conventional absorber/stripper process is more cost-efficient for this solvent system. The process has been resimulated in Aspen Plus® within HiPerCap. The optimum lean loading is confirmed to be 0.12 mole CO_2/mole CESAR1 solvent leading to a reboiler specific energy duty of 3.02 GJ/tonne CO_2 (Fig. 4). A thermodynamic model of CESAR1 solvent system was developed in the CESAR project [6]. The model was validated against the test data from the pilot plant at Esbjerg with a satisfactory degree of fit. Flue gas is extracted after the FGD (G1 in Fig.2) and the required steam for the stripper reboiler is extracted from the IP/LP crossover (S1 in Fig. 3).

Fig. 4. Reboiler duty of CESAR1 solvent versus CO_2 lean loading

2.4. Compression train

The compression train is modelled as a four stage intercooled compression with an installed dehydration unit of the CO_2 stream between stage 3 and 4 as shown in Fig. 5. A molecular sieve unit based on temperature swing was chosen for the dehydration of the CO_2 stream to reach pipeline specification of 50 ppm. The compression train is simulated in Aspen Plus® with the GERG-2008 equation of state.

Fig. 5. Compression train with staged intercooling

2.5. Precipitating solvent system cases

Absorption of CO_2 in aqueous amino acid salt solutions can lead to the formation of precipitates, depending on the particular amino acid and the concentration in solution [7]. Because of precipitation, higher specific CO_2 capacity is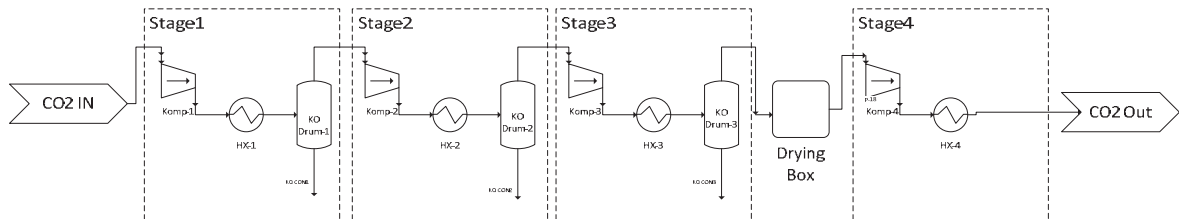 expected, as the CO_2 reaction equilibrium shifts towards the formation of more product [8]. Other advantages include no vapour emissions, possibly higher stability as in case of taurine, and higher absorption rates as in the case of sarcosine and proline [9].

As mentioned previously, two different precipitating solvents were studied in the HiPerCap project: 1) Taurine and 2) α-Alanine in KOH (aqueous amino acid salt) solutions. As for the reference capture plant a conventional absorber/stripper process is considered, but with a proper choice of packing material, pumps and heat exchangers specifically designed for handling slurry systems. Both systems have been well characterized within HiPerCap.

3. Methodology

3.1. Assessment methodology

Assessment procedure

Since the various technologies addressed in the project have reached different technology readiness levels (TRL) it was decided to divide the overall procedure into two stages, of which the first stage is a screening stage with the aim of identifying the status of available data as well as potential environmental showstoppers. The second stage of the assessment procedure is called the evaluation stage.

The figures used for the assessment are the result of experimental and modelling activities within the HiPerCap project and by activities undertaken in previous projects. In order to make a fair comparison, the technologies are scaled up to capture at least 85% of the CO_2 from the reference power plant. This involves experimental measurements, verifying a model with the experimental separation process data, scaling up the model, integrating it into the entire capture process and finally integrating it with the reference power plant before undertaking the benchmarking and comparison activities.

Screening stage

As mentioned previously the screening stage will identify which technologies have sufficient data to be assessed and which have met the minimum performance requirements. The screening stage will consist of two separate parts undertaken in parallel. Firstly, the verification of the data quality in which the measurements and model results will be assessed to ensure they have the relevant detail to undergo the evaluation stage and to show that the measured results are accurately reflected in the scaled up models. Secondly, an assessment of the environmental KPI to show that no potential environmental show stoppers have been identified. The criteria to be used include: maturity according to EU definition, footprint, max CO_2 flow, CO_2 captured, unwanted impurities in captured CO_2 stream, availability of measured or modelled data, constraints for obtaining information (legal, financial, time etc.). Information at this stage from the technology developer within HiPerCap are given in a questionnaire specifically established within the project.

Evaluation Stage

The purpose of the evaluation stage is to give a ranking for each of the technologies based on the energy performance and to ensure they are not negatively impacted by the drive to increase the energy performance of the novel technology compared with the state of the art capture process. For the technologies that pass the screening stage, integration of the capture process with the reference power plant will be undertaken. The data collected from these activities will be used to calculate the energy and cost KPIs and rank the technologies to find the two breakthrough technologies that are the most promising for the specific HiPerCap application.

Assessment criteria

The objective of the environmental KPI assessment is to show that there are no known environmental impacts of the new technology that are likely to prove detrimental to its further development. This is a pass or fail assessment

that will look into the liquid, solid and gas wastes and emissions from each of the technologies in as much detail as possible considering the relative immaturity of the technologies.

The objective of the activity involving verification of data quality and proof of concept in the screening stage is to ensure the reliability of the values used for the assessment of the technologies before more detailed work is undertaken. Based on the answers in the technology developer questionnaires mentioned previously, the provided data will be checked for completeness and reliability on basis of relevant physical and chemical principles. In particular, data regarding steam and electricity consumption will be evaluated, as these will be the key for the assessment of the power output losses caused by CO_2 capture. In case of doubt, technology developers will be asked to provide supporting experimental data including mass and energy balance checks for their experiments. If specific data are based on modelling (i.e. flowsheeting) activities, the technology developers will be asked to provide proof for the reliability of their models, e.g. by comparing model predictions with experimental (lab) data.

The objective of the cost KPI is to show that in reducing the energy consumption of the novel capture process compared to the state of the art technology, the other cost factors are not sacrificed to the extent that they will negatively affect the attractiveness of the novel capture process. For each of the technology types, absorption, adsorption and membranes, key cost drivers are identified. For each of the novel technologies the cost drivers will be investigated and compared to respected industry references for that type. For absorption technologies, this will be the state of the art technology. For adsorption and membrane technologies, the novel technologies will be compared with cases defined in the NETL report Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture [10].

The objective of the Energy KPI assessment is to assess the impact of the capture process on the performance of the reference coal fired power plant and use this as the main input to ranking the capture processes (see Fig. 6). The measure for the energy performance is called Specific Energy Penalty of Avoided CO_2 (SEPAC) analysis separate for each technology category (see Eq. 1). This measure compares the power output of the reference power plant with and without the novel capture process in place, normalized for the emission of CO_2 avoided through application of capture technology. Each novel technology will be compared to the state of the art capture process to show it has met its energy reduction goals.

SEPAC is defined as follows:

$$SEPAC = \frac{P_{ref} - P}{\phi_{CO_{2ref}} - \phi_{CO_2}} \qquad (1)$$

With

- P = net electric output of the power plant in MW$_e$
- ϕ_{CO2} = the emitted flow of CO_2 in kg_{CO_2}/s

Workflow

With many parties involved in the execution, definition of the workflow and scope boundaries is important so that everyone understands their role and that consistency is ensured across the workflow and technologies. Fig. 7 shows a block diagram of the separation technology integrated with the capture process and with the reference power plant, broken down into different scopes, which are defined further in Table 5.
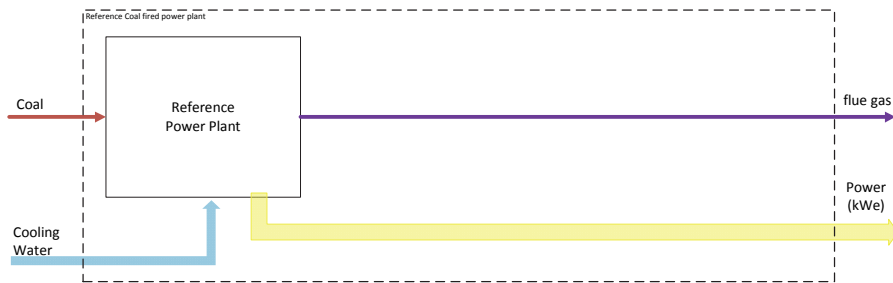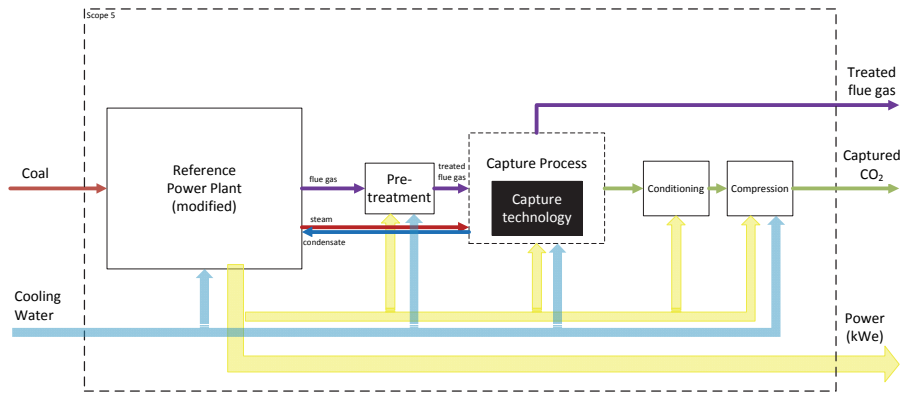
Fig. 6. Comparison of the energy flows for the reference coal fired power plant both with and without the capture technology integrated.
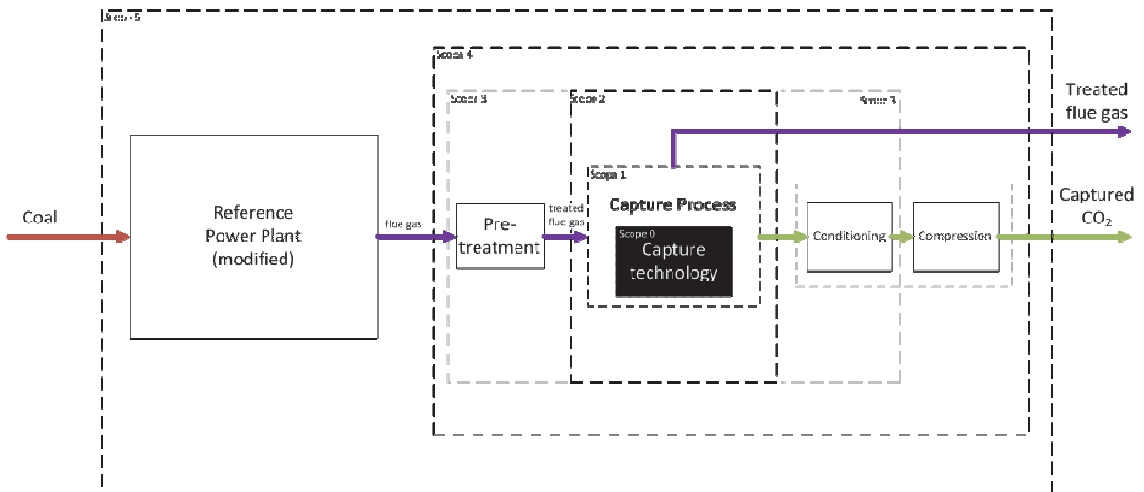

Fig. 7. Definition of generic scopes of work for the Power Plant and Capture Plant.

Table 5: Definition of Scopes and responsible people/partners

#	Scope name	Responsible party	Description
0	Experimental Separation technology	Technology Developers	
1	Model of Separation Technology	Technology Developer + Process Modellers	Model of separation technology at experimental scale
2	Scaled Separation Technology	Process Modellers	Separation technology scaled up to the reference power plant
3	Scaled Capture process - (As scope 2 + pre-treatment + conditioning)	Process Modellers	Separation technology plus required flue gas pre-treatment and CO_2 conditioning process units at reference power plant scale to be defined by process modellers and technology developers
4	Scaled Capture process + compression (Scope 3 + compression)	Process Evaluators	Complete capture process ready for integration with reference power plant and pipeline network.
5	Power Plant and Capture Process (Scope 4 + power plant)	Process Evaluators	Complete capture process integrated with reference coal fired power plant and CO_2 compression.

3.2. Computational assumptions

Capture reference plant

As mentioned previously, the conventional absorber/stripper process using the CESAR1 solvent system and CO_2 compression unit were simulated in Aspen Plus® within the HiPerCap project. A sketch of the process as modelled in Aspen Plus® is shown in Fig. 8.). The most important process unit input and specification data are given in Table 6.
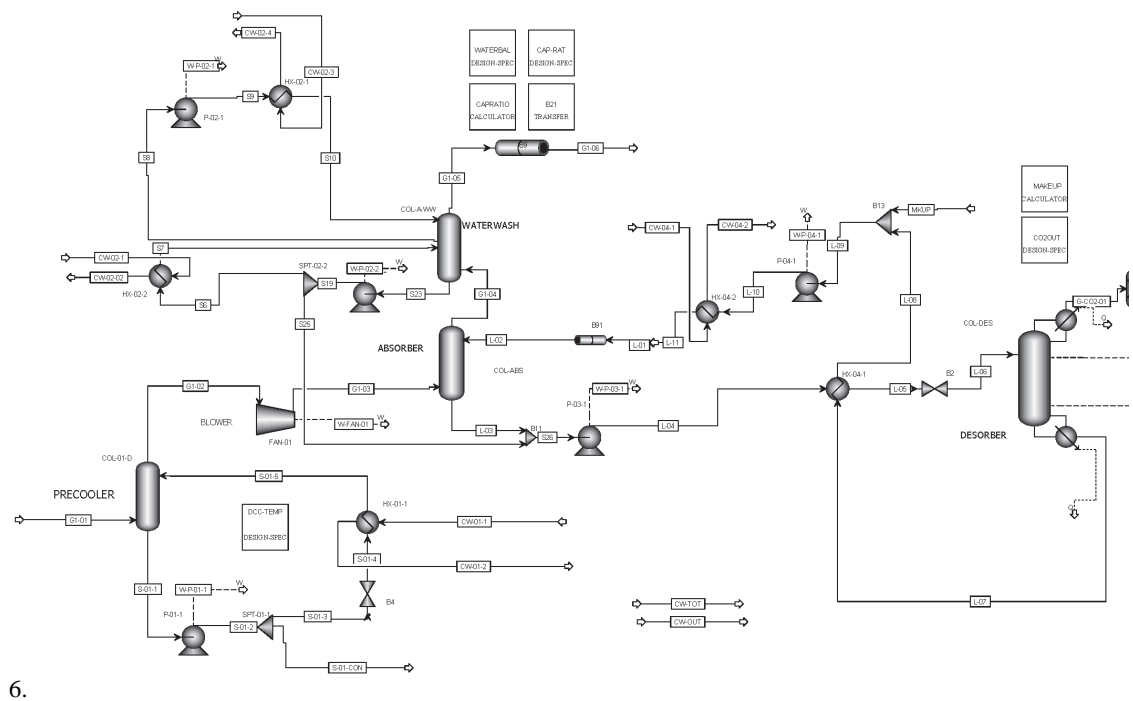

Fig. 8. Aspen Plus® interface of the CESAR1 reference capture plant process model including CO_2 compression unit (encapsulated in the figure 8, see Figure 5 for details)

Table 6. Most important process unit specifications and input data for the reference capture plant case

Parameter	Predefined/fixed value	Comments
Capture rate	90 %	Optimal for reference technology, but minimum capture for all technologies is 85% on an annual basis
Packing material in absorber/stripper	Sulzer Mellapak 2X	Including water-wash sections
Absorber/stripper flue gas velocity	Maximum 70% of flooding velocity	
Pressure drop in pre-cooler, absorber, stripper	2 kPa, 7 kPa, 7 kPa	
Pre-cooler and lean cooler process outlet streams	40°C	
Cross heat-exchanger temperature approach	5°C	cold in – hot out
Operating pressure in reboiler	2 bara	

Compression train

The CO_2 product specification and compressor train unit specifications and input data are given in Table 7.

Table 7. CO_2 product specification and compressor train process unit (see Figure 5) specifications and input data

Stream/unit	Parameter	Value
CO_2 product	Water content	≤ 50 ppm
	Purity	$\geq 95\%$
	Pressure	110 bara
	Temperature	≤ 30ºC
Compressor	Type	Integrally geared centrifugal turbocompressor
	Efficiency stage 1	80 %
	Efficiency stage 2	80%
	Efficiency stage 3	80%
	Efficiency stage 4	75%
	Driver efficiency	95%
Intercooler	Pressure drop	2 %
	Temperature approach	10ºC
	Heat transfer coefficient	400 W/m^{2}K
Dehydration	Pressure drop	2 %

Precipitating solvent systems

In order to obtain estimates for the energy performance of the process and unit sizes, process flow sheet calculations have been performed using black-box approaches mainly for the columns. Other units such as heat exchangers and pumps are modelled separately in Aspen Plus® similar to that for the reference case. A VLSE model is developed, including physico-chemical properties such as density, heat capacity, etc. based on correlations obtained from experimental and literature data. Routines in MATLAB® calculates the corresponding properties of all process streams and units in the process. It is important to note that much more experimental data was available for the process using taurine than alanine. Thus, the corresponding model also shows a better fit and higher confidence for the process using taurine.

The flowsheet used for simulating the two cases is as shown in Fig. 9. The feed flue gas stream is obtained from the direct contact cooler and the blower as defined in the reference CO_2 capture plant case. As mentioned previously the rest of the scheme is that of a conventional absorber/stripper plant. It is important to note that no water wash is considered here, since no vapor loss of amino-acids is expected. The water balance in the system is tuned by tuning the temperature of the gas stream leaving the stripper section. The blower electricity consumption is updated to match the pressure drop in the absorber of the two cases.

The main modelling assumptions are associated with the outlet conditions of the separation columns. Table 8 gives an overview of how temperature, CO_2 content and H_2O content of these streams have been determined in the model while Table 9 shows some fixed process specifications and parameters.

Table 8. Assumptions used to calculate the conditions of separation column outlets.

Location	Temperature	CO_2 content	H_2O content
Absorber top	Energy balance	CO_2 capture ratio	Vapour pressure of water
Absorber bottom	Energy balance	Approach to equilibrium	Water balance
Desorber bottom	Reboiler temperature	Lean loading	Water balance
Desorber top	Energy balance	Pressure balance	Vapour pressure of solvent

Fig.9. Flowsheet used for simulating the CO_2 capture plant using precipitating solvent systems

Table 9. Fixed process specifications and parameters.

Process specification		unit
Flue gas inlet CO_2 fraction	0.14046	mol/mol
Flue gas inlet H_2O fraction	0.07193	mol/mol
Flue gas inlet flow rate	26 356.52	mol/s
Flue gas inlet temperature	50.3	°C
Flue gas inlet pressure	1.12	bar
CO_2 capture ratio	0.90	mol/mol
Amino acids concentration at absorber inlet	4.0	mol/litre
Lean cooler temperature	40	°C
KOH concentration at absorber inlet	4.0	mol/litre
Absorber pressure drop	0.07	bar
Approach to equilibrium at absorber bottom	0.90	$P_{CO2,liq}/P_{CO2,gas}$
Temperature approach in main heat exchanger	5	°C
Condenser temperature	49.95 (taurine), 47.69 (alanine)	°C
Reboiler temperature	120	°C

4. Results and discussion

It should be noted that the two cases with precipitating solvents are also based on separation by absorption making it easier to compare with the reference capture case than the adsorption and membrane based technologies. However, the same methodology for assessment is used as described in Section 3.1.

With the flue gas conditions as listed for G1 in Table 1 both the reference capture plant and the two precipitating system cases have been simulated according to Section 2 and 3 (at scope 3 level according to Fig. 7). The compression train has then been simulated with the CO_2 stream conditions from all three cases as input (scope 4 level). Based on the steam- and electric- requirement in the process blocks at scope 4 level, the power plant has been re-simulated and net electric output determined. As the flue-gas conditions given in Table 1 are hardly affected, no further simulations at scope 3 and 4 levels are necessary.

In Table 10 the major performance data is given, while the CO_2 stream inlet conditions and compressor duty for the compressor train are given in Table 11 for the three capture plant cases. A summary of the total energy requirement, the net plant efficiency and specific emission of CO_2 is given in Table 12 for the three capture plant cases. The cooling water duty for the lean cooler, the stripper condenser and the compressor intercoolers is given in Table 13 for the three capture plant cases.

As can be seen from Table 12, the overall efficiency penalty is lower than the reference case for the two precipitating cases. The improvement is 0.5% and 7%, respectively for the Taurine and α-Alanine cases. The improvement for the reboiler duty is higher (5 % and 16%, respectively), but the auxiliary power duty is increased mainly due to pumping of more fluid (slurry) as L/G is increased from 1.9 for the reference case to 15.6 and 6.2, respectively for the two precipitating solvent systems. However, the compressor duty for the Taurine case is lower due to higher operating pressure of the stripper than the reference case, while it is slightly higher for the α-Alanine case. Nevertheless, none of the two systems fulfils the target of 25% improvement in overall energy performance. As seen from Table 10 and 11, the electric load for capture of the reference case (91 kJ/kg CO_2) and the electricity used for compression (348 kJ/kg CO_2) constitutes almost 40% of the SEPAC value (Table 12). Since electricity requirement for absorption systems in general is almost the same, this means that the SRD needs to be reduced with 42% (or 1.8 MJ/kg) in order to achieve a total energy reduction of 25%.

The cooling duties as given in Table 13 indicates directly the irreversible losses in the process. Most of the efficiency loss of a power plant (without capture) is rejected into the steam condenser of the said plant. For the amine absorption based plant, most of the energy provided from the power plant is lost as low temperature heat. The energy required to keep the water-balance is directly linked to the cooling of the top of the absorber to counteract the effect of the heat of absorption. As seen from Table 13 the total cooling duty required in this section is in favor of the α-alanine case with the Taurine above the reference case (both water-wash and lean cooler duties). Oppositely, the cooling water requirement for cooling of the stripper steam in the stripper condenser is in favor of the Taurine case with the α-alanine case higher than the reference case. If considered the net increase in cooling duty for the total integrated plant (last line of Table 13), the Taurine case is better than the α-Alanine case, which again is slightly better than the reference case. However, as already indicated the efficiency loss due to the auxiliary power duty (blower, pumps) as given in Table 12 is much higher for the Taurine case than both the other two cases.

It should be noticed that the uncertainty level in the data for the two precipitating systems is higher due to the simplified models and even higher for the α-Alanine due to limited available experimental data used for the model. Thus, the results may have been different with improved models. Additionally, it should be mentioned that other process configurations have shown better energy performance [10], but as for the reference case (determined in [5]), it might be that these configurations adds to the capital expenses, and the simple absorber/stripper configuration will turn out to be the best process configuration anyway. At least it is difficult to conclude based on the energy numbers alone, but the analysis gives clear indications about the energy losses.

Though the focus here in this work is energy, also other criteria will be used in the overall assessment in the HiPerCap project. It should be emphasized for example that emission of the solvent is not an issue for the two precipitating systems studied here, but still there is some concern in that respect related to the piperazine content of the CESAR1 solvent used in the reference case. In any case, additional water wash sections are needed, which will add to the capital cost of the plant. Another aspect is that the slurry system in the precipitating cases might be more

difficult to handle and control. However, the CESAR1 solvent may also easily precipitate under certain conditions and since this needs to be avoided for this solvent system, the control system must be properly designed.

Table 10: Some key results from simulation of a conventional absorber/stripper process with CESAR1 (reference), Taurine, and α-Alanine as solvent systems, respectively

Parameter	Unit	CESAR 1	Taurine	α-Alanine
CO_2 capture	kg/s	146.6	146.6	146.6
SRD	MJ/kg	3.02	2.89	2.54
Electric load capture*	kJ_{el} /kg CO_2	91	193	132
Absorber L/G	kg/kg	1.9	15.6	6.2
Steam/CO_2 mass ratio**	kg/kg	1.22	1.17	1.03
Absorber packing height	m	16.5	15	15
Stripper packing height	m	10	10	10
Lean loading	mol/mol	0.12	0.41	0.45
Rich loading	mol/mol	0.62	0.51	0.67
Solvent weight percent	%	40	54	48

*exclusive CO_2 compression, ** S1 steam quality

Table 11: CO_2 stream inlet conditions and compressor duty for the compressor train for the three capture cases

Parameter		Unit	CESAR 1	Taurine	α-Alanine
CO_2 stream inlet temperature		°C	30.8	30.8 C	30.8 C
CO_2 stream inlet pressure		bara	2.0	3.92	1.8
CO_2 stream inlet mass flowrate		kg/s	148.0	147.3	148.1
CO_2 stream inlet density		kg/m^3	3.48	6.91	3.11
CO_2 stream inlet Composition					
	CO_2	vol. %	97.8	98.9	97.6
	H_2O	vol. %	2.2	1.1	2.2
Compressor duty stage 1		MW_e	13.6	11.0	14.1
Compressor duty stage 2		MW_e	13.3	10.7	13.7
Compressor duty stage 3		MW_e	12.6	10.0	13.0
Compressor duty stage 4		MW_e	11.5	8.9	12.0
Electric load CO_2 compression		kJ_{el}/kg CO_2	348	276	360

Table 12: Summary of the total energy requirement, the net plant efficiency and specific emission of CO_2 for the three capture cases

Parameter	Unit	CESAR 1	Taurine	α-Alanine
Power plant net output without capture	MW_e	746.0	746.0	746.0
Power plant efficiency without capture	%	44.12	44.12	44.12
Power plant net output with capture	MW_e	581.1	581.9	592.6
Power plant efficiency with capture	%	34.28	34.33	34.96
Specific reboiler duty	GJ/t CO_2	3.02	2.89	2.54
Specific CO_2 emission without capture	g/kWh$_{net}$	804.7	804.7	804.7
Specific CO_2 emission with capture	g/kWh$_{net}$	101.1	101.0	99.1
Overall efficiency penalty	%-points	9.70	9.65	9.02
Efficiency loss steam extraction	%-points	5.9	5.6	4.8
Efficiency loss compressor duty	%-points	3.0	2.4	3.1
Efficiency loss auxiliary power duty (blower, pumps)	%-points	0.8	1.7	1.1
SEPAC	GJ/t CO_2	1.10	1.09	1.02

Table 13: Cooling water duty for CCS plant and power plant

Parameter	Unit	CESAR 1	Taurine	α-Alanine
Flue gas DCC cooler duty	MW_{Th}	44	44	44
Absorber WW cooler duty	MW_{Th}	257	0	0
Lean cooler duty	MW_{Th}	68	362	237
Stripper condenser duty	MW_{Th}	125	65	153
CO_2 Compression train cooling duty	MW_{Th}	89	78	91
Specific cooling duty (CCS only)	$MW_{Th}/kg\ CO_2$	3.98	3.74	3.59
1. Net Cooling duty capture plant	MW_{Th}	583	549	526
2. Power plant condenser duty without capture	MW_{Th}	787	787	787
3. Power plant condenser duty with capture	MW_{Th}	443	457	495
Net Increase in cooling duty (1. + 3. - 2.)	MW_{Th}	238	219	233

5. Conclusions

An assessment and benchmarking methodology has been developed for comparing various technologies for post-combustion capture within the HiPerCap project. To date the methodology has been used for assessing two precipitating solvent systems. These two systems are benchmarked against a reference case based on a promising solvent system demonstrated in the EU-funded project CESAR. The aim for the project is to develop post-combustion type of technologies with a reduced overall energy penalty for the integrated capture plant with 25% compared to the reference plant. Though there is a slight improvement, of which the system with α-Alanine shows the best energy wise performance, neither of the systems assessed here meet this target. However, the uncertainty level in the numbers is higher for these two systems compared to the reference case and the models used for the capture process should be improved before a final conclusion can be made. The use of the SEPAC KPI for assessing the energy consumption gives a fair comparison for the different technologies although it dilutes the improvements made against the state of the art because over 40% of the value is independent of the separation technology. This highlights the need for standardising the KPIs and methodologies for comparison. The HiPerCap project is just starting the assessment phase and it must be emphasized that other types of technologies will be assessed before completion at the end of 2017. Since the TRL levels are different, other criteria will be used in the assessment and benchmarking. For example as mentioned previously, any emission of the solvent is not an issue for the two precipitating systems studied here, but still there is some concern related to the piperazine content of the CESAR1 solvent used in the reference case.

Acknowledgements

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