Carbon capture and utilisation technologies applied to energy conversion systems and other energy-intensive applications

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Outline

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2. Carbon capture and utilisation technologies
3. Major design assumptions
4. Plant modelling, simulation and thermal integration
5. Evaluation of carbon capture and utilisation technologies for energy-intensive applications
6. Conclusions

I. Introduction

The following work was performed within the project: *"Developing innovative low carbon solutions for energy-intensive industrial applications by Carbon Capture, Utilization and Storage (CCUS) technologies"*

Specific project objectives:

- **Investigation of fossil fuel-intensive industrial processes e.g. heat & power, metallurgy, cement, petro-chemistry**
- **Energy vectors poly-generation (power, H_2, SNG, MeOH)**
- **Evaluation of various carbon capture and utilisation technologies e.g. reactive gas-liquid & gas-solid systems**
- **Techno-economical and environmental evaluations of energy-intensive industrial applications with CCUS**

Energy vector poly-generation concepts based on gasification process with CO_2 capture

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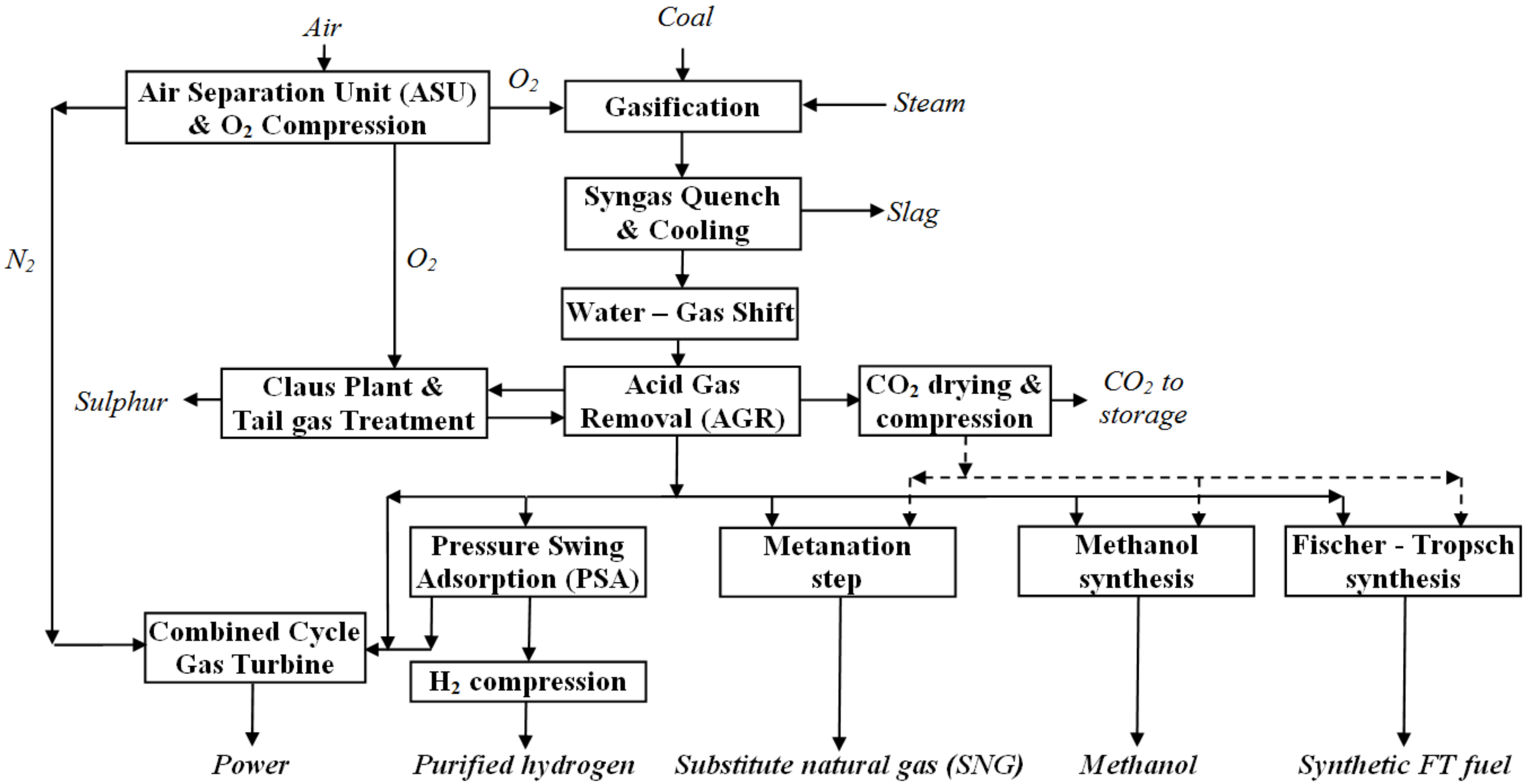
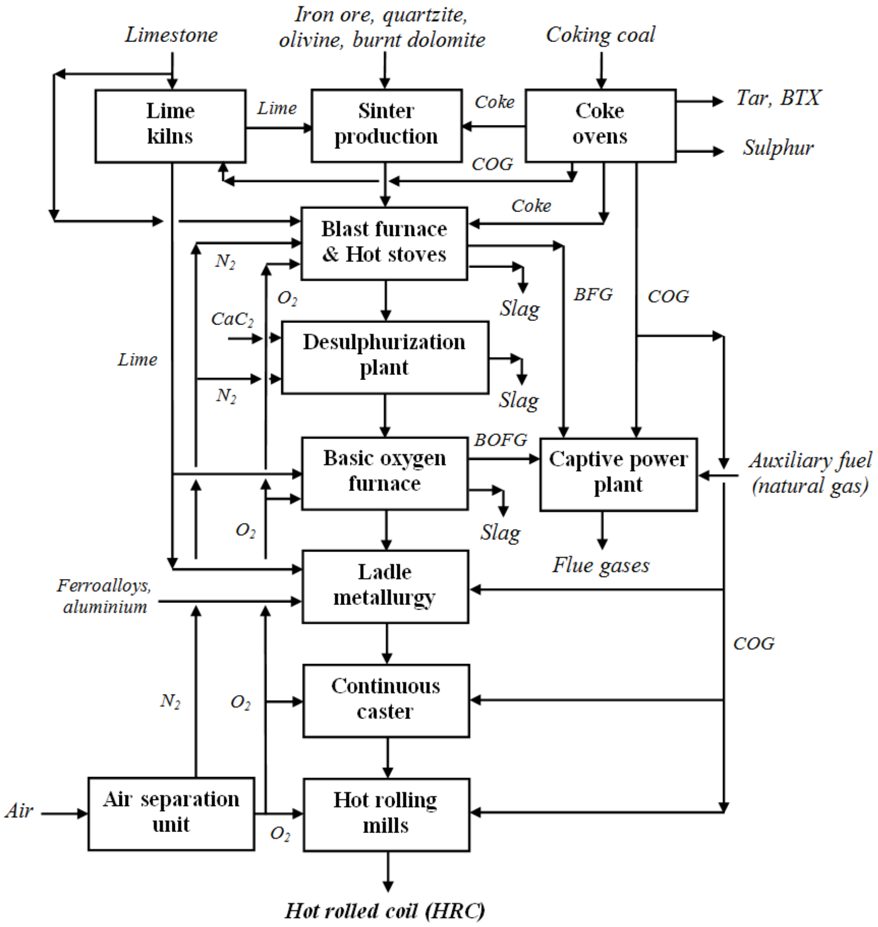
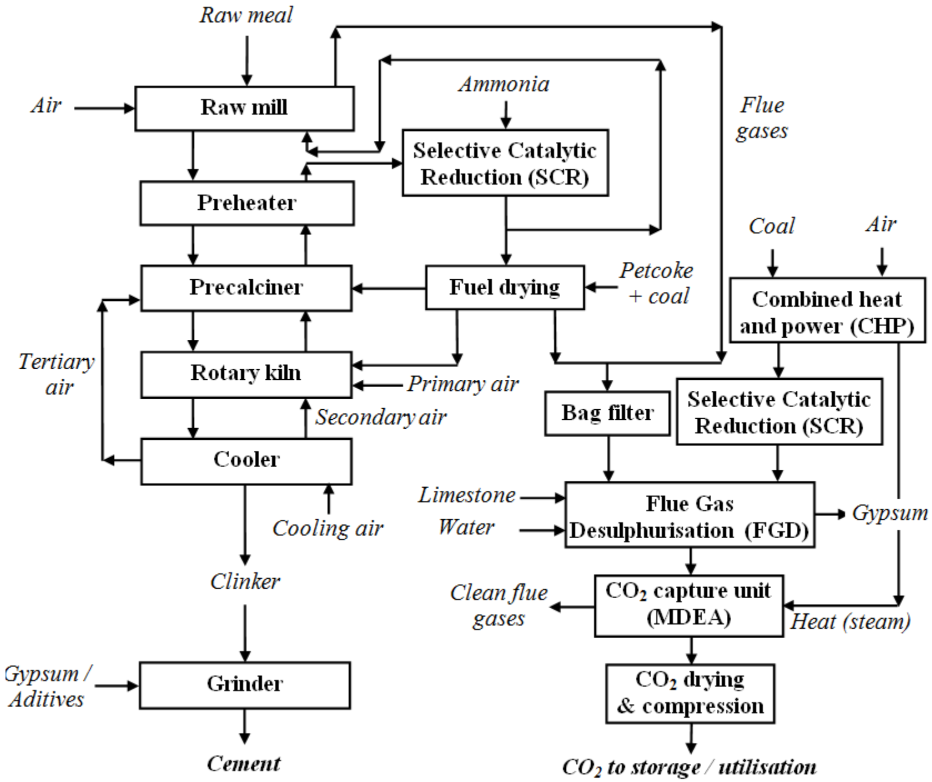


Decarbonisation of energy-intensive industrial processes (non-power applications)



Integrated steel mill



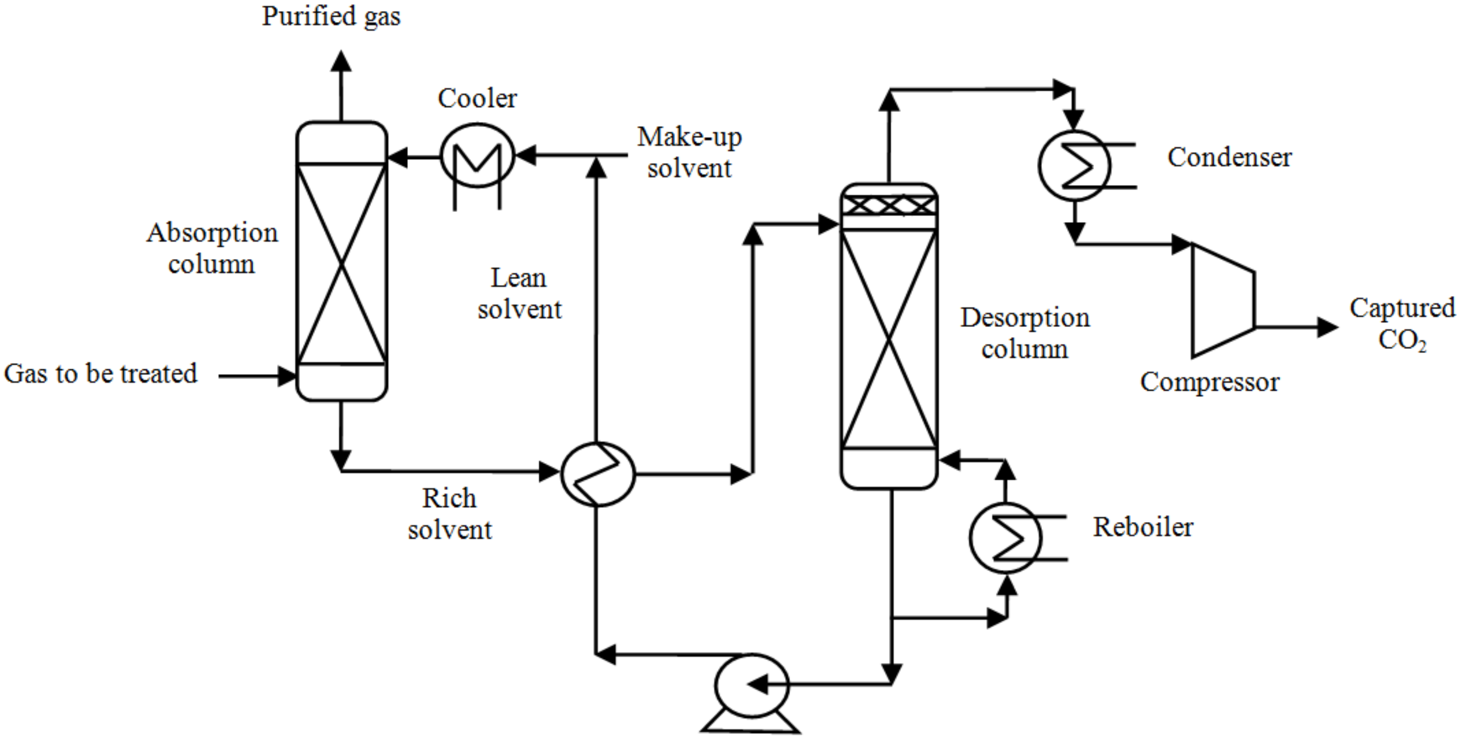
Cement production plant

II. Carbon capture and utilisation

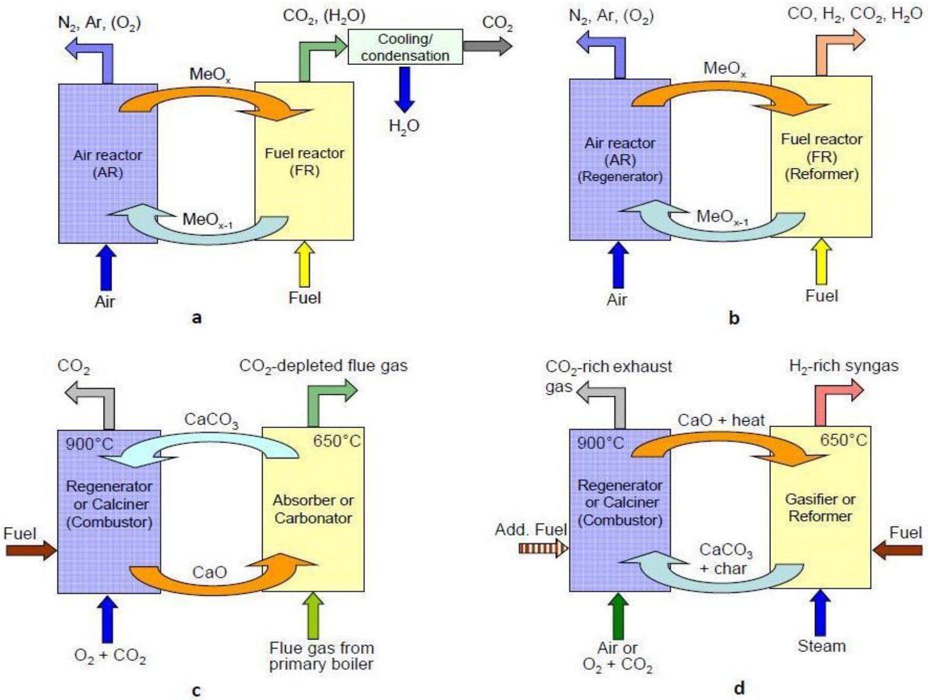
CO_2 capture based on gas-liquid absorption

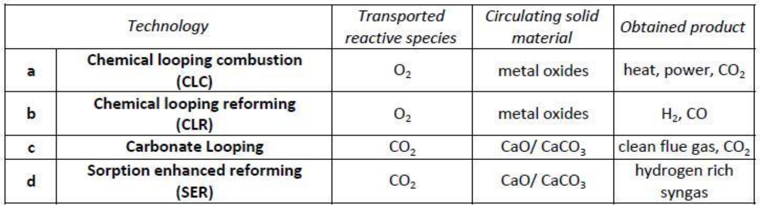
Chemical reactions for tertiary alkanolamine (e.g. MDEA):

$$R_3N + CO_2 + H_2O \longleftrightarrow HCO_3^- + R_3NH^+$$



CO_2 capture based on chemical & calcium looping systems





	Technology	*Transported reactive species*	*Circulating solid material*	*Obtained product*
a	**Chemical looping combustion (CLC)**	O_2	metal oxides	heat, power, CO_2
b	**Chemical looping reforming (CLR)**	O_2	metal oxides	H_2, CO
c	**Carbonate Looping**	CO_2	$CaO/ CaCO_3$	clean flue gas, CO_2
d	**Sorption enhanced reforming (SER)**	CO_2	$CaO/ CaCO_3$	hydrogen rich syngas

Main advantages:

- **Inherent CO_2 capture**
- **High temperature heat recovery potential**
- **Fuel versatility**
- **Poly-generation capability**

CO_2 capture based on calcium looping (CaL)

Chemical reactions for post-combustion capture:

- Carbonation reactor:

$$CaO + CO_2 \xrightarrow{500\text{–}650^{0}C} CaCO_3$$

- Calcination reactor (required extra heat input):

$$CaCO_3 \xrightarrow{800\text{–}950^{0}C} CaO + CO_2 \quad \Delta H = 178\ kJ/mole$$

A distinct design option for pre-combustion CO_2 capture is Sorbent Enhanced Water Gas Shift (SEWGS):

$$CaO + CO + H_2O \xrightarrow{500\text{–}650^{0}C} CaCO_3 + H_2$$

Energy vectors poly-generation

- **Hydrogen production (water gas shift - WGS):**

$$CO + H_2O \rightarrow H_2 + CO_2$$

- **Substitute natural gas (SNG) production:**

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

- **Liquid hydrocarbons production (FT fuel):**

$$nCO + (n+\frac{m}{2})H_2 \rightarrow C_nH_m + nH_2O$$

- **Methanol and Di-Methyl Ether (DME) production:**

$$CO + 2H_2 \rightarrow CH_3OH \rightarrow CH_3OCH_3$$

III. Major design assumptions

1. Power plants: Integrated gasification combined cycle / Super-critical pulverised coal (400 - 600 MW_e net)

2. Other industrial applications: Integrated steel mill (4 Mt/y), cement production plant (1 Mt/y)

3. Carbon capture rate: 90%

4. CO_2 capture (pre- & post-combustion): MDEA / CaL

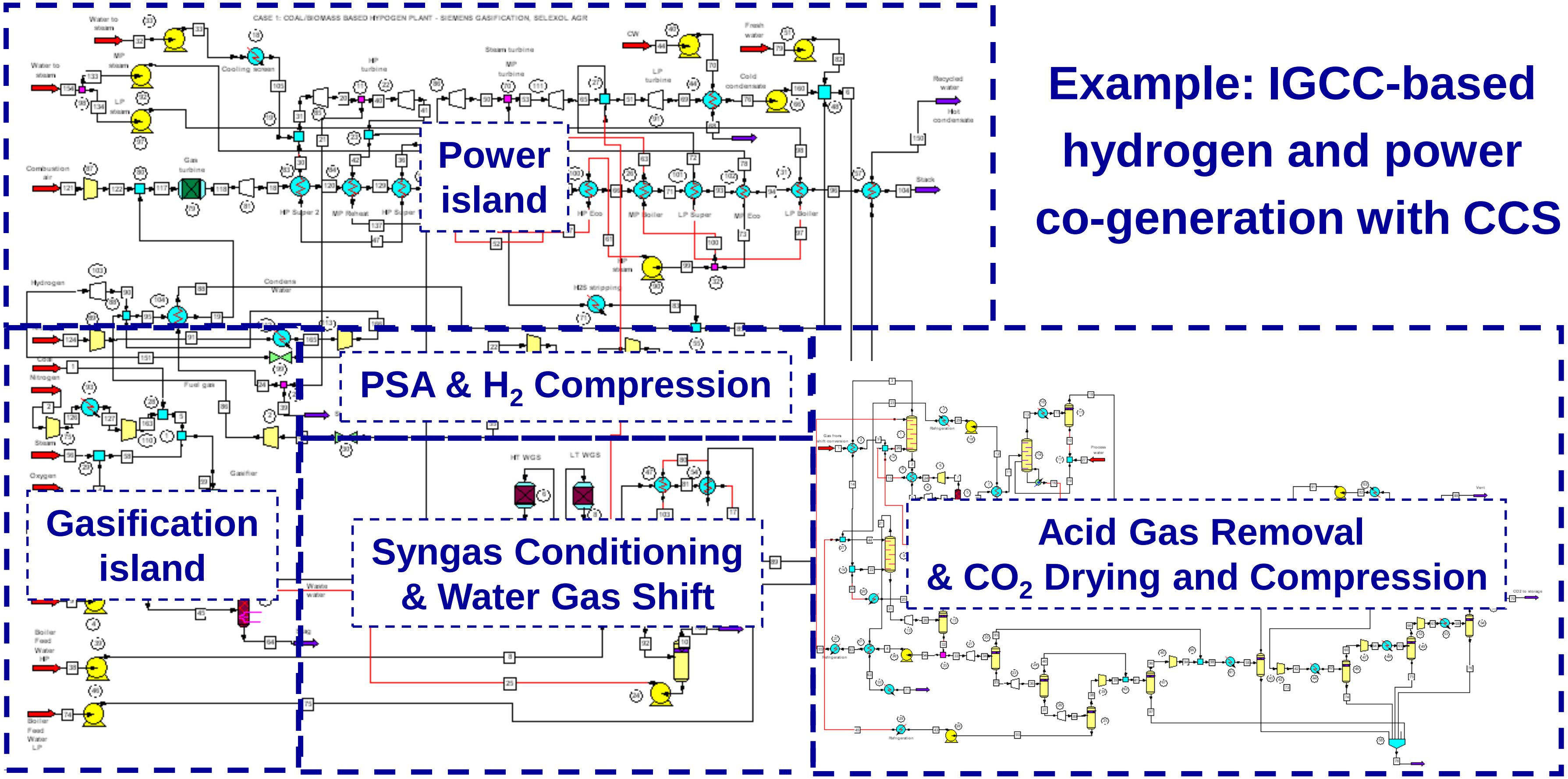
5. CO_2 purity & pressure: >95% (vol.) / 120 bar

6. Other energy carriers: H_2, SNG, Methanol, FT fuel

7. Fuel: Coal, natural gas (auxiliary fuel for steel mill)

IV. Plant modeling, simulation and thermal integration

Investigated case studies were simulated using process flow modelling (ChemCAD software)



Example: IGCC-based hydrogen and power co-generation with CCS

Optimization of plant energy efficiency by heat and power integration

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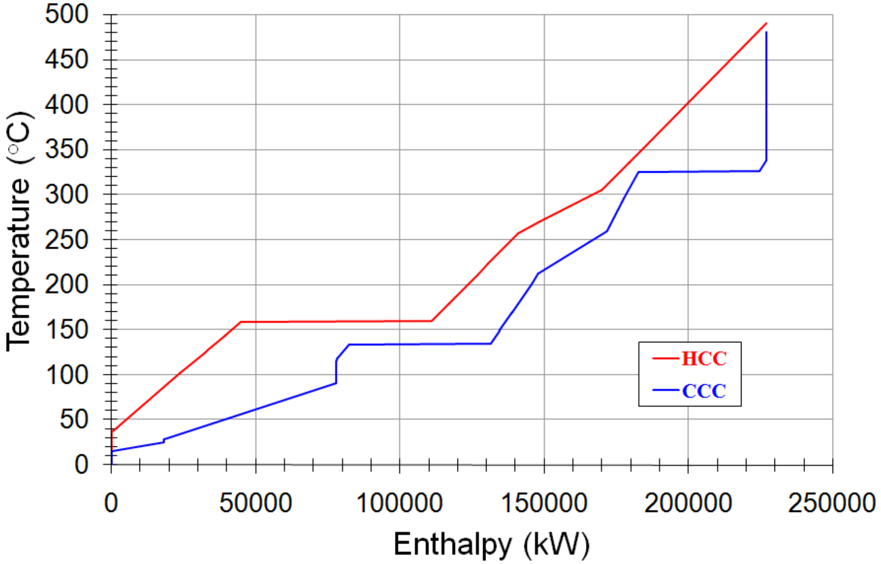
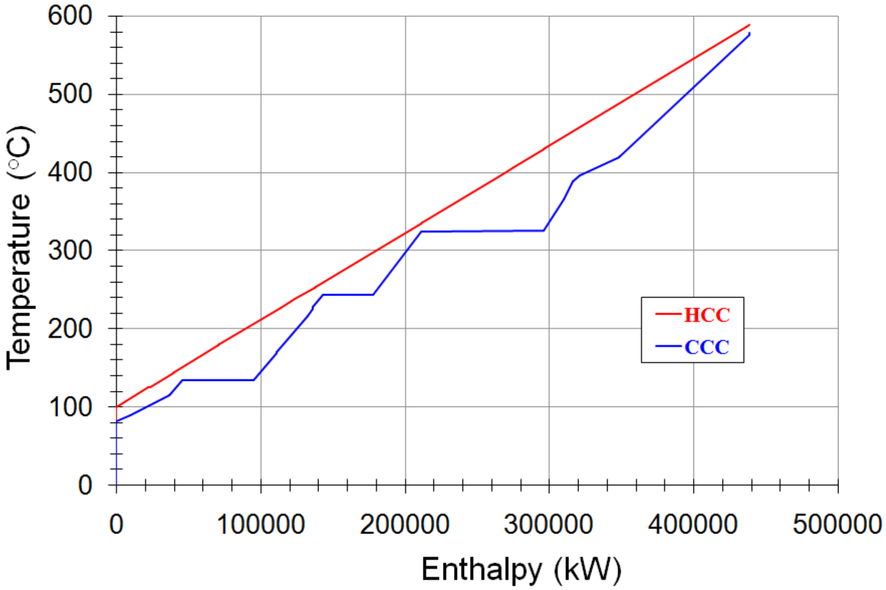
Example: IGCC-based hydrogen and power co-generation with CCS



Composite curves for syngas treatment line



Composite curves for hydrogen-fuelled CCGT

V. Evaluation of CCUS technologies for energy-intensive industrial applications

Investigated energy-intensive industrial applications:

(i) IGCC power plants (dry feed gas quench gasifier)

Case 1a – Plant without carbon capture (benchmark)

Case 1b – Post-combustion CO_2 capture (MDEA)

Case 1c – Pre-combustion CO_2 capture (MDEA)

Case 1d – Post-combustion CO_2 capture (CaL)

Case 1e – Pre-combustion CO_2 capture (CaL)

(ii) Super-critical PC power plants

Case 2a – Plant without carbon capture (benchmark)

Case 2b – Post-combustion CO_2 capture (MDEA)

Case 2c – Post-combustion CO_2 capture (CaL)

Investigated energy-intensive industrial applications:

(iii) Integrated steel mills

Case 3a – Plant without carbon capture (benchmark)

Case 3b – Post-combustion CO_2 capture (MDEA) – A^*

Case 3c – Post-combustion CO_2 capture (MDEA) – B^{**}

Case 3d – Post-combustion CO_2 capture (CaL) – A^*

Case 3e – Post-combustion CO_2 capture (CaL) – B^{**}

***A – CO_2 capture from hot stoves & steam / power plant**

****B – CO_2 capture from hot stoves, steam / power plant, lime kilns & coke ovens**

(iv) Cement production plants

Case 4a – Plant without carbon capture (benchmark)

Case 4b – Post-combustion CO_2 capture (MDEA)

Case 4c – Post-combustion CO_2 capture (CaL)

IGCC power plants

		Case 1a	Case 1b	Case 1c	Case 1d	Case 1e
Coal flowrate	t/h	150.50	150.50	166.91	228.14	221.88
Coal thermal energy	MW_{th}	1052.25	1052.25	1166.98	1595.12	1551.35
Gas turbine output	MW_e	334.00	334.00	334.00	334.00	334.00
Steam turbine output	MW_e	225.30	139.56	200.72	384.60	380.71
Expander output	MW_e	1.42	1.42	1.18	1.78	1.42
Ancillary power	MW_e	76.11	95.86	108.82	176.41	156.05
Net power	MW_e	484.61	379.12	427.08	547.97	560.08
Net power efficiency	%	46.05	36.03	36.59	34.35	36.10
Carbon capture rate	%	0.00	90.00	90.00	90.00	90.00
CO_2 emissions	kg / MWh	759.57	92.15	85.51	99.82	82.83
SPECCA	MJ / kg	-	3.25	2.99	4.03	3.18

Super-critical PC power plants

		Case 2a	Case 2b	Case 2c
Coal flowrate	t/h	156.74	198.35	216.74
Coal thermal energy	MW_{th}	1095.87	1386.79	1515.37
Steam turbine output	MW_e	502.32	541.30	649.60
Ancillary power	MW_e	27.45	65.68	105.38
Net power	MW_e	474.87	475.62	544.22
Net power efficiency	%	43.33	34.29	35.91
Carbon capture rate	%	0.00	90.00	90.00
CO_2 emissions	kg / MWh	800.58	89.55	76.84
SPECCA *	MJ / kg	-	3.07	2.37

*** SPECCA - Specific primary energy consumption for CO_2 avoided**

$$= \frac{Heat\ rate_{CO_2\ capture} - Heat\ rate_{no\,capture}}{Emissions_{CO_2\ no\,capture} - Emissions_{CO_2\ capture}}$$

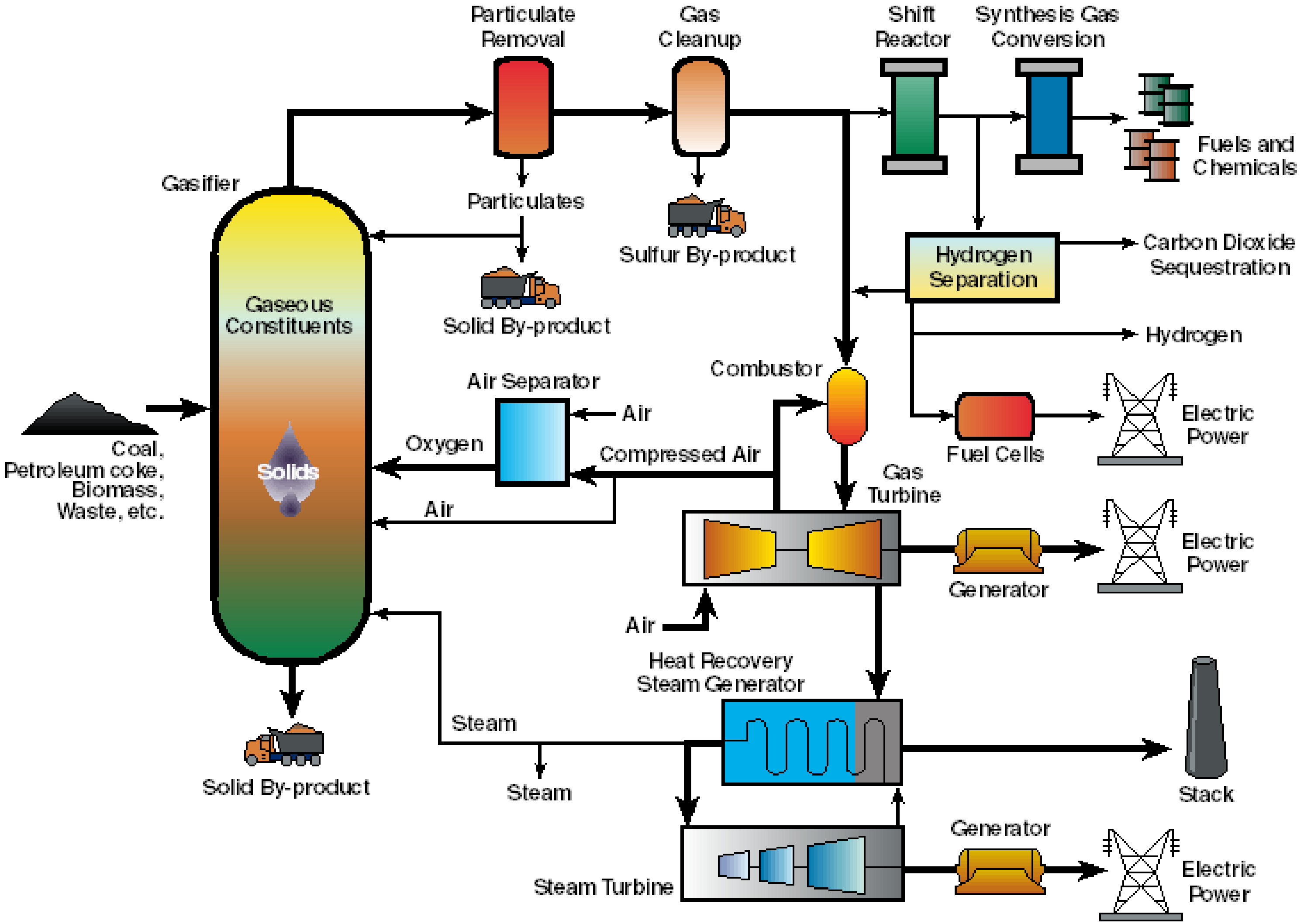
Integrated steel mills

		Case 3a	Case 3b	Case 3c	Case 3d	Case 3e
Fuel thermal energy	MW_{th}	669.78	517.25	544.00	882.04	1156.79
Gas turbine output	MW_e	-	192.00	202.31	91.06	91.06
Steam turbine output	MW_e	224.68	101.76	107.33	269.64	366.04
Ancillary power	MW_e	9.68	1.59	1.64	76.04	132.57
Net power	MW_e	215.00	292.17	308.00	284.66	324.53
Net power efficiency	%	32.10	56.48	56.61	32.27	27.79
CO_2 emissions power	kg / MWh	2455.33	370.60	369.67	152.39	242.40
Carbon capture rate	%	0.00	90.00	90.00	90.00	90.00
CO_2 emissions steel	kg / tHRC	2092.45	1048.36	833.54	1203.61	640.01
Captured CO_2	kg / tHRC	0.00	1300.88	1615.81	824.45	1495.12

Cement production plants

		Case 4a	Case 4b	Case 4c
Coal flowrate	t/h	-	33.47	22.00
Coal thermal energy	MW_{th}	-	234.06	153.81
Steam turbine output	MW_e	-	54.42	58.01
Ancillary power	MW_e	16.24	34.14	42.19
Net power	MW_e	-	20.28	15.82
Net power efficiency	%	-	8.66	10.28
Carbon capture rate	%	0.00	90.00	90.00
CO_2 emissions	kg / t cement	770.44	55.83	58.37
Captured CO_2	kg / t cement	0.00	1214.15	962.19

Gasification-based energy vector poly-generation system with CO_2 capture



Various energy vectors and power co-generation based on gasification (Case 1c)

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		SNG	Methanol	FT fuel
Coal thermal energy	MW_{th}	1224.51	298.02	1224.51
Gross power output	MW_e	164.75	40.12	193.25
SNG thermal output	MW_{th}	800.00	-	-
Methanol thermal output	MW_{th}	-	150.00	-
FT fuel thermal output	MW_{th}	-	-	700.00
Ancillary power demand	MW_e	116.23	22.56	76.45
Net power output	MW_e	48.52	17.56	116.80
Net electrical efficiency	%	3.96	5.89	9.53
SNG / MeOH / FT efficiency	%	65.33	50.33	57.16
Cumulative efficiency	%	69.28	56.22	66.70
Carbon capture rate	%	60.00	50.00	48.00
CO_2 specific emissions	kg / MWh	8.25	24.32	37.45

VI. Conclusions

- Various energy-intensive industrial applications (power generation, integrated steel mill, cement production) were evaluated in view of decarbonisation

- Modelling, simulation and heat & power integration tools were used to asses and optimize the plant performances

- Calcium looping method looks very promising to deliver high energy efficiency in comparison to the reactive gas-liquid absorption for energy-intensive applications

- Energy vectors poly-generation concepts are promising to further improve the technical and environmental performances (e.g. overall energy efficiency, specific CO_2 emissions, plant flexibility etc.)

Thank you for your attention!

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