Economic aspects of a full-scale packed bed CLC reactor, comparison with other zero emission technologies

DEMOCLOCK Business Brunch

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Agenda

1. Introduction

a. Amec Foster Wheeler at a glance

b. What is CCS technology?

c. Technical and Policy challenges

2. Results of the Techno-economic assessments

a. Plant summary

b. Methodological approach

c. Total Plant Cost

d. O&M

e. LCOE, CAC

f. Sensitivity cases

3. Summary Considerations

Agenda

Who we are
Amec Foster Wheeler at a glance

Market mix by revenue

Mining, Environment & Infrastructure, Clean Energy, Oil & Gas

7%

12%

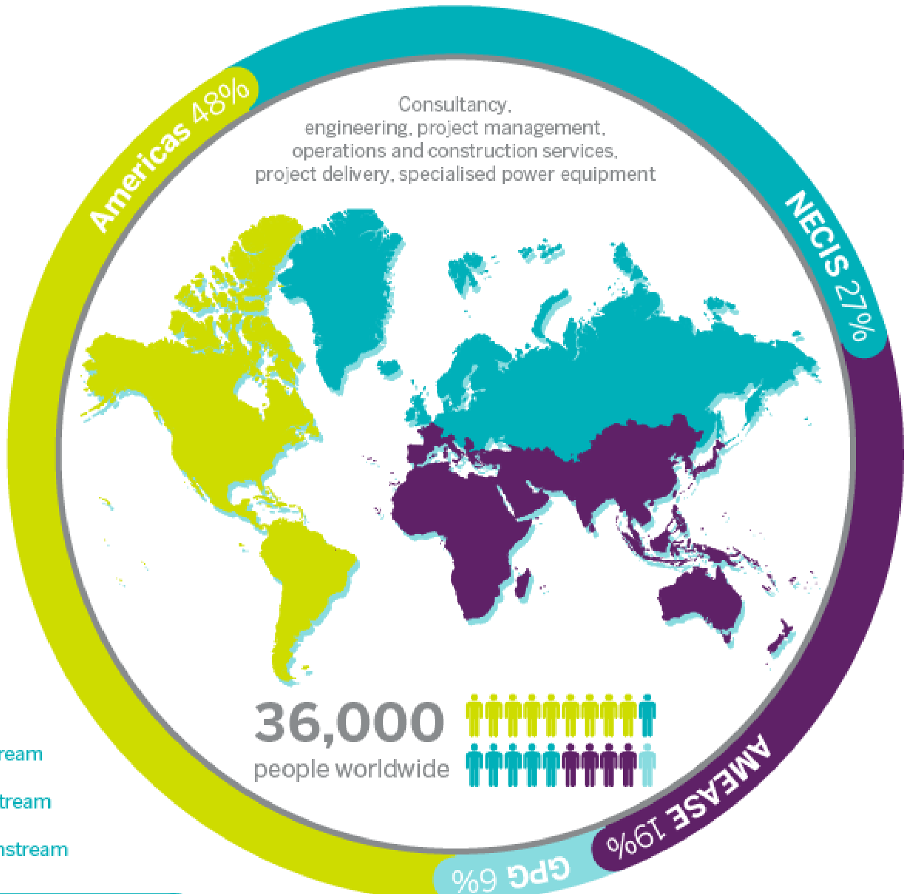
27%

Upstream 28%
Midstream 4%
Downstream 22%

54%

Business units

Americas, Northern Europe & CIS (NECIS),
Asia, Middle East, Africa & Southern Europe (AMEASE),
Global Power Group (GPG)



160+ year history

Operating in over 55 countries

Revenue **£5.5bn**

AMFW

Trading symbol

Economic assessment of full-scale CLC plant

Aim

Prepare the commercialization of the new CLC technology, attracting NEW customers for further developments

Objectives

- Evaluation of the cost of electricity (COE) and of CO_2 avoidance cost (CAC) in IG-CLC-CC integrated plants using packed bed reactors
- Comparison with benchmark technologies with near Zero emissions (Carbon Capture and Storage, CCS)
- Sensitivity economic analyses

What is CCS Technology?

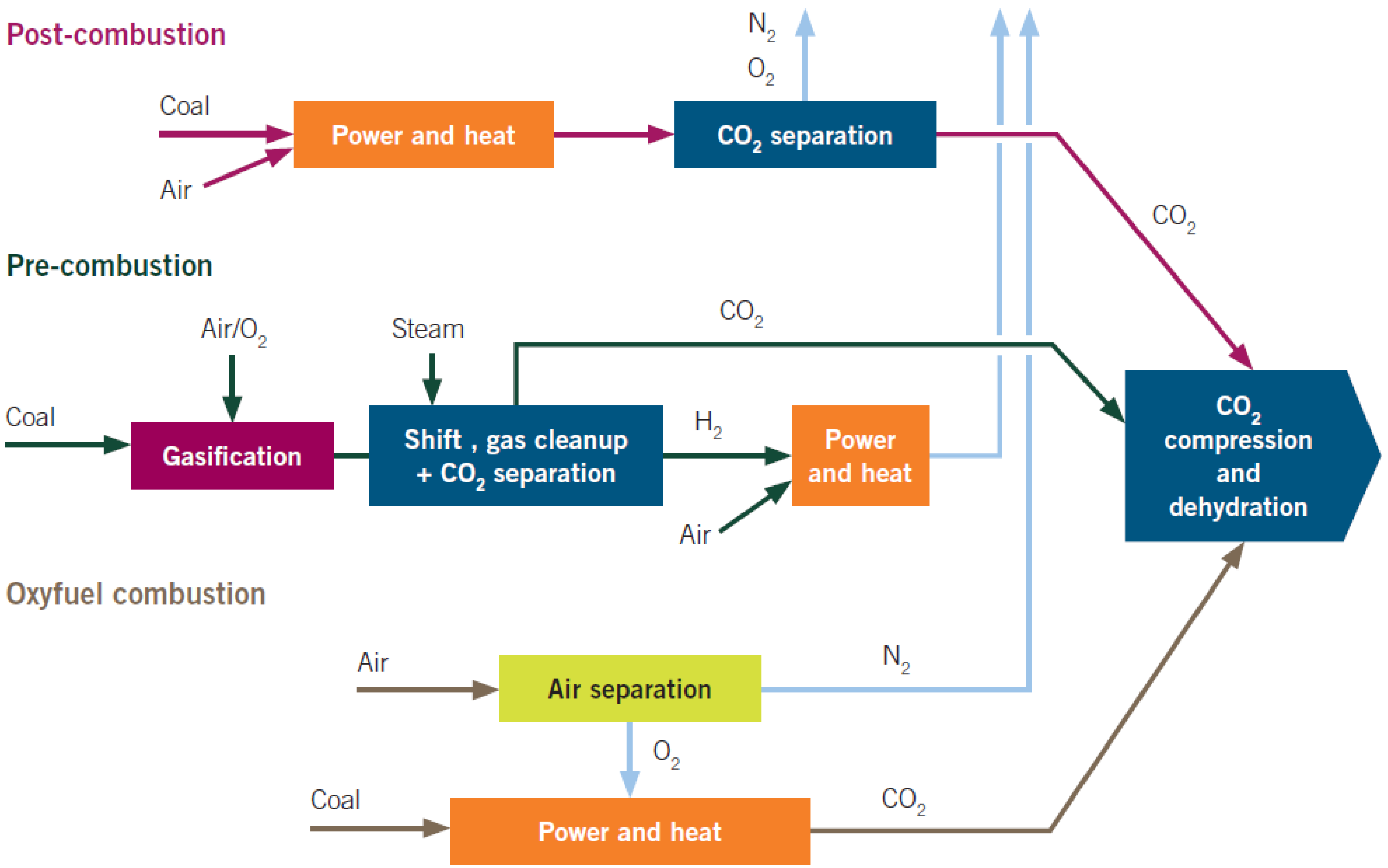
"Full Chain CCS" is broken down into three steps:

Capture → Transport → Storage

- CO_2 Capture (benchmark technologies)
  - Post Combustion
  - Pre Combustion
  - Oxy Combustion
- CO_2 Transportation
  - Pipeline
  - Ship
  - Truck
- CO_2 Storage
  - Depleted Reservoirs
  - Saline Aquifer
  - Enhanced Oil Recovery

from White Rose Project

Carbon Capture utilisation and storage
Benchmark technologies



Source: EPRI (2011a, p1-1)

Technical Challenges

- Post-Combustion Capture
  - size (volume) of equipment
  - prevention of emission of amine derivatives from absorber
- Pre-combustion Capture
  - plant complexity
- Oxy-combustion Capture
  - less demonstrated at scale
- All – Energy penalty (and hence higher running costs) compared to **unabated** fossil fuel power generation
- Transportation – maintaining desired phase
- Storage – ensuring full and safe containment

None of these are show-stoppers

Policy Challenges

- Public acceptance
- Who pays for the additional cost versus unabated power generation?
- How to incentivise investment?
- Who pays for the CO_2 transportation network & storage sites?
- Who is liable to keep the storage sites running safely in 20, 50, 200 years time?

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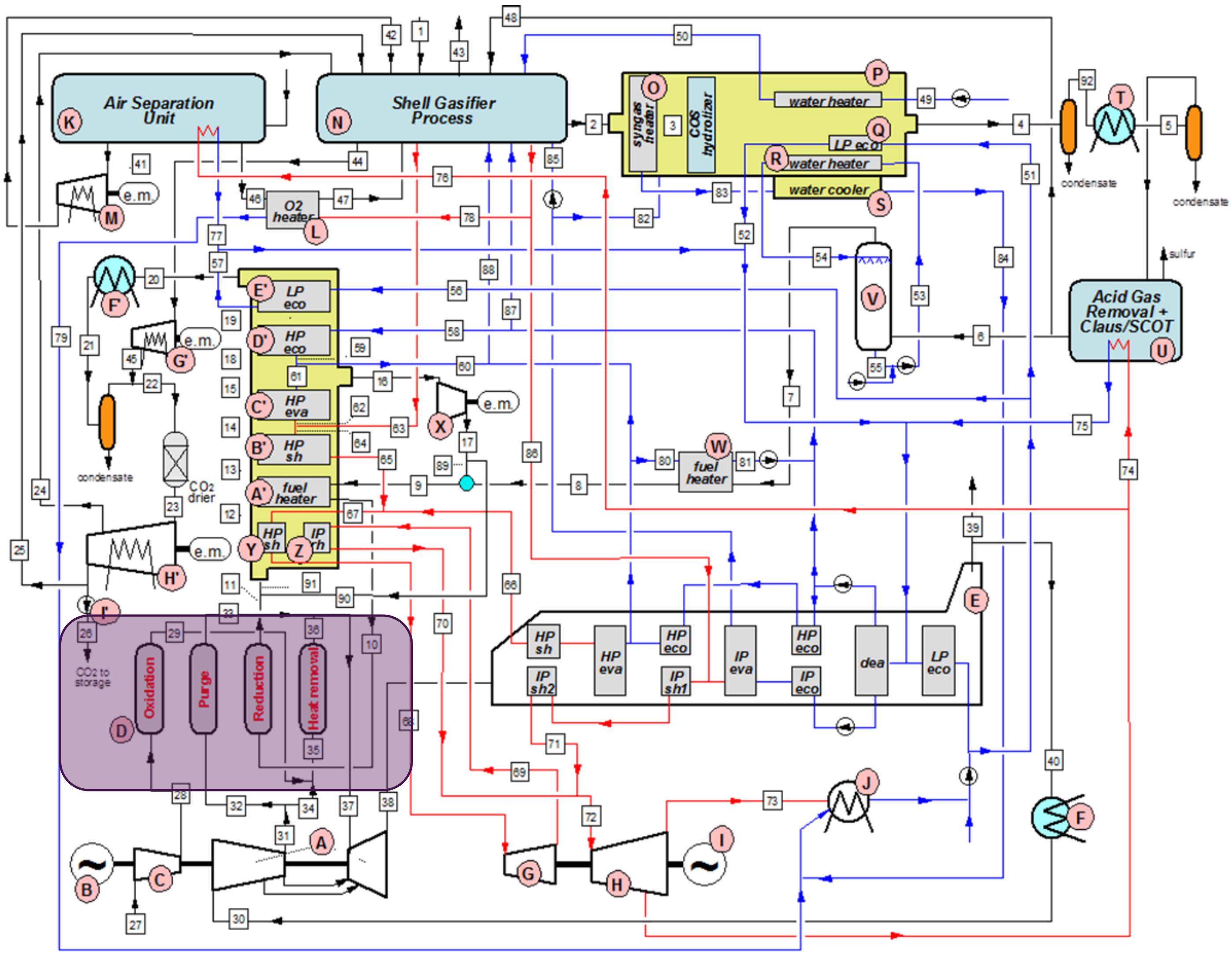
Assessed Plant configuration summary

Case	Feedstock	Technology	Main Product	CCS	Combustion Technology
1	Coal	IGCC	Power	No	GT
2	Coal	IGCC	Power	Yes	GT
3	Coal	IGCC	Power	Yes	CLC (PBR)
4 (*)	Coal	SC-PC	Power	No	Air-boiler
5	Coal	SC-PC	Power	Yes	Air-boiler
6	Coal	Oxy-SC-PC	Power	Yes	Oxy-boiler

(*) Reference technology for CO_2 avoidance cost calculation

Plant overview



Plant performance

Case 3: IGCC plant with CO2 capture (CCS) and Chemical Looping Combustion (CLC)

Coal input [t/h]	122.9	
Coal thermal input [MW_{LHV}]	853.9	
Gas Turbine Electric Power Output [MW]	**175.2**	
Steam Turbine Electric Power Output [MW]	**240.6**	
Auxiliary Power Demand [MW]	67.0	
Net Electric Plant Output [MW]	**348.8**	**35.3% IGCC**
Electric Efficiency [$\%_{LHV}$]	**40.8**	**35.2% USCPC**
CO_2 mass flow rate release to ambient [t/h]	11.7	**35.7% OxyPC**
Specific Emission of CO_2 [g/kWh]	33.5	
Carbon Capture Ratio [%]	**96.1**	**~ 90% others**

Methodological approach

Sequential steps

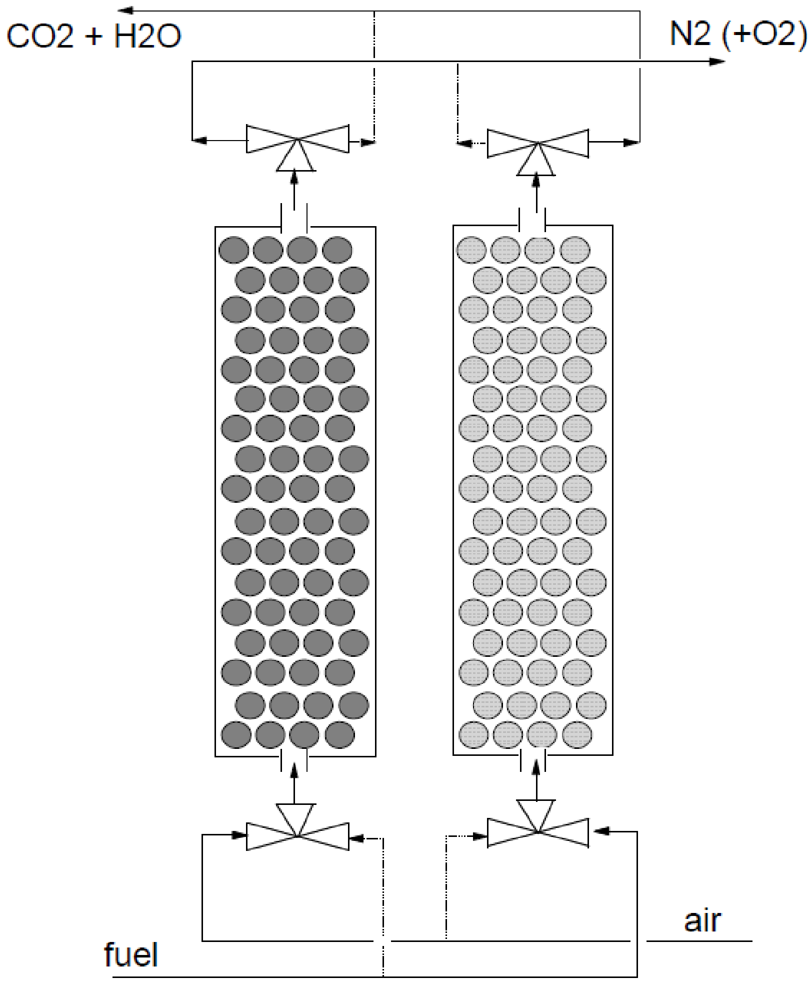
1. Acquisition/finalization of plant performance and H&MBs
2. Preparation of sized equipment list
3. Estimate Total Plant Cost (TPC) and Total Capital Requirement (TCR)
4. Estimate the Operating and Maintenance costs (O&M)
5. Estimate the plant revenues
6. Calculate the Levelized Cost of Electricity (LCOE)
7. Calculate of the CO_2 avoidance cost (CAC)
8. Comparison between plants adopting benchmark technologies (SC-PC and IGCC) and CLC plant

$$CO_2 \text{ Avoidance Cost (CAC)} = \frac{LCOE_{CCS} - LCOE_{Reference}}{CO_2\text{ Emissions}_{Reference} - CO_2\text{ Emissions}_{CCS}}$$

9. Sensitivity analyses (main key factors) in order to estimate the attractiveness of CLC plants

Main input data for CLC Packed Bed Reactor

- Performance at lab scale
- Packed Bed Reactors (PBR) in vertical CS pressure vessels coated with refractory surface
- 14 reactors (I.D. 5.5m, I.L. 11m)
  - 3 oxidation phase
  - 3 reduction phase
  - 7 heat removal phase
  - 1 purge phase
- Bed material lifetime: 5 years
- Industrial specific bed material cost: 2,500 €/t



Total Plant Cost (TPC)
Bases and methodology

Defined in general accordance with the White Paper *"Toward a common method of cost estimation for CO2 capture and storage at fossil fuel power plants"* (March 2013), produced collaboratively by authors from EPRI, IEAGHG, Carnegie Mellon University, MIT, IEA, GCCSI and Vattenfall

Total Plant Cost

Direct Materials

- Machine / equipment
- Bulk materials
- I&C equipment
- Electrical equipment
- Transport

Construction

- Mechanical erection
- Instr. / Ele. installation
- Painting/Insulation
- Site preparation
- Civil works
- Buildings

Other costs

- Temporary facilities
- Freight, taxes and insurance
- License fees

EPC services included in above items / Project Contingency: 10% of the above items.

Total Plant Cost (TPC)
Case 3

Project Democlock
Date: May 2015 REV. 0

CASE 3 - ESTIMATE SUMMARY
(IGCC w CCS & CLC)

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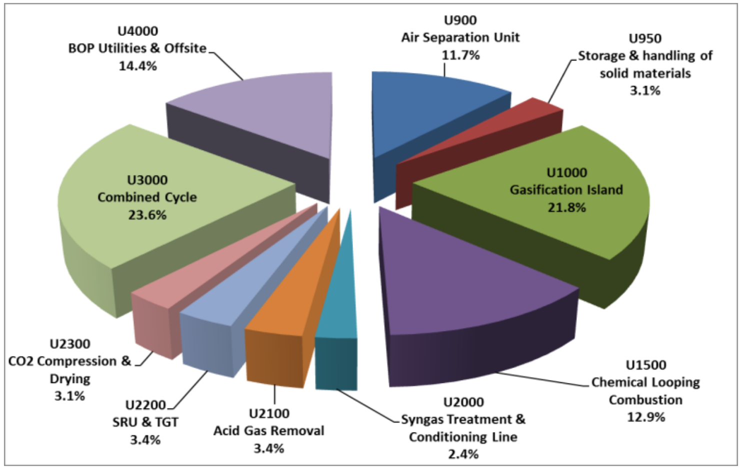
POS	DESCRIPTION	Unit 900 €	Unit 950 €	Unit 1000 €	Unit 1500 €	Unit 2000 €	Unit 2100 €	Unit 2200 €	Unit 2300 €	Unit 3000 €	Unit 4000 €	TOTAL €
1	DIRECT MATERIALS	77,011,000	21,472,000	144,107,000	91,960,000	13,548,000	17,907,000	16,975,000	16,495,000	151,217,000	104,998,000	655,690,000
2	CONSTRUCTION	32,871,000	7,472,000	60,224,000	20,770,000	8,635,000	13,359,000	10,609,000	11,547,000	67,709,000	29,712,000	262,908,000
3	OTHER COSTS	5,494,000	1,589,000	10,109,000	14,339,000	1,526,000	2,274,000	6,302,000	2,026,000	13,361,000	6,996,000	64,016,000
4	**TOTAL INSTALLATION COST**	**115,376,000**	**30,533,000**	**214,440,000**	**127,069,000**	**23,709,000**	**33,540,000**	**33,886,000**	**30,068,000**	**232,287,000**	**141,706,000**	**982,614,000**
5	PROJECT CONTINGENCY	11,538,000	3,053,000	21,444,000	12,707,000	2,371,000	3,354,000	3,389,000	3,007,000	23,229,000	14,171,000	98,263,000
	TOTAL PLANT COST	**126,914,000**	**33,586,000**	**235,884,000**	**139,776,000**	**26,080,000**	**36,894,000**	**37,275,000**	**33,075,000**	**255,516,000**	**155,877,000**	**1,080,877,000**

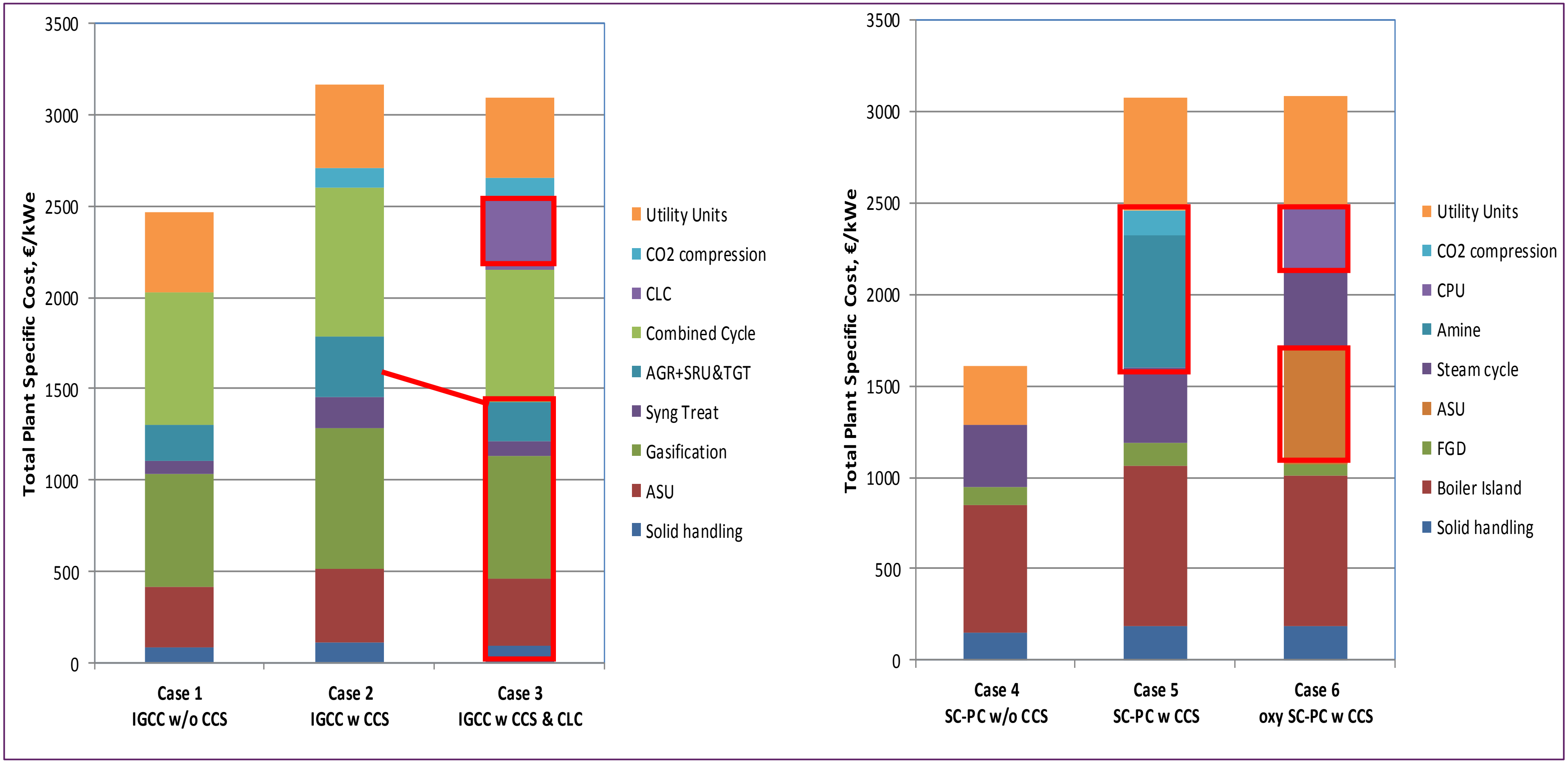
REMARKS

1) ESTIMATE ACCURACY +/- 35%
2) TODAY COSTS @ 1Q2015
3) EXCLUSIONS:
   - TAXES AND LOCAL AUTHORITIES
   - CAPITAL AND OPERATION SPARE PARTS
   - START-UP COSTS
   - FINANCIAL/LEGAL/INSURANCE COSTS
   - OWNER'S COST
4) 10% PROJECT CONTINGENCY
5) EPC SERVICES COSTS INCLUDED

UNIT	
900	ASU
950	Storage and Handling of solid materials
1000	Gasification Island
1500	Chemical Looping Combustion
2000	Syngas treatment & conditioning line
2100	Acid Gas Removal
2200	SRU & TGT
2300	CO_2 Compression & Drying
3000	Combined Cycle
4000	BOP Utilities&Offsites
349	MWe, Net Power Output
3099	€/kWe, Specific Investment Cost



Specific Total Plant Cost



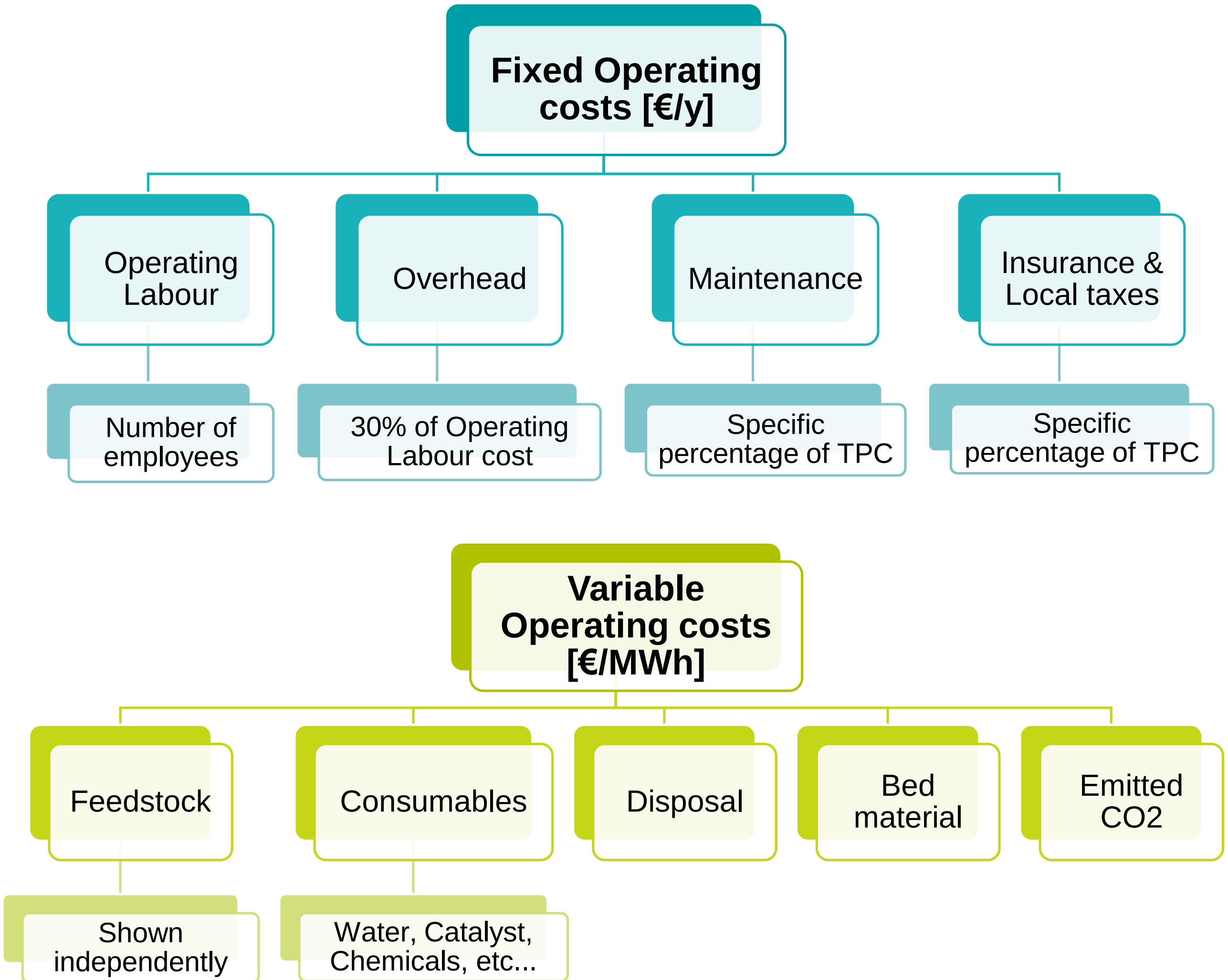
Total Capital Requirement (TCR)
Bases and methodology

Total Capital Requirement (TCR) is the sum of the TPC and the following items:

- *Interest during construction*, assumed same as discount rate (8%)
- *Spare parts cost*, assumed as 0.5% of the TPC
- *Working capital*, including 30 days inventories of fuel and chemicals
- *Start-up costs*, consisting of:
  - 2% of TPC to cover modifications to equipment that are needed to bring the unit up to full capacity
  - 25% of fuel cost for one month to cover inefficient operation that occurs during the start-up period
  - 3 months O&M costs to include training
  - 1 month of catalyst, chemicals and maintenance materials costs
- *Owner's costs*, assumed as 7% of TPC

TCR is tipically 30-35% higher than TPC

Operating & Maintenance (O&M) costs



Labour cost

Number of personnel required to operate the plant
IGCC: 133 people SC-PC: 105 people

Coal IGCC Plants					
	ASU	**Gasification**	**Power Island & Utilities**	**TOTAL**	**Notes**
OPERATION					
Area Responsible	1	1	1	3	daily position
Assistant Area Responsible	1	1	1	3	daily position
Shift Superintendent		5		5	1 position per shift
Electrical Assistant		5		5	1 position per shift
Shift Supervisor	5	5	5	15	3 positions per shift
Control Room Operator	5	10	10	25	5 positions per shift
Field Operator	5	30	20	55	10 positions per shift
Subtotal				**111**	
MAINTENANCE					
Mechanical group		4		4	daily position
Instrument group		7		7	daily position
Electrical group		5		5	daily position
Subtotal				**16**	
LABORATORY					
Superintendent+Analysts		6		6	daily position
Subtotal				**6**	
TOTAL				**133**	

Maintenance cost

- Estimated as a percentage of the TPC

Power plants	
Plant Sections	**Maintenance cost as percentage of the total installed cost**
Gasification Island	3.0 %
Feedstock handling and storage, CO_2 compression, Boiler Island, DeNOx, DeSOx, CPU	2.5 %
ASU, AGR, SRU&TGT, Syngas Treatment, CLC unit, CO_2 amine abs.	2.0 %
Balance of Plant	1.5 %
Combined Cycle (1)	5.0 %
Steam Cycle (2)	2.0 %

Note: 1) IGCC-based plants;
2) SC-PC-based plants.

- Statically split as 60% maintenance materials and 40% maintenance labour

Example of O&M costs

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	Case 1 €/year	Case 2 €/year	Case 3 €/year
Fixed Costs			
Direct labour	6,650,000	6,650,000	6,650,000
Adm./gen overheads	1,995,000	1,995,000	1,995,000
Insurance & Local taxes	9,066,200	10,047,400	10,808,800
Maintenance	27,742,700	29,941,100	31,237,300
Subtotal	**45,453,900**	**48,633,500**	**50,691,100**
Variable Costs (Availability = 87%)			
Feedstock	59,556,000	65,874,000	62,590,000
Water Makeup	911,000	1,113,900	1,089,600
Catalyst	74,000	2,096,000	1,088,000
Chemicals (including Solvent)	1,542,000	1,723,000	1,688,000
CLC bed material	0	0	5,752,000
Subtotal	**62,083,000**	**70,806,900**	**72,207,600**
TOTAL O&M COSTS	**107,536,900**	**119,440,400**	**122,898,700**
Specific O&M COSTS (€/kWh)	**0.038**	**0.049**	**0.046**

The operating lifetime of the packed bed reactor material leads to higher O&M costs (replacement cost)

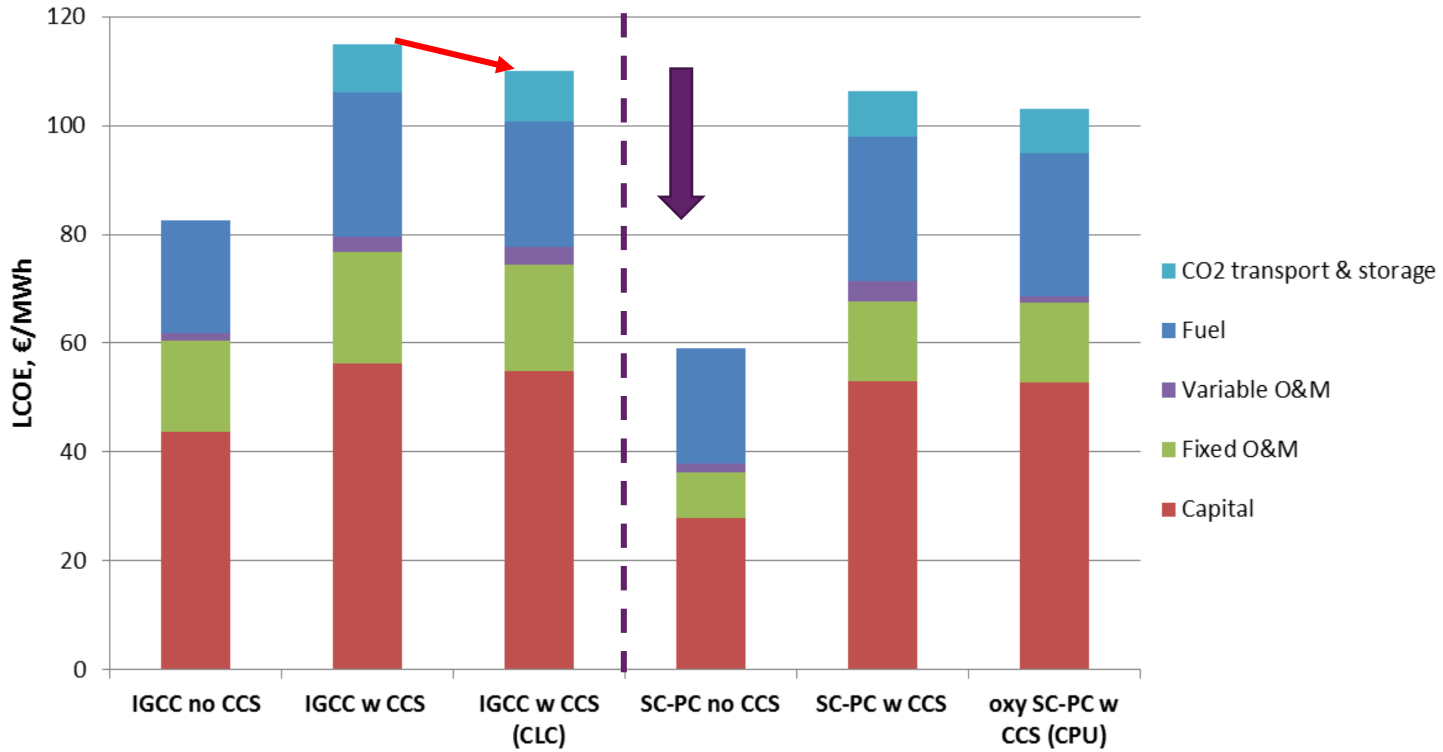
Simplified Financial Analysis

Main macroeconomic assumptions

Item	Cost
Coal	2.6 €/GJ$_{LHV}$ 65.05 €/t
Limestone	40 €/t
Raw water	0.2 €/m^3
Sulphur selling price	80 €/t
Ash, slag and gypsum net disposal cost	0 €/t
CO_2 transport and storage	10 €/t $_{stored\ CO2}$
CO_2 emission cost	0 €/t $_{emitted\ CO2}$
CLC bed material	2,500 €/t

Levelized Cost of Electricity (LCOE)

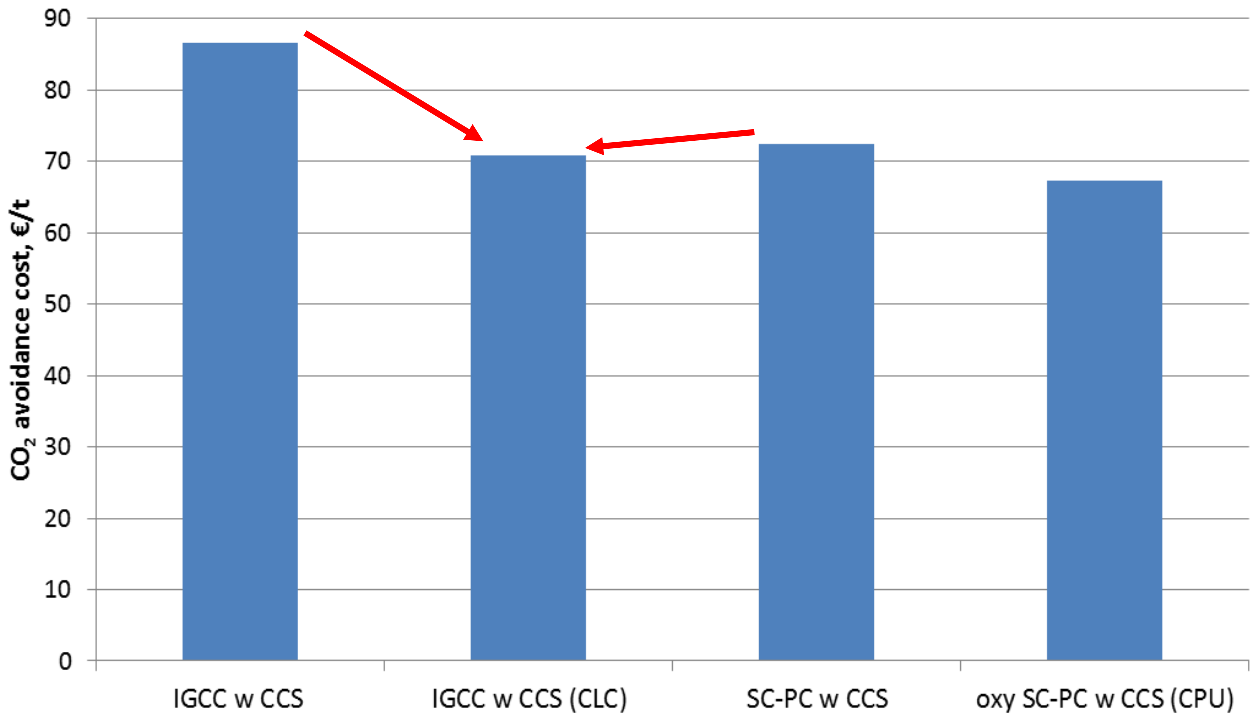
- LCOE of the CLC plant is slightly lower than the one of the benchmark IGCC
- SC-PC based power plants show lower LCOE



Bituminous Coal: 2,6 €/GJ (LHV); Discount rate: 8%
CO_2 transport & storage: 10 €/t; 87-90% capacity factor; Constant €, 2015.

CO_2 Avoidance Cost (CAC)

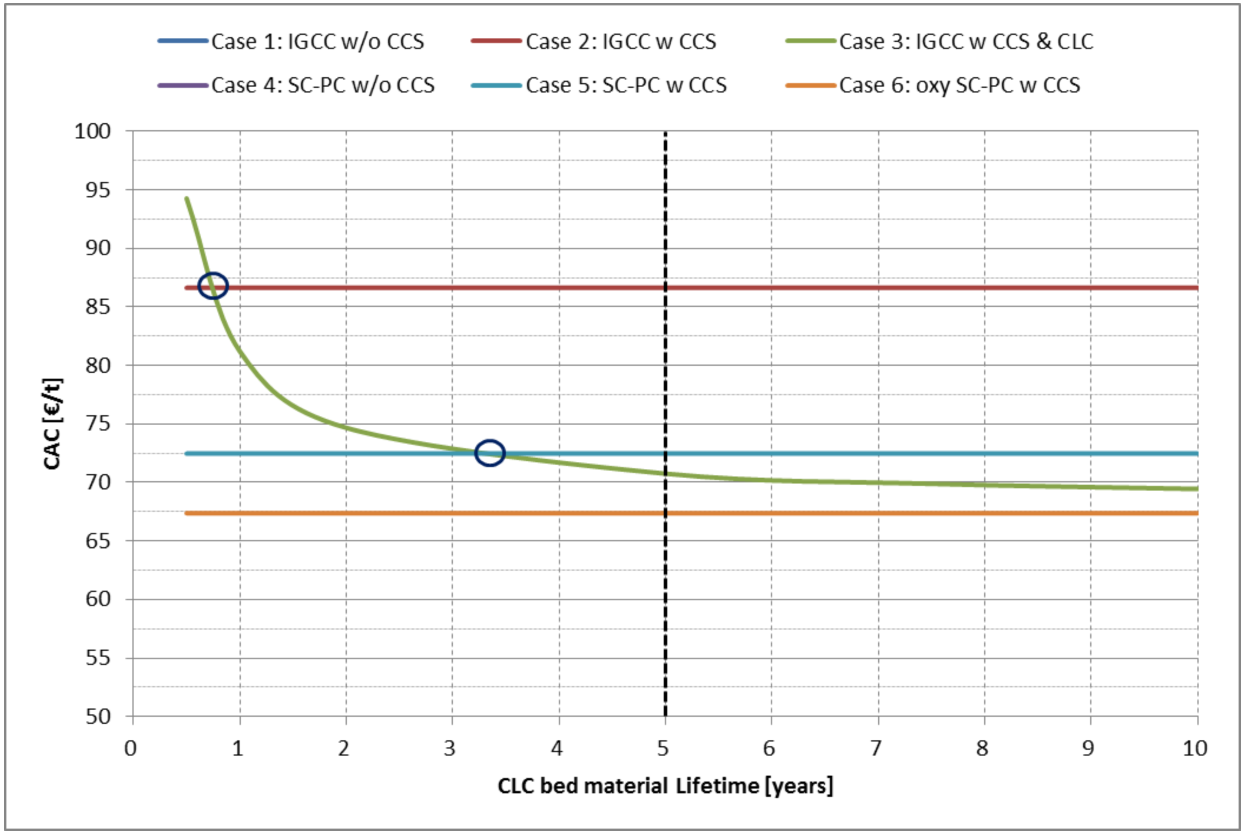
- Based on CAC, CLC plant is more attractive than benchmark IGCC and SC-PC plants with CCS, due to its higher intrinsic CO_2 capture rate



Reference Plant: SC-PC without CO_2 capture
Bituminous Coal: 2,6 €/GJ (LHV); Discount rate: 8%
CO_2 transport & storage: 10 €/t; 87-90% capacity factor; Constant €, 2015.

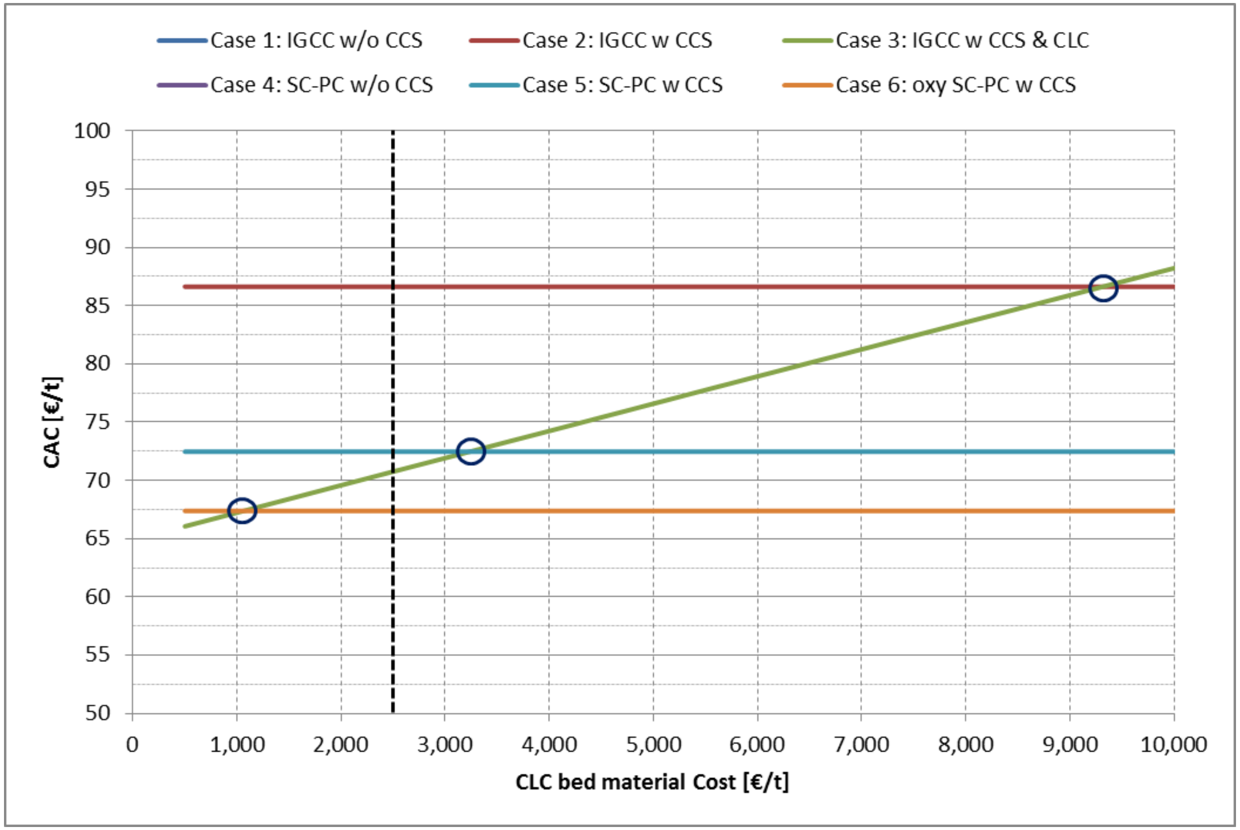
Sensitivity analyses
CLC bed lifetime

- Affects maintenance and operating costs (replacement) of the CLC unit
- CLC plant is more attractive than IGCC and SC-PC plants with CCS when the bed lifetime is respectively greater than 9 months and 3.25 years



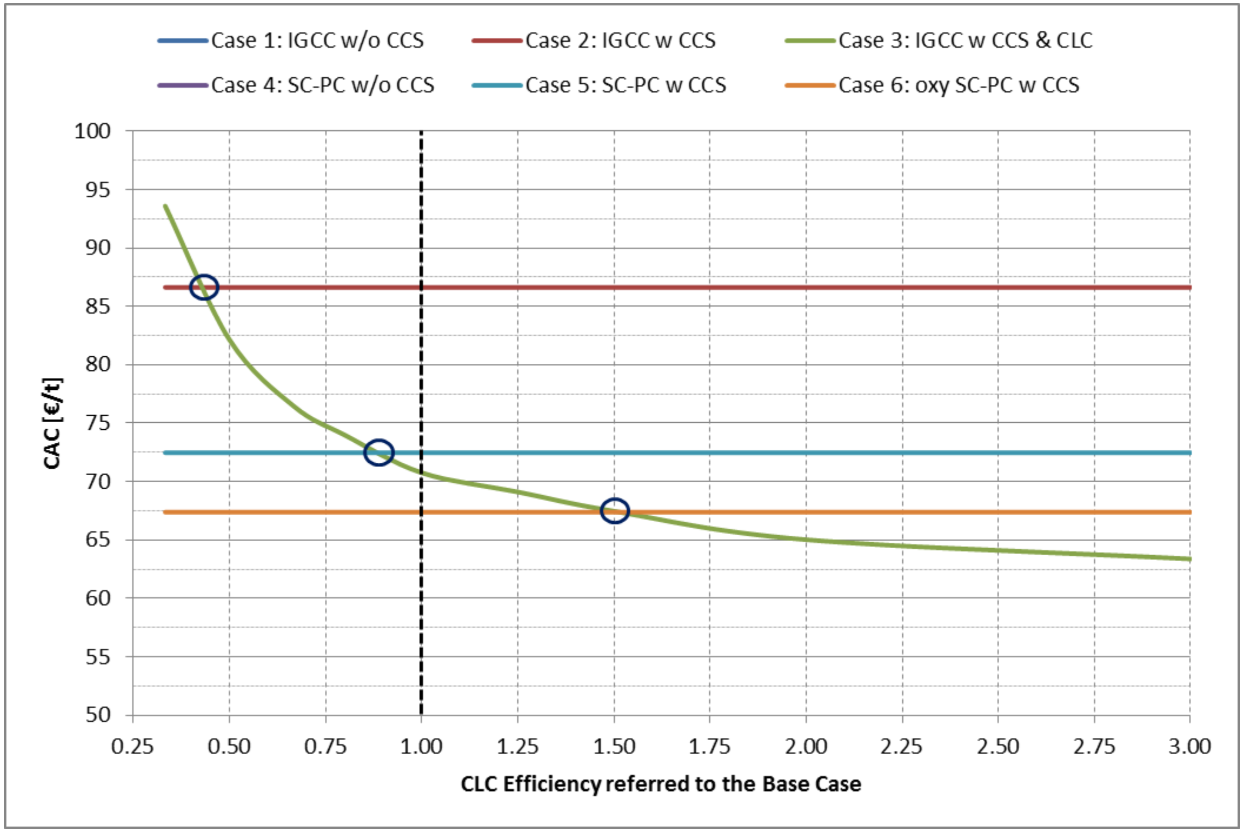
Sensitivity analyses
CLC bed material cost

- Affects both investment and maintenance/replacement costs of the CLC unit
- CLC plant is more attractive than IGCC and SC-PC plants with CCS when the bed material cost is respectively lower than 9,000 €/t and 3,200 €/t



Sensitivity analyses
CLC reactor performance

- Affects required bed surface/volume or reactor vessel number. In turn, both investment and maintenance/replacement costs of the CLC unit are affected



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Summary Considerations

- Carbon dioxide Avoidance Cost of the CLC plant is lower than the cost of the gasification and similar to those of the boiler plants with carbon capture
  - **Higher net electric efficiency of the CLC technology (40.8%)**
  - **Higher carbon capture rate (96.1%)**
- CLC unit (bed material, reactor pressure vessels, heat recovery section) requires additional capital requirement
- Some technological barriers need to be overcome before commercialization of the packed bed CLC process in a full-scale power plant
- CLC technology is an **ATTRACTIVE OPTION** for carbon dioxide capture in power plants, especially if further improvements of the bed material performance / lifetime / cost will be achieved in the future

Look forward for **NEW COMPANIES** to demonstrate the scalability of the process and its **FULL PROFITABILITY** at large scale amec foster wheeler

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