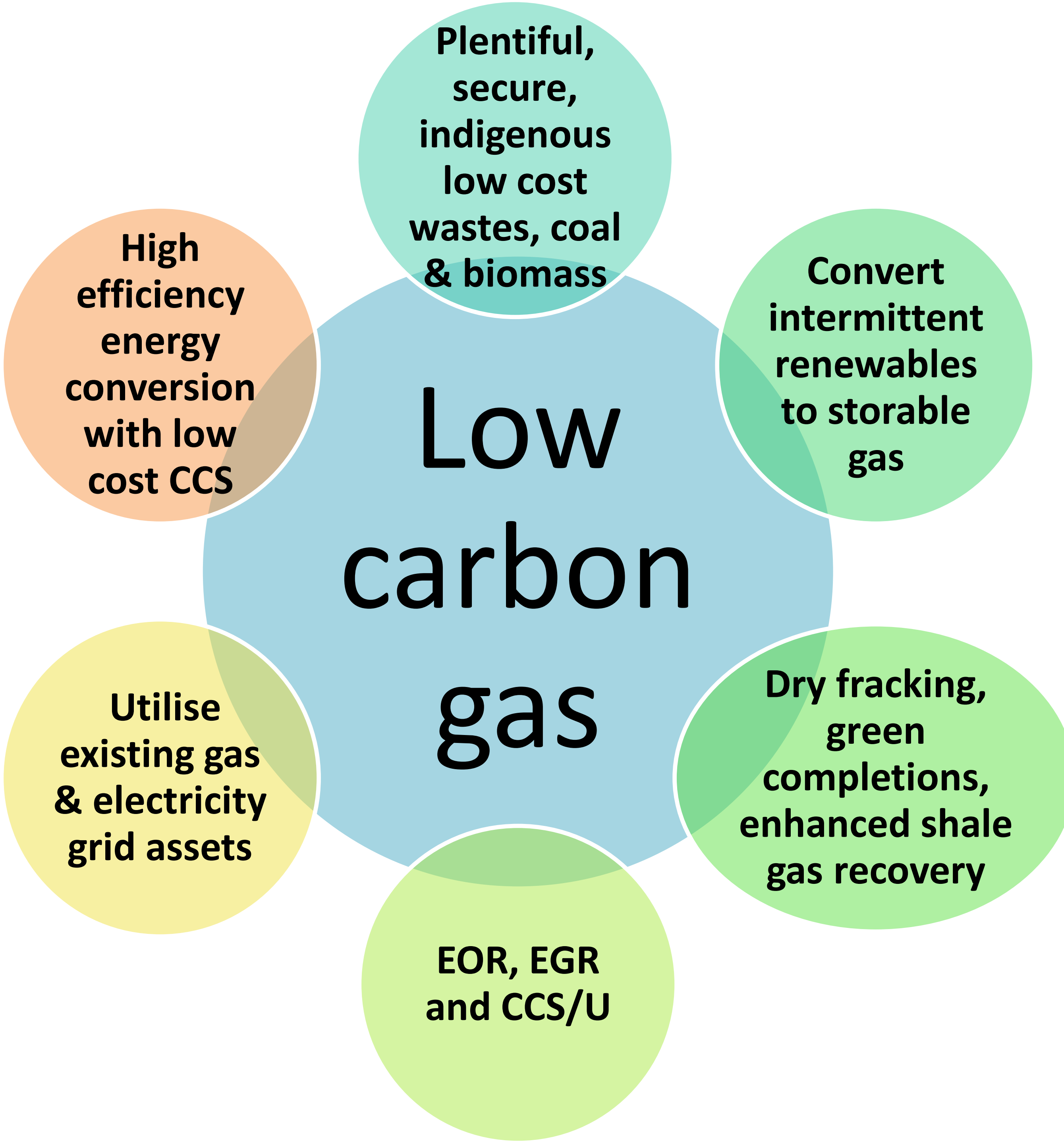
Plentiful, secure, indigenous low cost wastes, coal & biomass
Convert intermittent renewables to storable gas
Dry fracking, green completions, enhanced shale gas recovery
EOR, EGR and CCS/U
Utilise existing gas & electricity grid assets
High efficiency energy conversion with low cost CCS
Low carbon gas

ACKNOWLEDGEMENTS

- DNV GL Group (Previously Advantica plc)
- Johnson Matthey plc.
- Davy Process Technology Ltd.
- Jacobs Engineering Group Inc.
- GE Energy Inc.
- Timmins CCS Ltd
- Waste Recycling Group Ltd
- Kier Group plc
- Envirotherm GmbH
- Tectronics Ltd
- CNG Services Ltd
- Greenhill LLP
- Planet Hydrogen Ltd.

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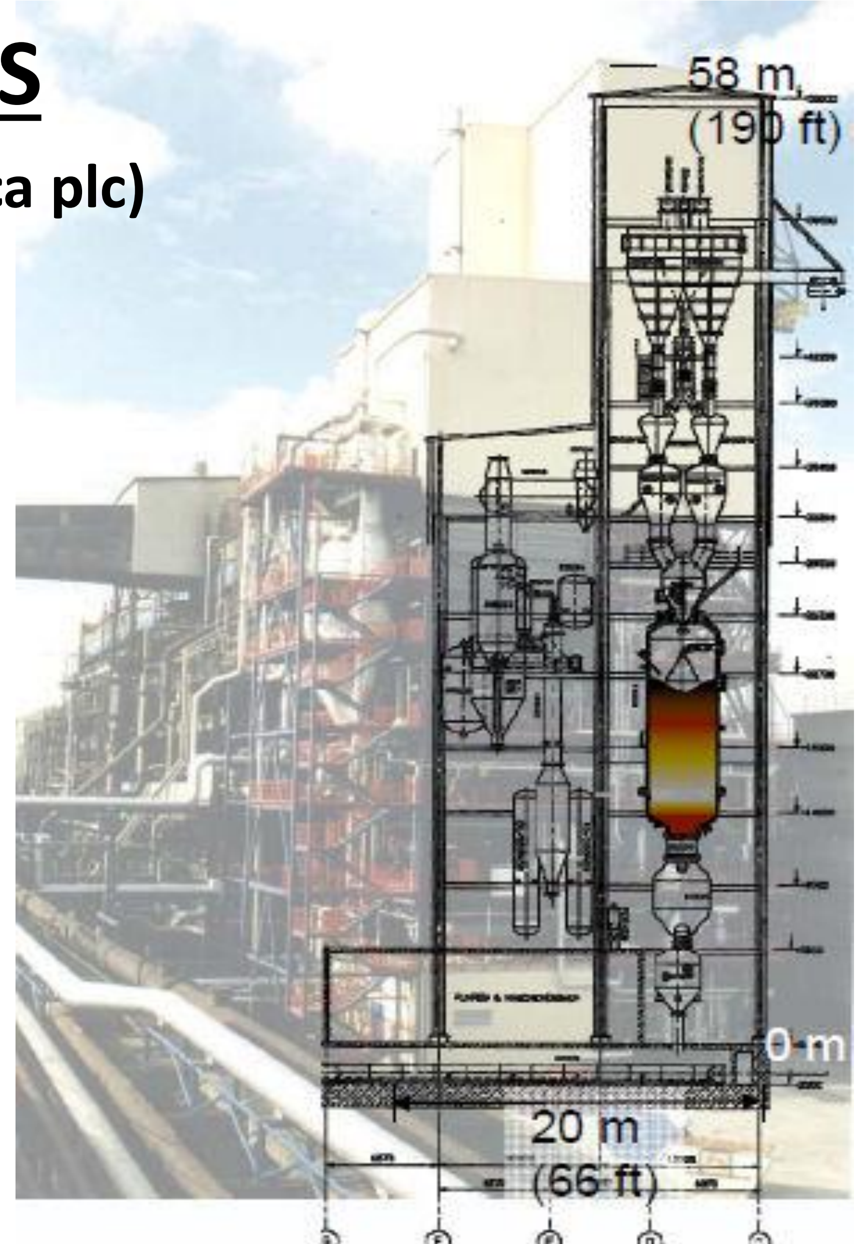


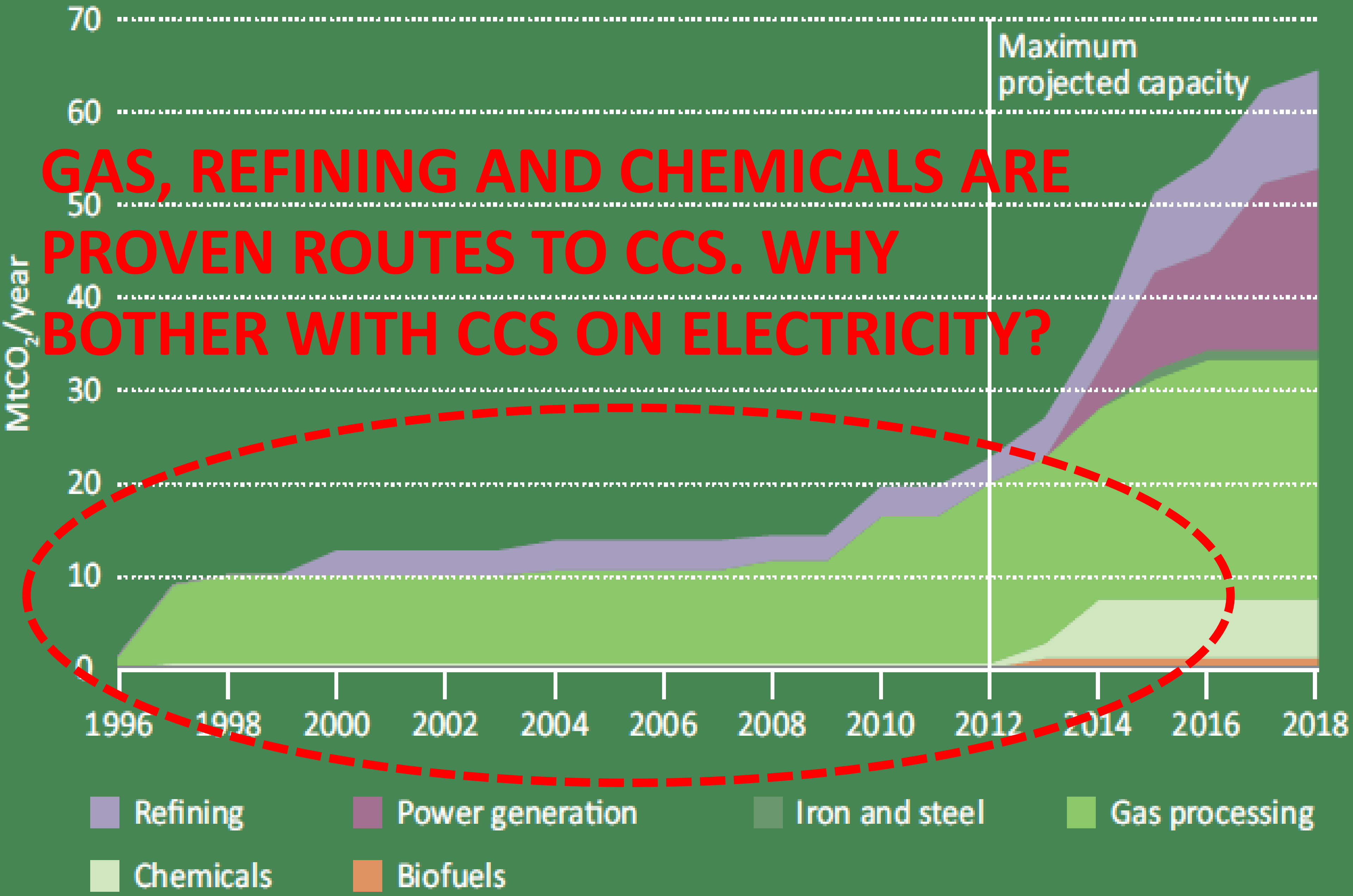
British Gas Lurgi multi-fuel gasifier at SVZ Schwarze Pumpe

PROFITABLE CCS

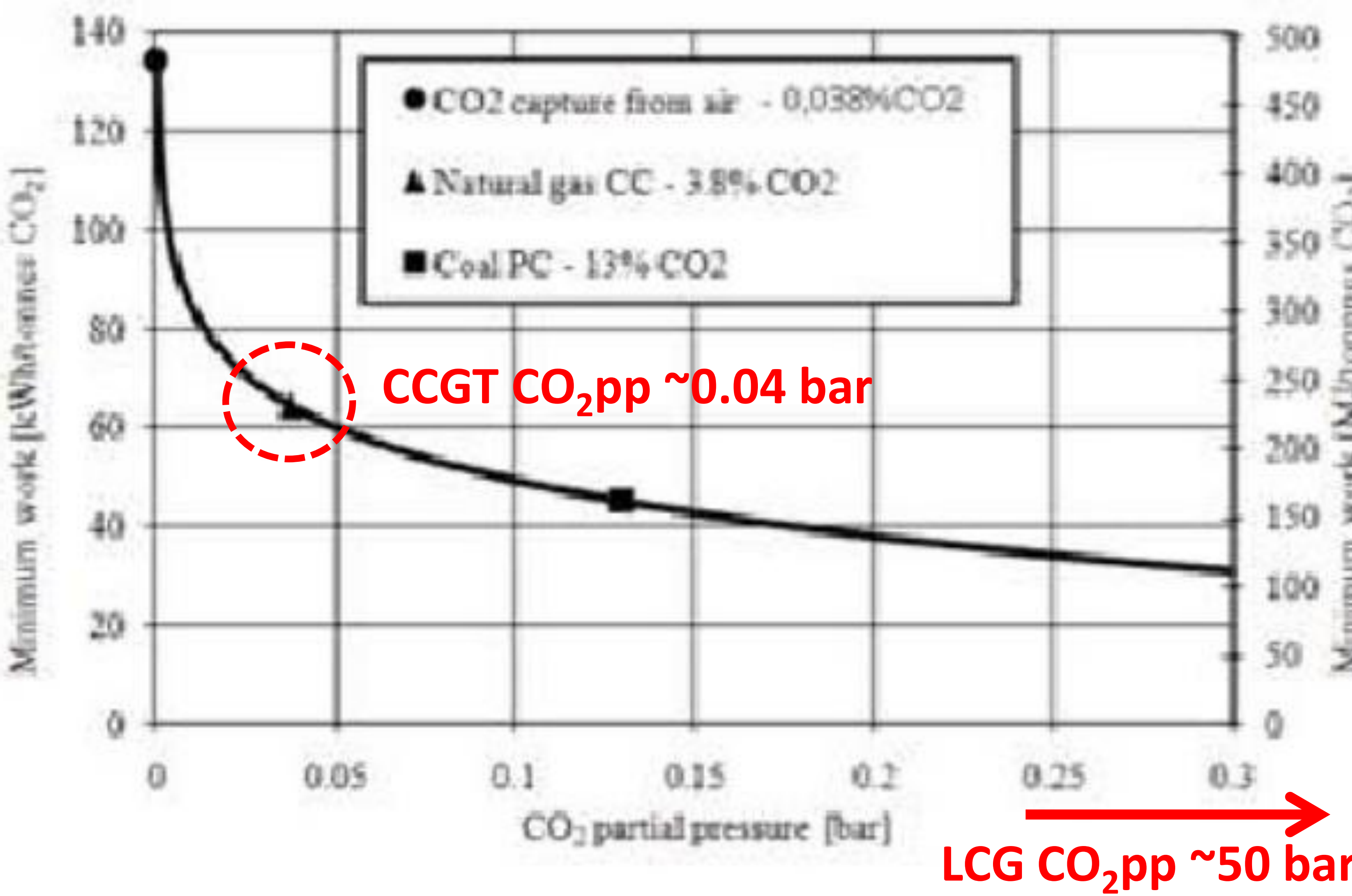
- NEGATIVE COST FUEL: WASTE IS UK'S CHEAPEST MOST PLENTIFUL FUEL @ £-8/GJ AVOIDED COST OF LANDFILL TAX AND 50 -65% BIOGENIC CARBON CONTENT
- HIGH EFFICIENCY: CONVERT 50% WASTE:30% BIOMASS:20% COAL TO LOW CARBON GAS @ ~77% EFFICIENCY WITH CCS.
- METHANE SYNTHESIS: IS INHERENTLY CARBON CAPTURE READY AT HIGH CO_2 PARTIAL PRESSURE (CO_2 CONC'N x PRESSURE).
- LOW COST CCS: 55% OF CARBON IN LCG IS SEPARATED AS sCO_2 ZERO MARGINAL COST WASTE BY-PRODUCT OF LCG.
- SELL: CHEAP HIGH PURITY sCO_2 TO INDUSTRY FOR CCU, OR FOR ENHANCED OIL AND GAS RECOVERY AND CCS.

- -ve EMISSIONS 60 bar LCG @ 45 p/therm (£15/MWh)
- 150 bar HIGH PURITY sCO_2 @ 40p/tonne
- PROFIT 2030 CfD/CFP, ex by-products/haz waste: 150p/th

2.2 Large-scale CO_2 capture projects



CCS ENERGY REQUIREMENT v CO_2 PARTIAL PRESSURE



work requirement for separation is expressed as energy requirement per tonnes CO_2

COMPARATIVE CO_2 PARTIAL PRESSURES FOR VARIOUS TECHNOLOGIES

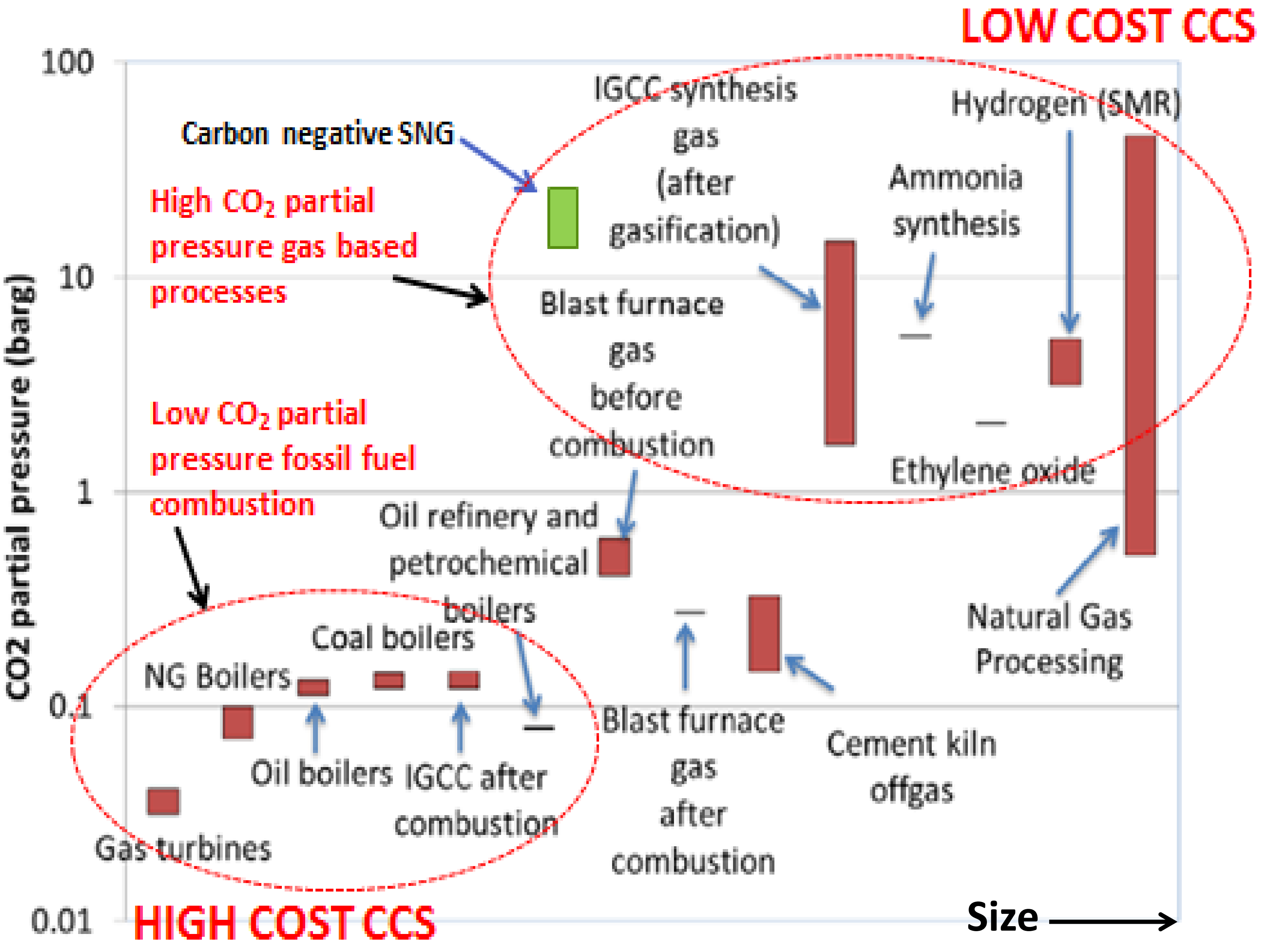


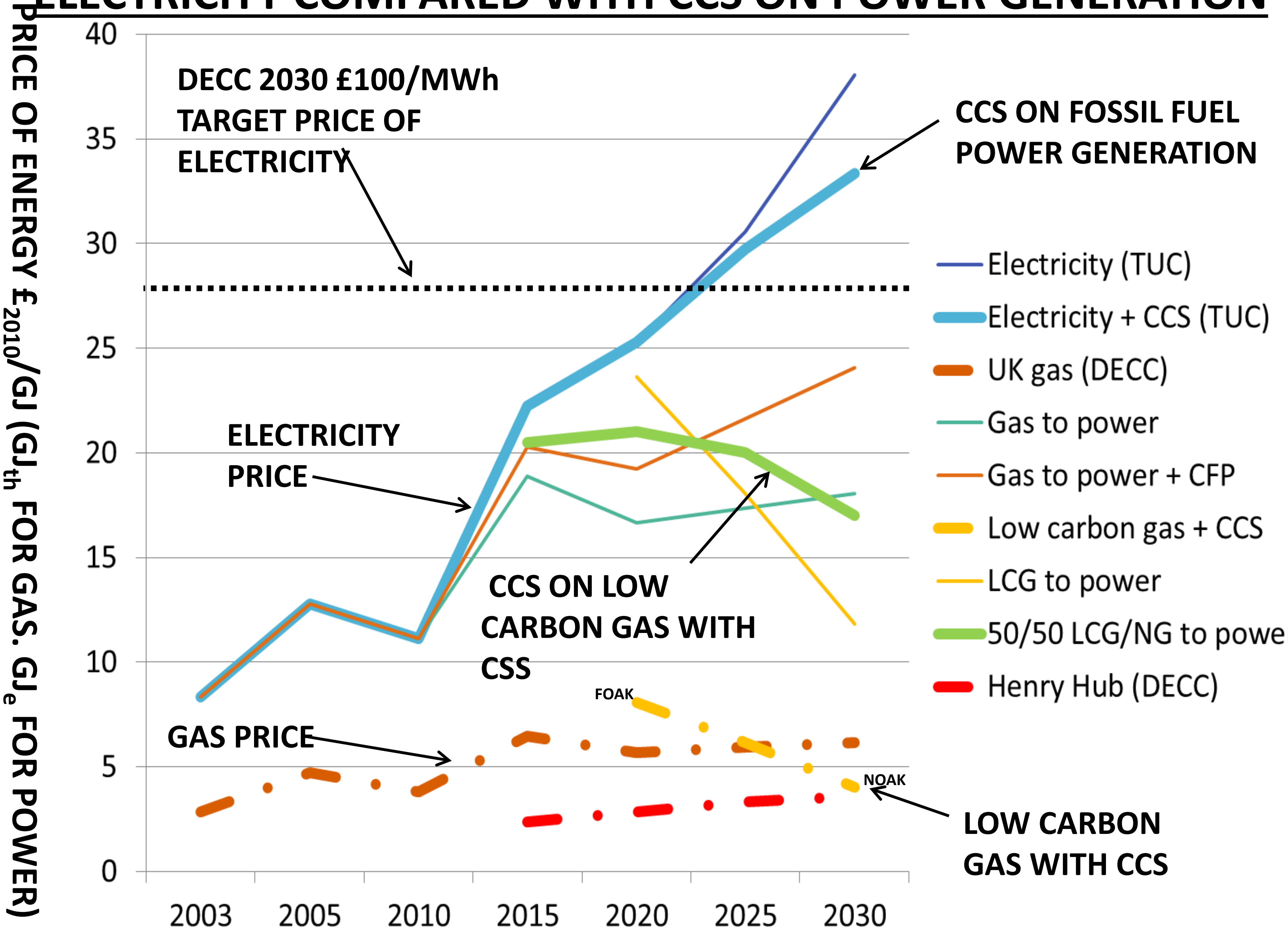
Table 5. Suitable CO_2 capture technologies for CO_2 streams of varying concentrations and partial pressures

CO_2 source		CO_2 purity (by volume)	CO_2 pressure		Possible capture processes						
Process	Sector	High purity ⬅ Oxygen enhanced ⬅ Syn-gas ⬅ Flue gas	Typical stream pressure (kPa)	Typical partial pressure (kPa)	Clean-up only (e.g. dehydration)	Cryogenic	Physical solvents	Adsorbents	Membranes	Chemical solvents	Timmins CCS
Ethylene oxide	Chemicals	100%	2 500	2 500	☑						
Fermentation	Biofuels	100%	100	100	☑						
Cement kiln (oxyfuel)*	Cement	>90%	100	95	☑						
Oxyfuel and chemical looping coal	Power	80%-98%	100	90	☑	☑					
DRI (coal- or gas-based hydrogen)	Iron and steel	20%-96%	100 to 500	uncertain			☑	☑	☑	☑	
IGCC (oxyfuel)*	Power	20%-40%	2 000 to 7 000	500 to 3 000			☑				
Acid gas clean-up	Gas processing	2%-65%	900 to 8000	20 to 5 000			☑		☑	☑	
BF gas (top gas recycling)	Iron and steel	60%-75%	100	60 to 75				☑			
Ethylene production	Chemicals	8%-18%	2800	200 to 500				☑	☑		
Hydrogen production	Chemicals (ammonia, methanol etc.), refining	15%-20%	2 200 to 2 700	300 to 550				☑			
IGCC (airblown)	Power	12%-14%	2 000 to 7 000	250 to 1 000					☑		
BF gas	Iron and steel	14%-33%	100	14 to 33						☑	
Cement kiln (airfired)	Cement	14%-40%	100	14 to 40						☑	
Pulverised coal	Power	12%-14%	100	12 to 14						☑	
Process heaters	Refining, chemicals	3%-13%	100	3 to 13						☑	
Gas boiler	Power	7%-10%	100	7 to 10						☑	
Gas turbine	Power	3%	100	3						☑	
Low carbon gas	Gas making	99.6%	6000	4900							☑
			Need for subsequent compression:		Medium	Low	High	Low	Medium	High	Low

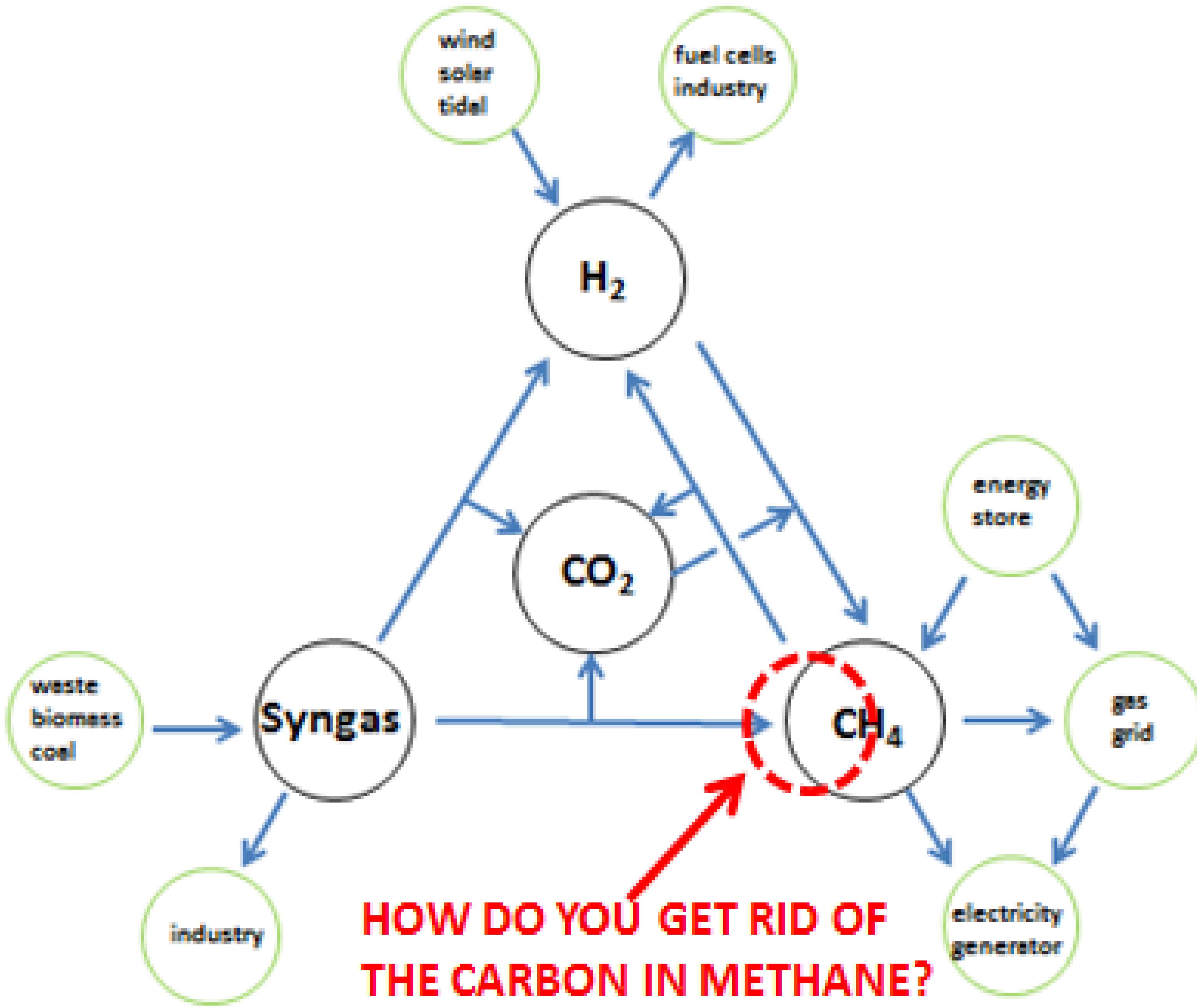
* Oxyfuel requires additional energy for the separation of air to produce oxygen.

COMPARATIVE ANALYSIS OF CCSA COST REDUCTION REPORT							CCS.costreductioncomparison.ARD.rev1.08122013	
£/MWh Levelised Cost of Base Load (80% load factor) Electricity at 2012 nominal values								
		Post comb'n Natural Gas	Post comb'n coal	Oxy fuel coal	IGCC pre comb'n coal	Average	Proportion of total	STORABLE/DISPATCH'E CARBON -VE SNG
2012	Efficiency loss	25%	19%	25%	17%[1]	21.50%		0.06%
	Generation and Capture	102.3	115.3	114.4	123.0	113.75	70.49%	40.0 to 45.0[3]
	Carbon floor cost	1.1	2.5	2.5	2.3	2.1	1.30%	-1.0
	Transport and Storage	40.7	48.7	48.7	44	45.525	28.21%	14.0 to 16.0
	Total	144.1	166.5	165.6	169.3	161.375		£53.0 to 60.0/MWh
	Capture rate	85%	85%	85%	85%	85%		109.50%
	Emissions gCO_2/kWh	80	168	180	108	134		(45) gCO_2/kWh[2]
	CCS cost/tonne CO_2	£244	£132	£133	£106	£153.8		£16.0/tonne CO_2
2028	Efficiency loss	11%	15%	15%	12%[1]	13.25%		0.06%
	Generation and Capture	79.4	81.8	80.7	88.0	82.475	87.76%	40[3]
	Carbon floor cost	2.5	5.5	5.5	5.3	4.700	5.00%	-3.15[4]
	Transport and Storage	3.7	8.0	8	7.5	6.800	7.24%	4.4 to 5.7
	Total	85.6	95.3	94.2	100.8	93.975		£39.1 to 39.6/MWh
	Capture rate	90%	90%	90%	90%	90%		109.30%
	Emissions gCO_2/kWh	45	106	106	102	90		(45) gCO_2/kWh[2]
	CCS cost/tonne CO_2	£75	£49	£53	£45	£55.5		£5.5/tonne CO_2
Notes	1	IGGC efficiency loss is incorrect. Should be lower due to high CO_2 partial pressure, and lower gas volume, compared with combustion.						
	2	Assumes -9.3% carbon negative SNG is fired in a state of the art 60% efficiency conventional Natural Gas fired CCGT.						
	3	Decarbonised SNG supplied at 40 to 45 p/therm wholesale cost, reducing to 40 p/therm in 2030.						
	4	Assumes negative emissions technologies are rewarded at same rate as 2030 Carbon Floor Price.						

CCS ON GAS MAKING CAN HALVE THE PRICE OF LOW CARBON ELECTRICITY COMPARED WITH CCS ON POWER GENERATION



METHANE: THE IDEAL GASEOUS ENERGY VECTOR. HOW DO YOU GET RID OF THE CARBON ATOM IN THE METHANE MOLECULE ?

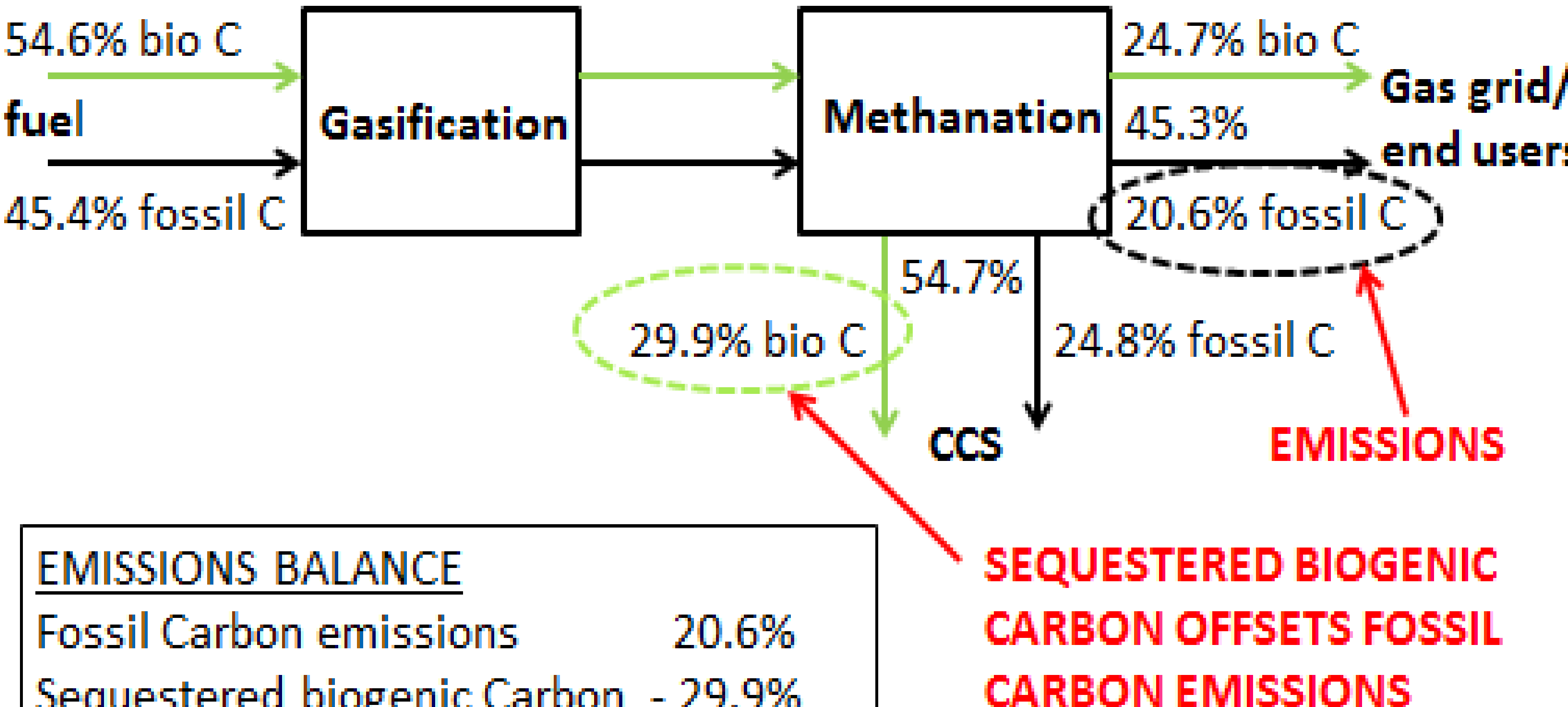


CARBON NEUTRAL SNG aka LOW CARBON GAS (LCG)

REACTION $2C + 2H_2O = CH_4 + CO_2$ PRODUCES 50:50% $CO_2:CH_4$.

55% OF TOTAL CARBON SEPARATED AS ZERO COST WASTE PRODUCT.

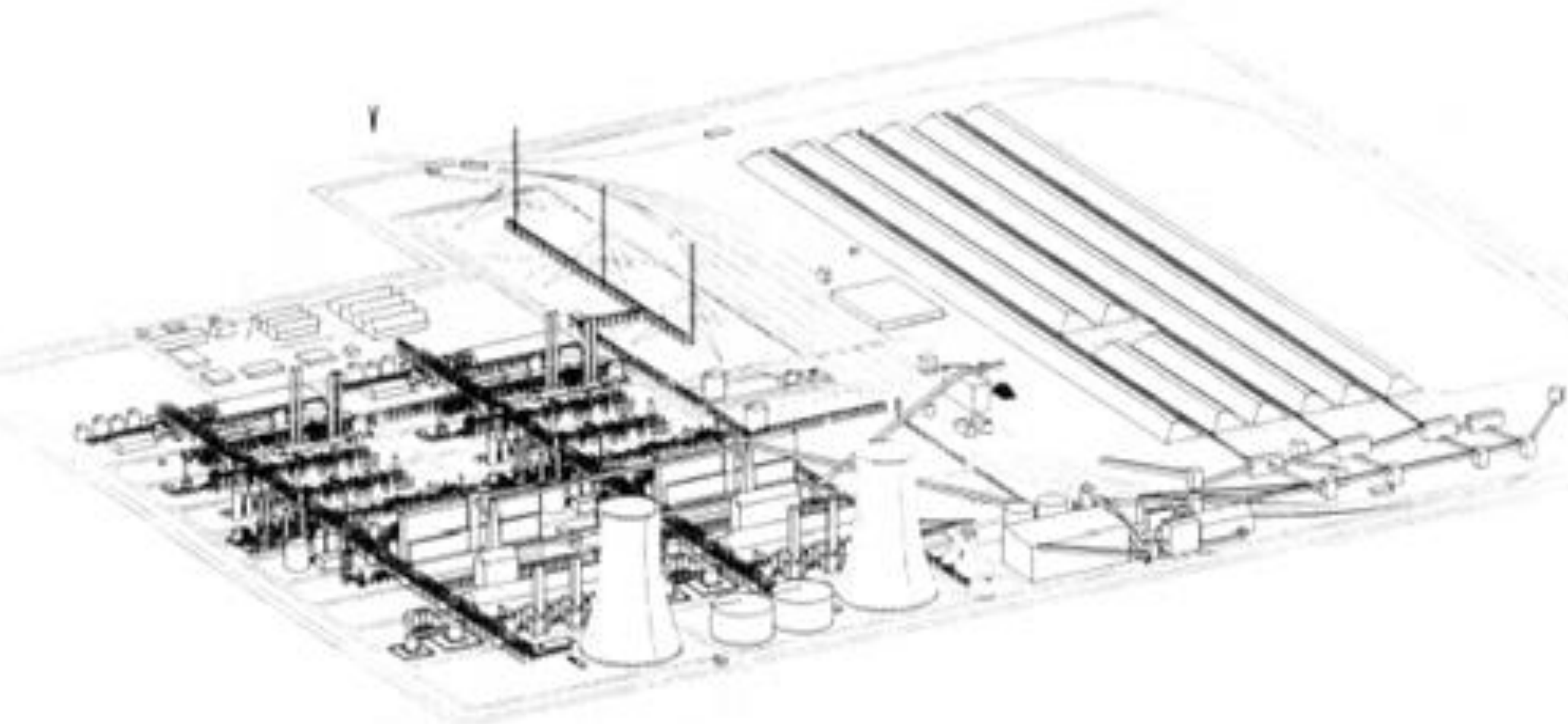
55% ADDITIONAL DECARBONISATION FROM PARTLY BIOGENIC FUEL.



EMISSIONS BALANCE	
Fossil Carbon emissions	20.6%
Sequestered biogenic Carbon	- 29.9%
NET NEGATIVE EMISSIONS	**- 9.3%**

BRITISH GAS HIGH TEMPERATURE HICOM CATALYST USED AT GREAT PLAINS: ELECTRICITY, SNG, CCS/EOR AND FERTILISER

HMG/BRITISH GAS PLANNED TO BUILD 20 TO 30 2 x 2.5 mtpa MODULAR SNG PLANTS TO PROVIDE UK'S GAS SUPPLY WHEN NORTH SEA GAS RAN OUT



WESTFIELD DEVELOPMENT CENTRE

Figs 51 to 58. BRITISH GAS WESTFIELD COAL TO SNG DEVELOPMENT CENTRE. MOTHBALLED 1992. BGL PLANT PHOTOGRAPHED AUGUST 2012

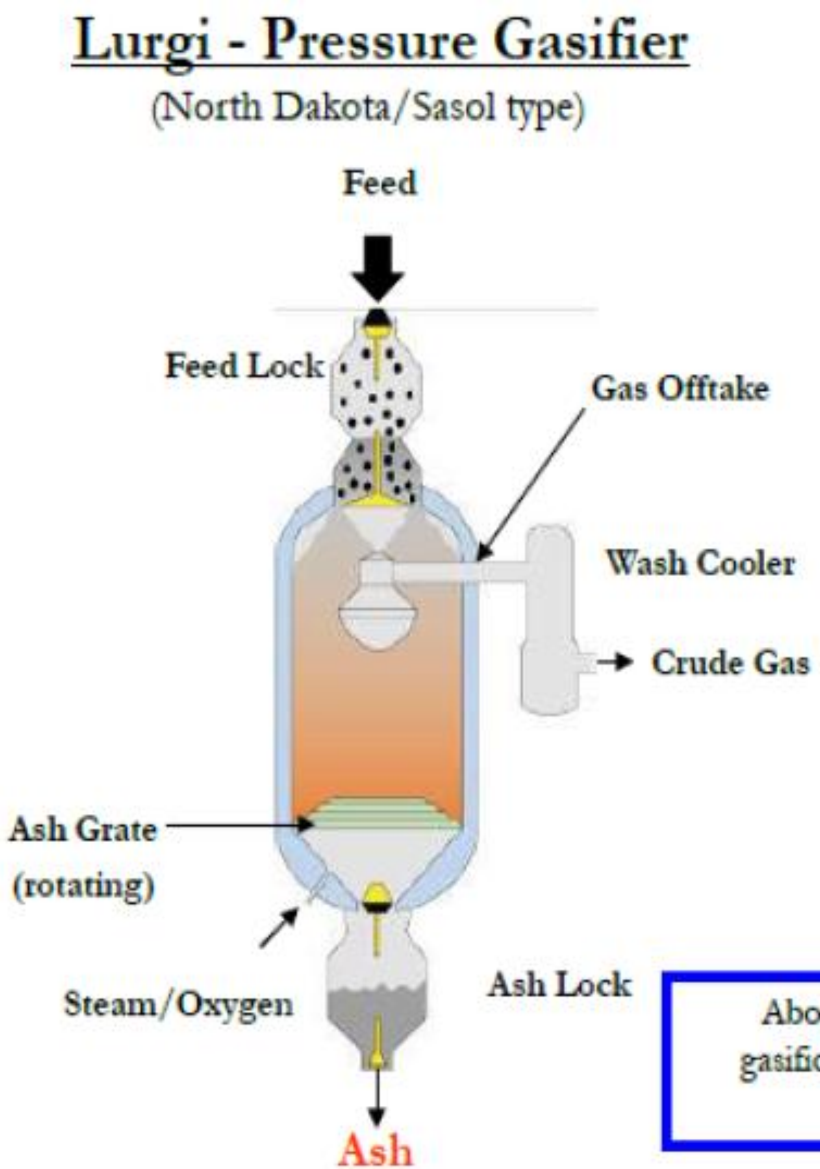
FIRST NEW CHINESE SNG PLANT AT DATANG USES BRITISH GAS HICOM CATALYSTS

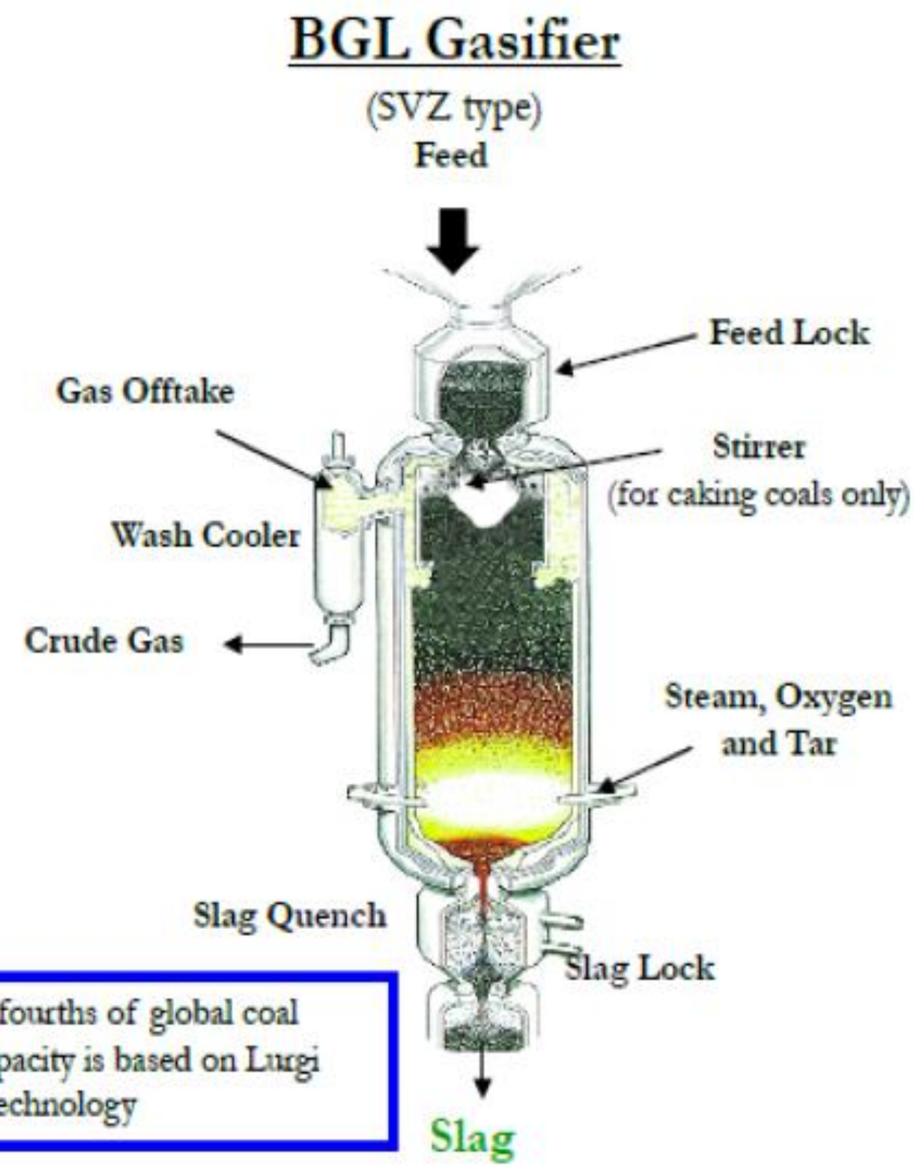
REFERENCE PROJECT: SVZ SCHWARZE PUMPE

- Commercial production of power, methanol and heat from waste
- Commercial scale 3.6m gasifier developed from Westfield experience
- Start-up in 2000
- Successful co-gasification of briquetted lignite and waste feedstocks

- **Full environmental certificate 1998**
- **Certified non-leaching vitrified slag**
- **20% coal:80% waste/biomass 2003**
- **UK EA Best Available Technology 2005**
- **UNEP approved to destroy POP's 2006**
- **In India awaiting re-use 2012**

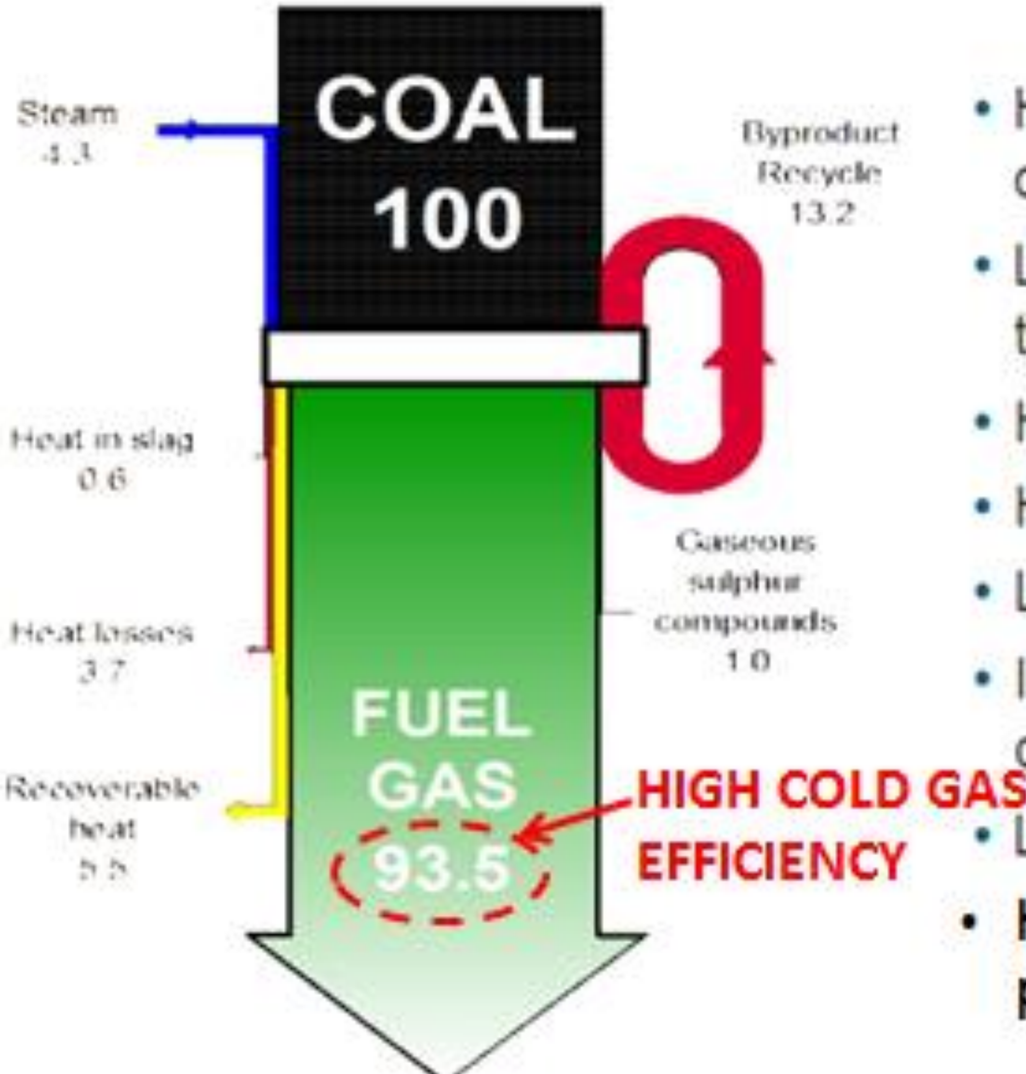
BGL SLAGGING GASIFIER BASED ON PROVEN LURGI DRY ASH GASIFIER. HIGH EFFICIENCY, LOW STEAM & OXYGEN USE





About three fourths of global coal gasification capacity is based on Lurgi technology

BGL: WORLD'S HIGHEST COLD GAS EFFICIENCY SOLID MULTI-FUEL CO-GASIFIER

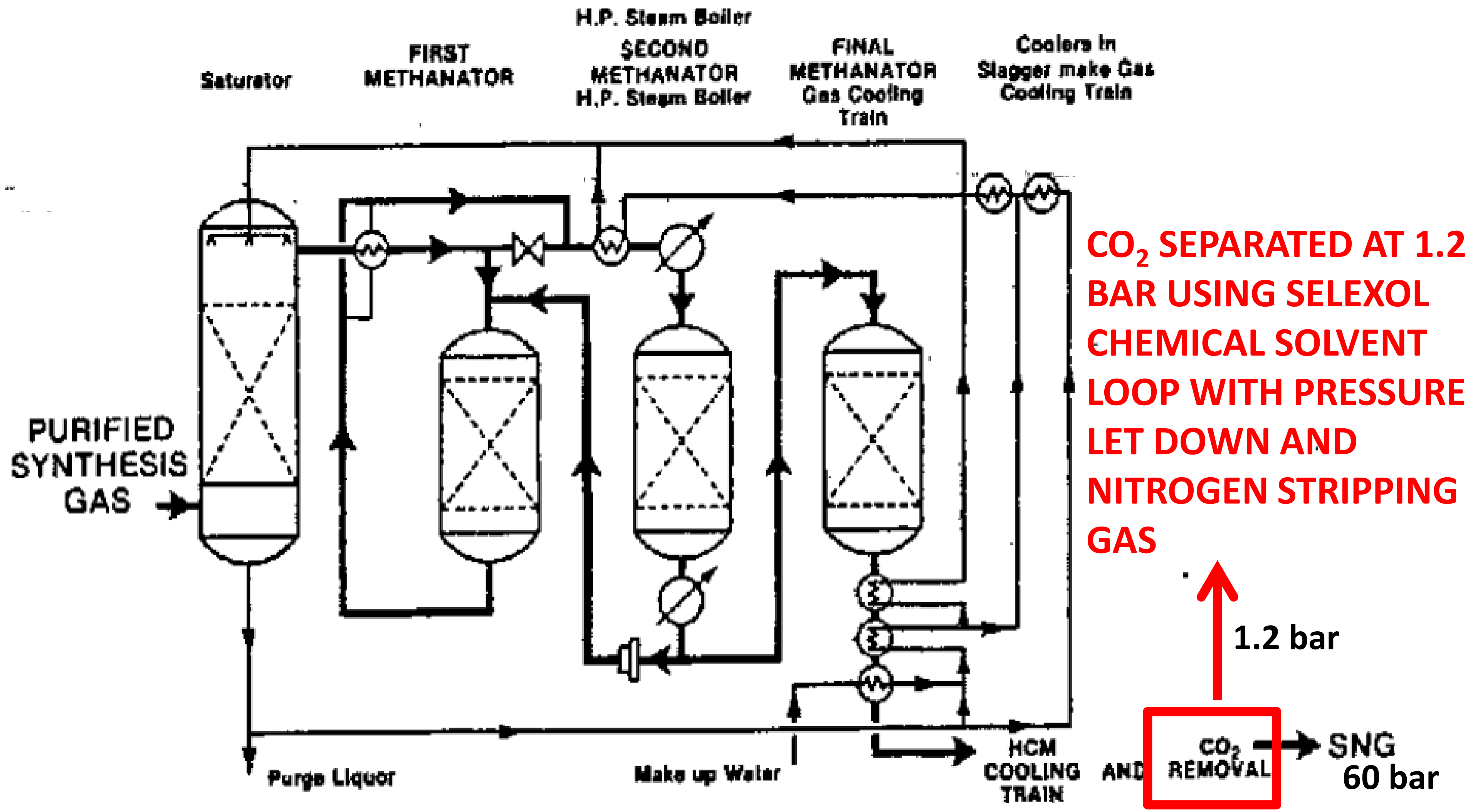


- Heat recovery from product gas by contact with coal bed
- Low oxygen consumption – 50-60% of that for entrained flow gasifiers
- High cold gas efficiency
- High carbon conversion
- Low gasifier outlet temperature
- Inexpensive and well proven conventional gas cooling train
- Low CO_2 content in Syngas
- **High Methane output suitable for SNG production**

BGL in China - Hulunbeier

BRITISH GAS HICOM HIGH EFFICIENCY COMBINED SHIFT AND CATALYTIC METHANATION PROCESS

Combined 'shift' and 'methanation' reactions reduces the quantity of heat exchange, and steam to be injected into, and subsequently removed from, the process. Exothermic methanation reaction is cooled by recycling SNG from second stage methanator to first stage methanator.



Novel Timmins low-energy CCS process

Timmins CCS Ltd

- Introduce recycle loop round CO shift stage to increase CO_2 concentration
- CO_2 Capture method:
  - Step 1: refrigeration condensation at full process pressure (c. 30-70 bar in pre-capture)
  - Step 2: Physical solvent wash with high pressure regenerator at full plant pressure, stripped by main process gas (CO Shift feed gas) + some low-grade heat
- Entire Step 2 regen' mixture is heated and recycled* to CO shift (no separation, 'closed-loop' for CO_2)
- All CO_2 leaves CCS capture process as liquid at full process pressure or as supercritical fluid
- Minimal liquid CO_2 pumping (compression) requirement to supercritical CO_2 pipeline

(NOTE: The description above is for the IGCC/Hydrogen/shift case. In the SNG/LCG case shift and methanation are combined in the HICOM process.)

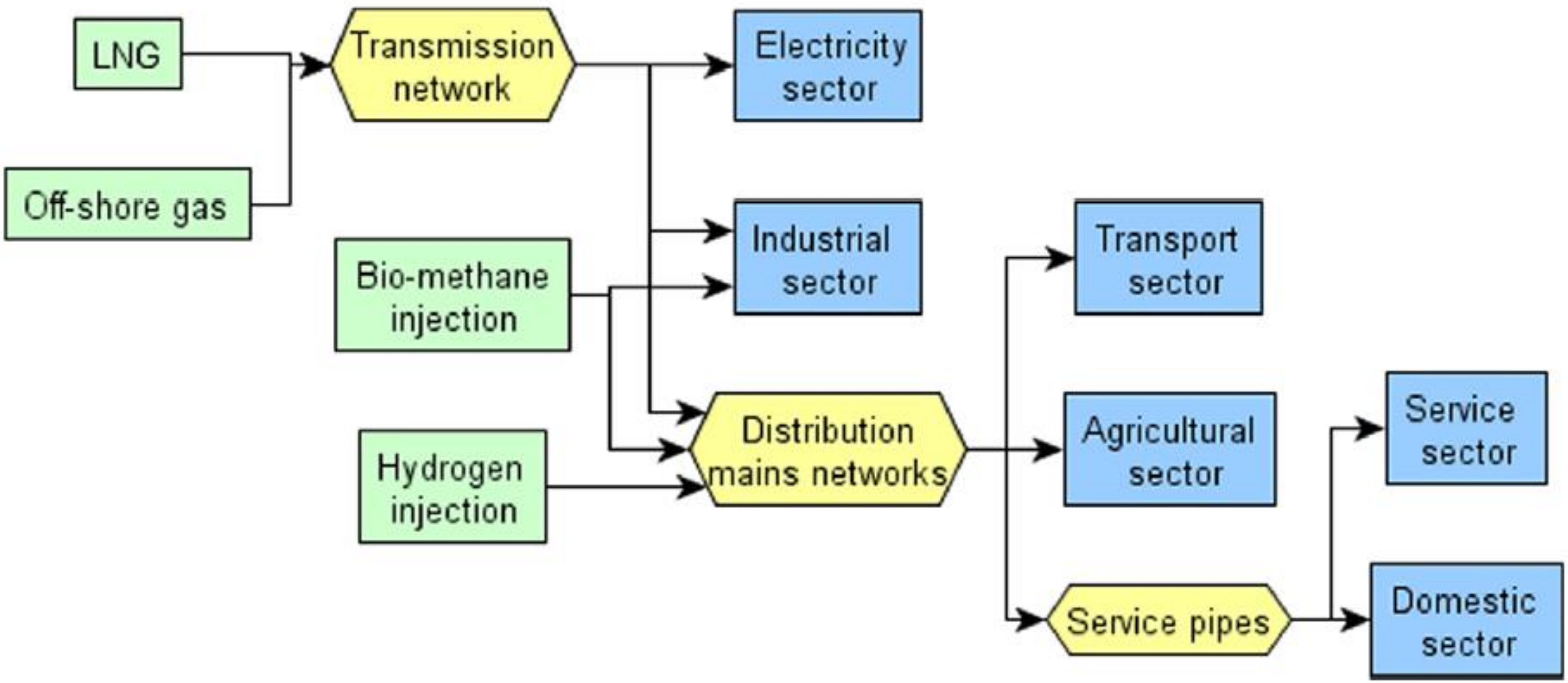
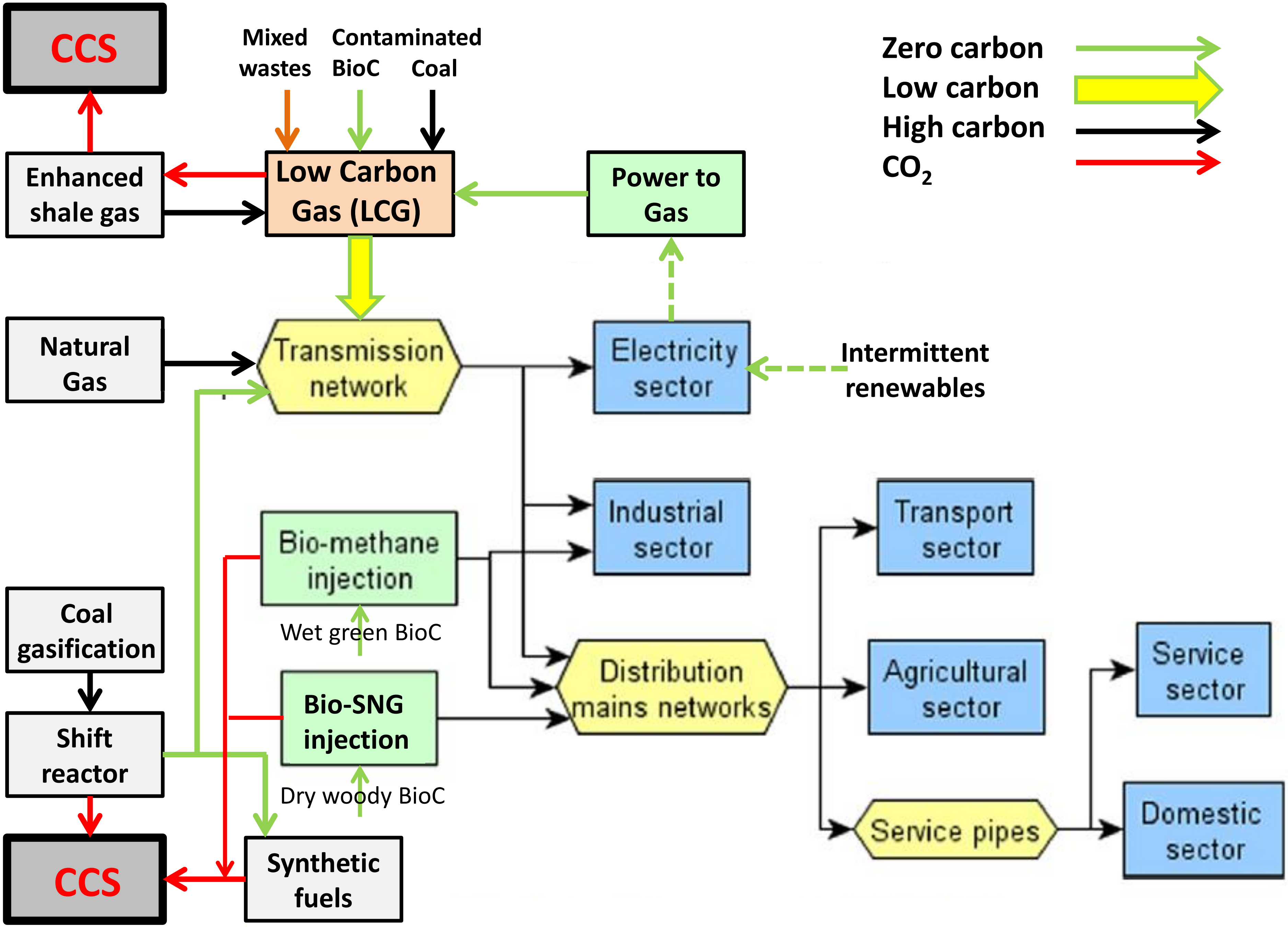
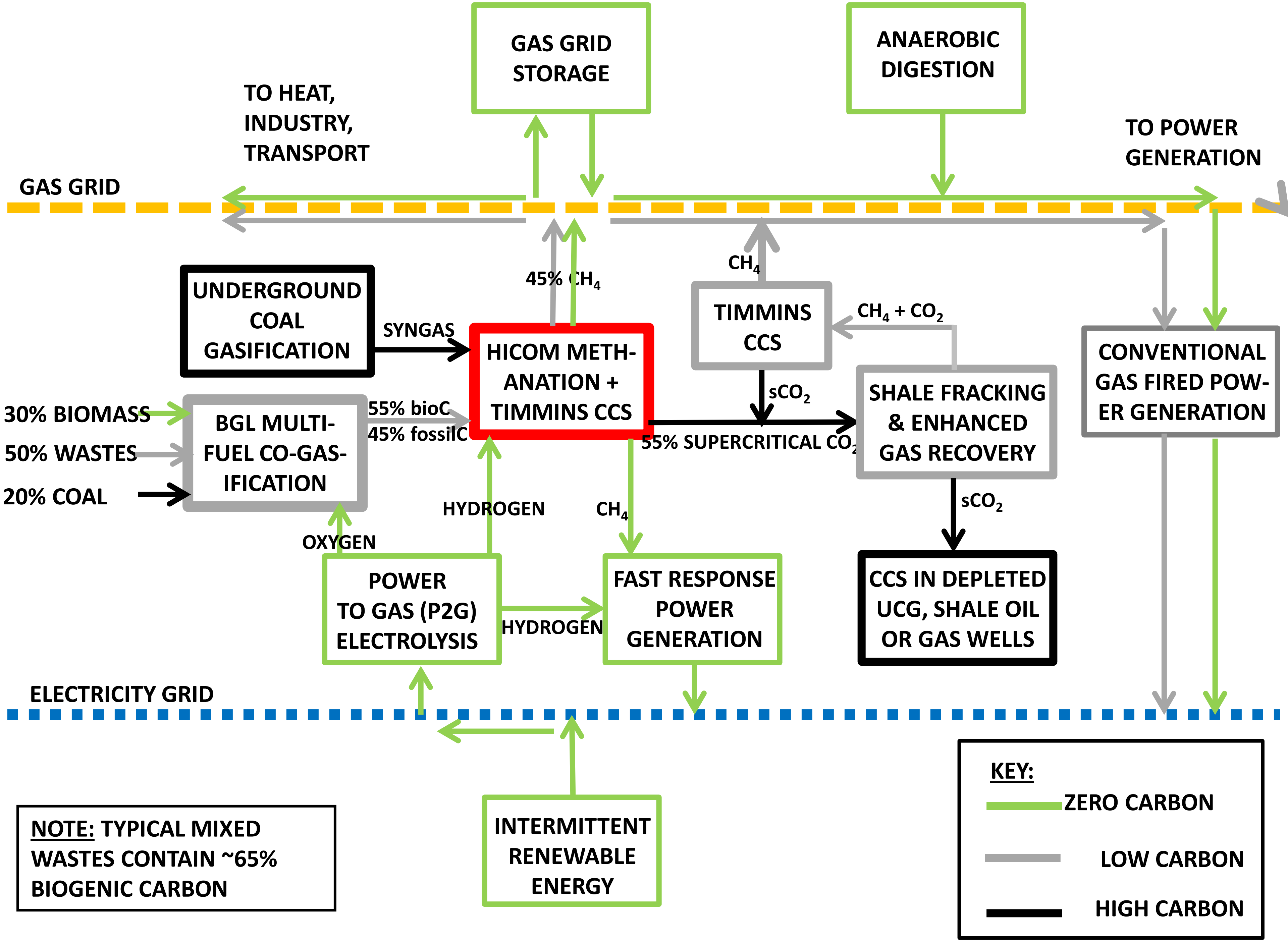
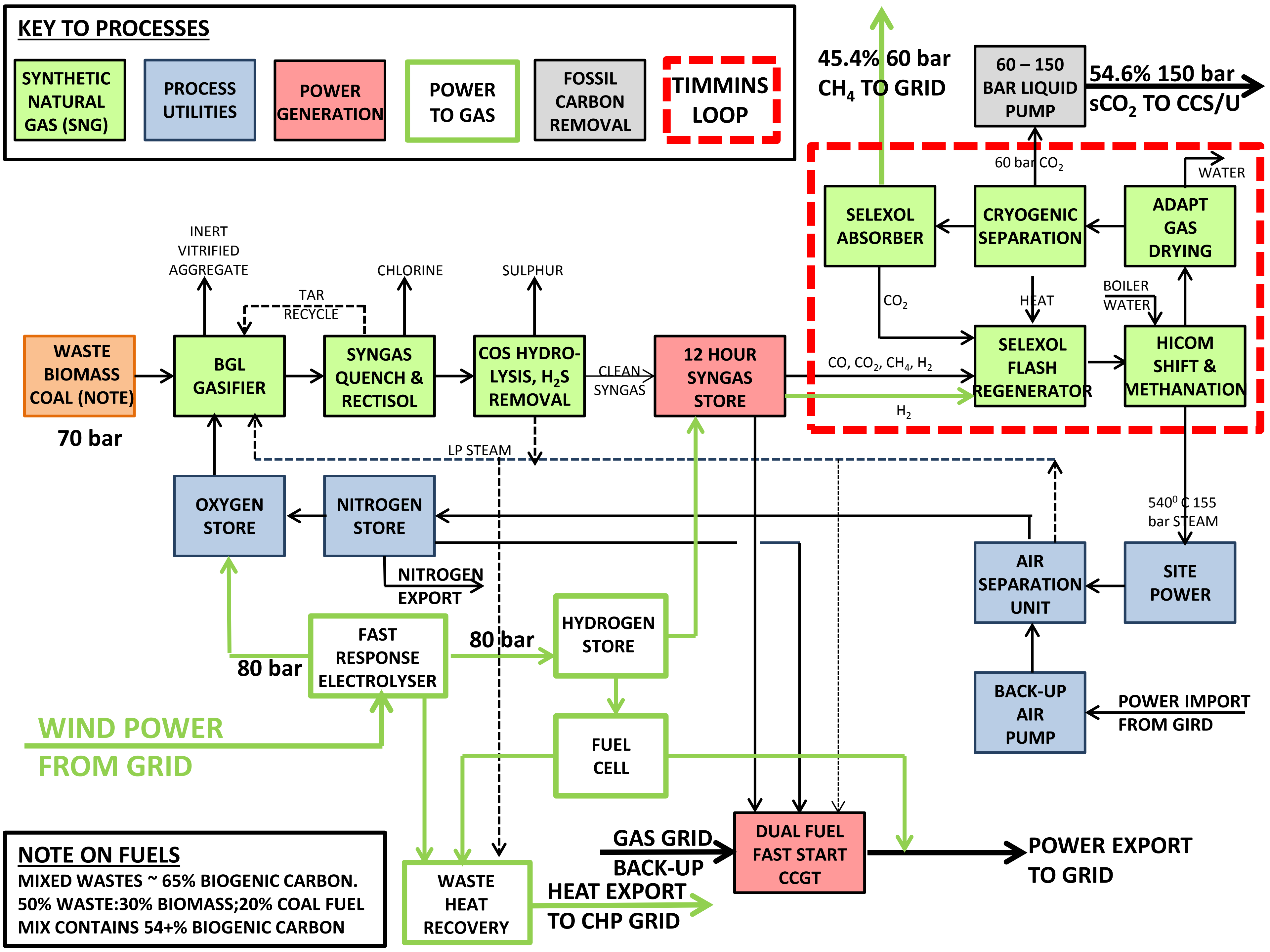


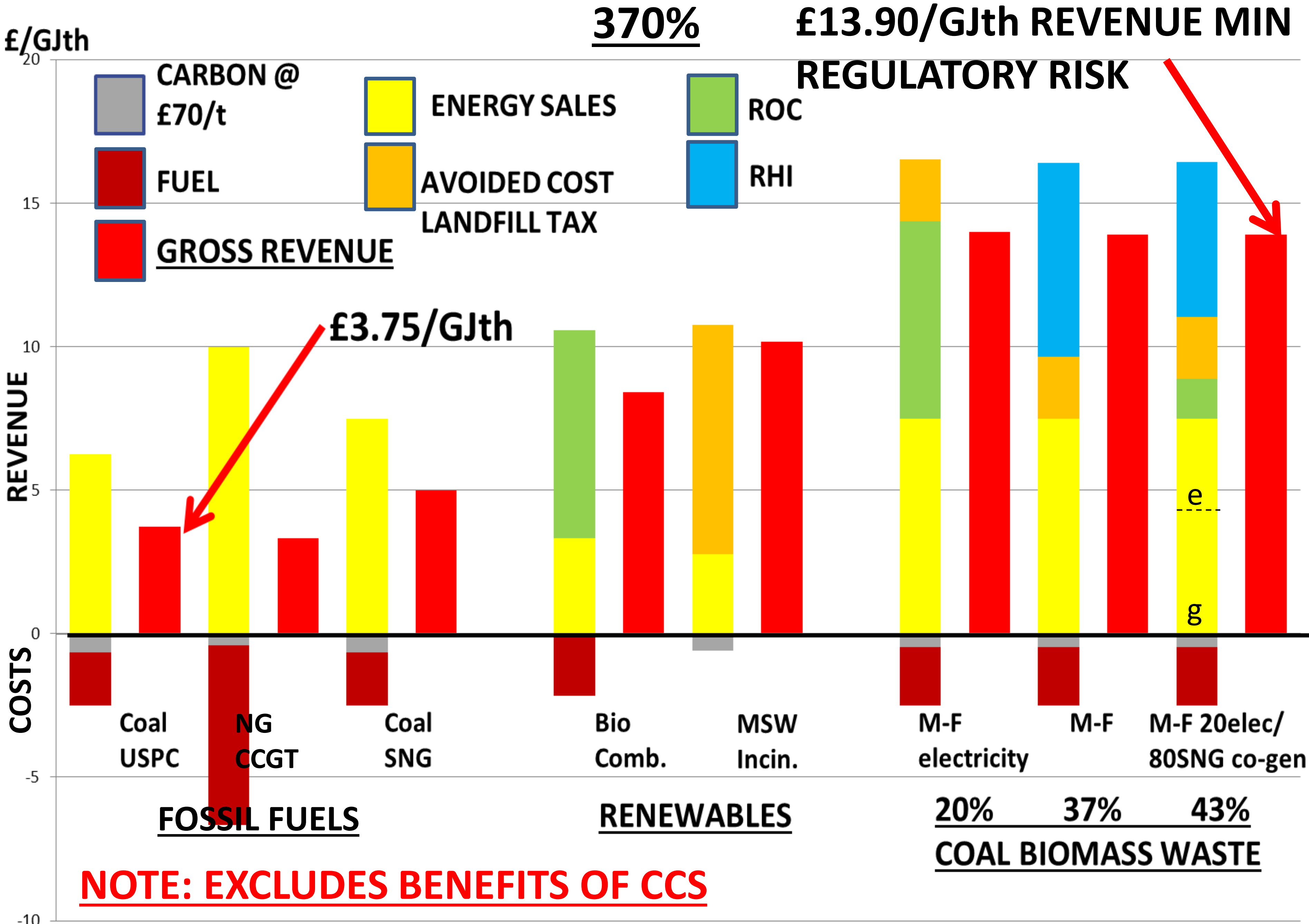
Fig. 6. Revised structure of the gas system in UK MARKAL.


CCS
Mixed wastes
Contaminated BioC
Coal
Zero carbon
Low carbon
High carbon
CO_2
Enhanced shale gas
Low Carbon Gas (LCG)
Power to Gas
Natural Gas
Transmission network
Electricity sector
Intermittent renewables
Industrial sector
Transport sector
Bio-methane injection
Wet green BioC
Coal gasification
Distribution mains networks
Agricultural sector
Service sector
Shift reactor
Bio-SNG injection
Dry woody BioC
Service pipes
Domestic sector
CCS
Synthetic fuels


GAS GRID STORAGE
ANAEROBIC DIGESTION
TO HEAT, INDUSTRY, TRANSPORT
TO POWER GENERATION
GAS GRID
45% CH_4
CH_4
UNDERGROUND COAL GASIFICATION
SYNGAS
HICOM METH-ANATION + TIMMINS CCS
TIMMINS CCS
$CH_4 + CO_2$
CONVENTIONAL GAS FIRED POW-ER GENERATION
sCO_2
SHALE FRACKING & ENHANCED GAS RECOVERY
30% BIOMASS
50% WASTES
20% COAL
BGL MULTI-FUEL CO-GAS-IFICATION
55% bioC
45% fossilC
55% SUPERCRITICAL CO_2
HYDROGEN
CH_4
sCO_2
OXYGEN
POWER TO GAS (P2G) ELECTROLYSIS
HYDROGEN
FAST RESPONSE POWER GENERATION
CCS IN DEPLETED UCG, SHALE OIL OR GAS WELLS
ELECTRICITY GRID
KEY:
ZERO CARBON
LOW CARBON
HIGH CARBON
NOTE: TYPICAL MIXED WASTES CONTAIN ~65% BIOGENIC CARBON
INTERMITTENT RENEWABLE ENERGY

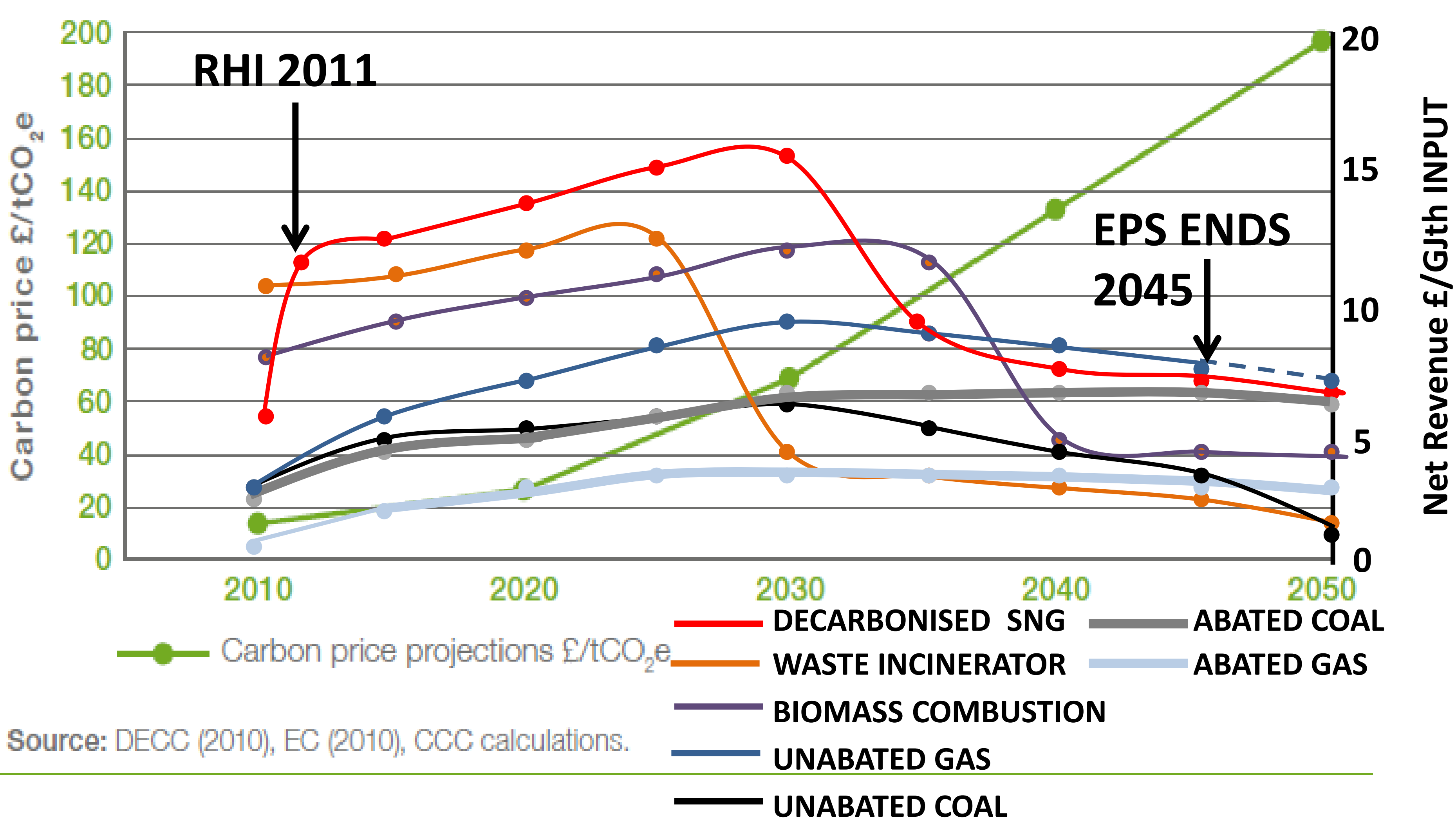

KEY TO PROCESSES
SYNTHETIC NATURAL GAS (SNG)
PROCESS UTILITIES
POWER GENERATION
POWER TO GAS
FOSSIL CARBON REMOVAL
TIMMINS LOOP
45.4% 60 bar CH_4 TO GRID
60 – 150 BAR LIQUID PUMP
54.6% 150 bar sCO_2 TO CCS/U
60 bar CO_2
WATER
SELEXOL ABSORBER
CRYOGENIC SEPARATION
ADAPT GAS DRYING
CO_2
HEAT
BOILER WATER
SELEXOL FLASH REGENERATOR
HICOM SHIFT & METHANATION
INERT VITRIFIED AGGREGATE
TAR RECYCLE
CHLORINE
SULPHUR
WASTE BIOMASS COAL (NOTE)
70 bar
BGL GASIFIER
SYNGAS QUENCH & RECTISOL
COS HYDRO-LYSIS, H_2S REMOVAL
CLEAN SYNGAS
12 HOUR SYNGAS STORE
CO, CO_2, CH_4, H_2
H_2
LP STEAM
540^0 C 155 bar STEAM
OXYGEN STORE
NITROGEN STORE
NITROGEN EXPORT
AIR SEPARATION UNIT
SITE POWER
BACK-UP AIR PUMP
POWER IMPORT FROM GIRD
FAST RESPONSE ELECTROLYSER
80 bar
80 bar
HYDROGEN STORE
FUEL CELL
WIND POWER FROM GRID
GAS GRID BACK-UP
DUAL FUEL FAST START CCGT
POWER EXPORT TO GRID
WASTE HEAT RECOVERY
HEAT EXPORT TO CHP GRID
NOTE ON FUELS
MIXED WASTES ~ 65% BIOGENIC CARBON.
50% WASTE:30% BIOMASS;20% COAL FUEL
MIX CONTAINS 54+% BIOGENIC CARBON

2030: DECARBONISED SNG ENHANCES FOSSIL FUEL 'SPREAD' BY 370%



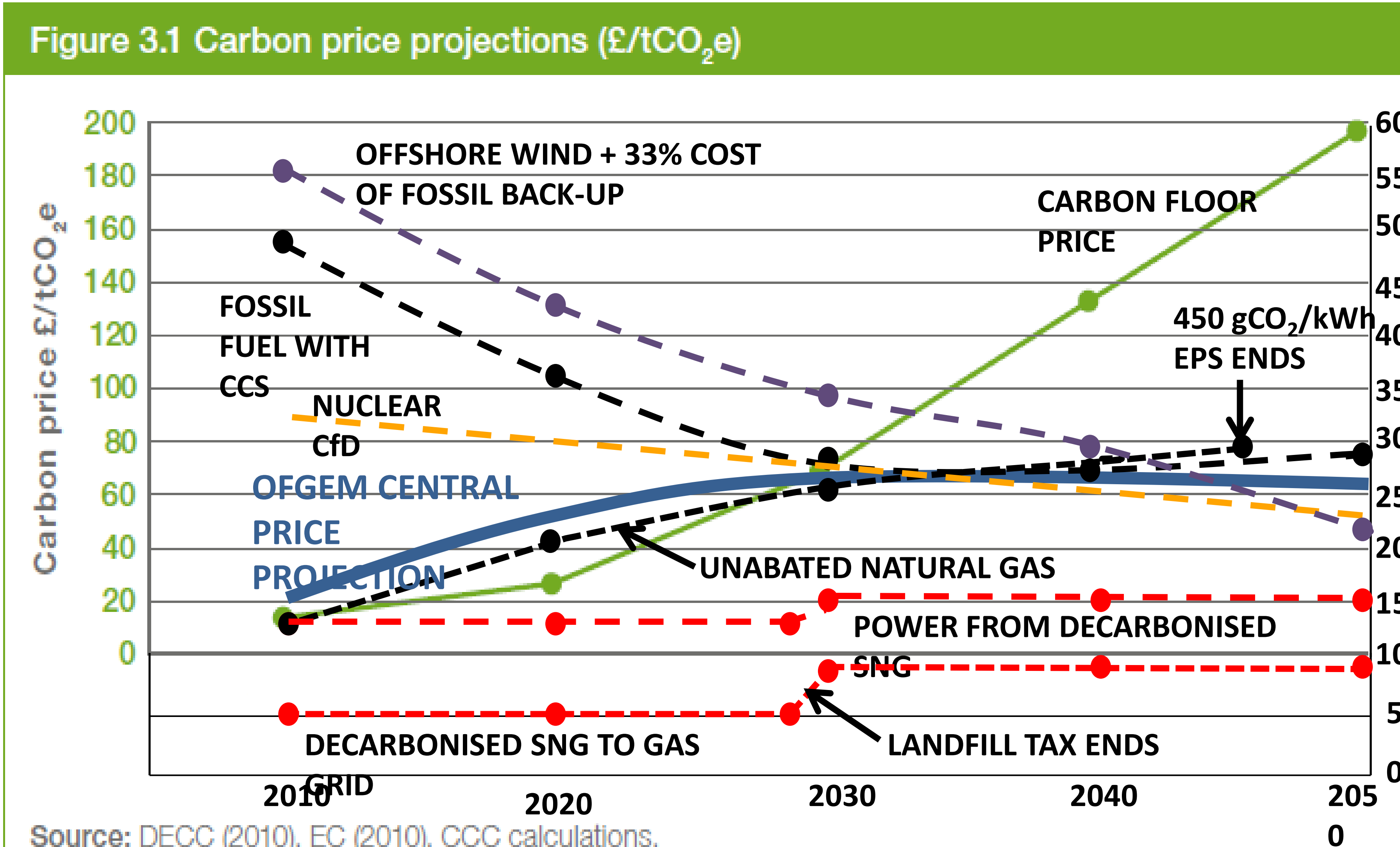
COMPARATIVE NET REVENUE PER GJth INPUT FUEL FOR THERMAL TECHNOLOGIES. CARBON FLOOR PRICE 2010 - 2050

Figure 3.1 Carbon price projections (£/tCO$_2$e)



Source: DECC (2010), EC (2010), CCC calculations.

DECARBONISED SNG WITH CCS: LOWEST COST STORABLE, DISPATCHABLE LOW CARBON ENERGY RESOURCE



1 £100/MWh 2030 LCOE INTERMITTENT WIND, NUCLEAR & CONVENTIONAL CCS

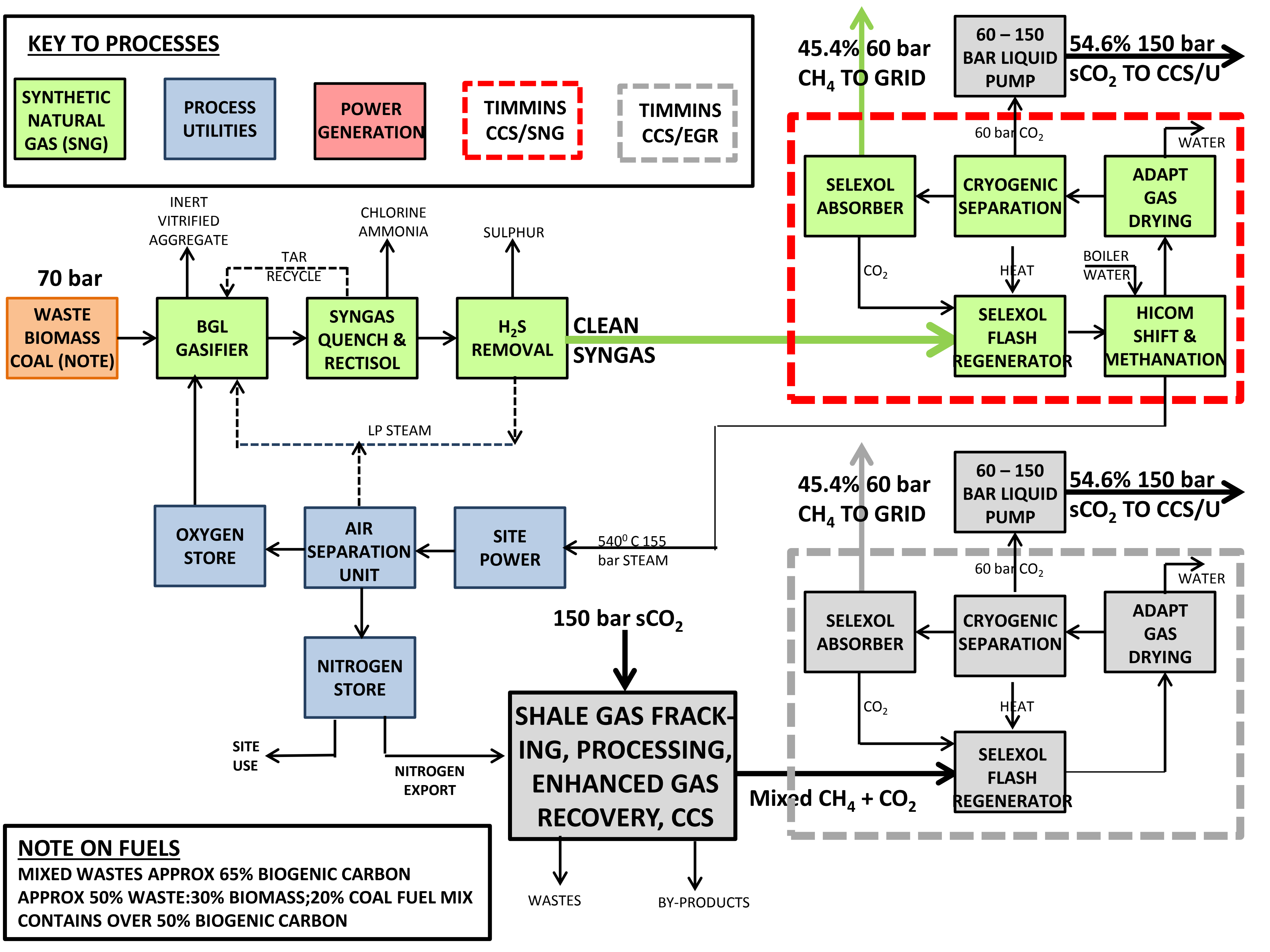
2 LOW COST SNG FROM LOW COST WASTE CONVERTED TO SNG AT 76% NET EFFICIENCY

3 NUCLEAR CfD MID £100 - £140/MWh 2012 REPORTED PRICE RANGE

IS SHALE GAS THE FRIEND OR FOE OF CCS?

BOWLAND SHALE GAS ~50:50 FREE:ADSORBED. 95% CH_4, BALANCE MAINLY CO_2 & N_2. INTEGRATING LOW COST sCO_2 FROM LCG WITH ESGR AND CCS CAN:

1. **DOUBLE EUR IN DEEP BOWLAND SHALE.**
2. **REDUCE SHALE GAS UNIT CAPEX BY 50%.**
3. **REDUCE WHOLE LIFE SHALE WELL CO_2 EMISSIONS BY 75%.**
4. **INCREASE LCG PROFITS BY USING FOR ESGR.**
5. **PROVIDE HIGH VALUE USES FOR sCO_2 FOR ADVANCED AND 'DRY' FRACKING.**
6. **PROCESS SHALE GAS ECONOMICALLY TO MEET GSMR.**



KEY TO PROCESSES
SYNTHETIC NATURAL GAS (SNG)
PROCESS UTILITIES
POWER GENERATION
TIMMINS CCS/SNG
TIMMINS CCS/EGR
45.4% 60 bar CH_4 TO GRID
60 – 150 BAR LIQUID PUMP
54.6% 150 bar sCO_2 TO CCS/U
60 bar CO_2
WATER
SELEXOL ABSORBER
CRYOGENIC SEPARATION
ADAPT GAS DRYING
CO_2
HEAT
BOILER WATER
SELEXOL FLASH REGENERATOR
HICOM SHIFT & METHANATION
INERT VITRIFIED AGGREGATE
CHLORINE AMMONIA
SULPHUR
TAR RECYCLE
70 bar
WASTE BIOMASS COAL (NOTE)
BGL GASIFIER
SYNGAS QUENCH & RECTISOL
H_2S REMOVAL
CLEAN SYNGAS
LP STEAM
OXYGEN STORE
AIR SEPARATION UNIT
SITE POWER
540⁰ C 155 bar STEAM
45.4% 60 bar CH_4 TO GRID
60 – 150 BAR LIQUID PUMP
54.6% 150 bar sCO_2 TO CCS/U
60 bar CO_2
WATER
SELEXOL ABSORBER
CRYOGENIC SEPARATION
ADAPT GAS DRYING
CO_2
HEAT
SELEXOL FLASH REGENERATOR
150 bar sCO_2
NITROGEN STORE
SITE USE
NITROGEN EXPORT
SHALE GAS FRACK-ING, PROCESSING, ENHANCED GAS RECOVERY, CCS
Mixed CH_4 + CO_2
NOTE ON FUELS
MIXED WASTES APPROX 65% BIOGENIC CARBON
APPROX 50% WASTE:30% BIOMASS;20% COAL FUEL MIX
CONTAINS OVER 50% BIOGENIC CARBON
WASTES
BY-PRODUCTS

LOW CARBON GAS: REVENUE STREAMS

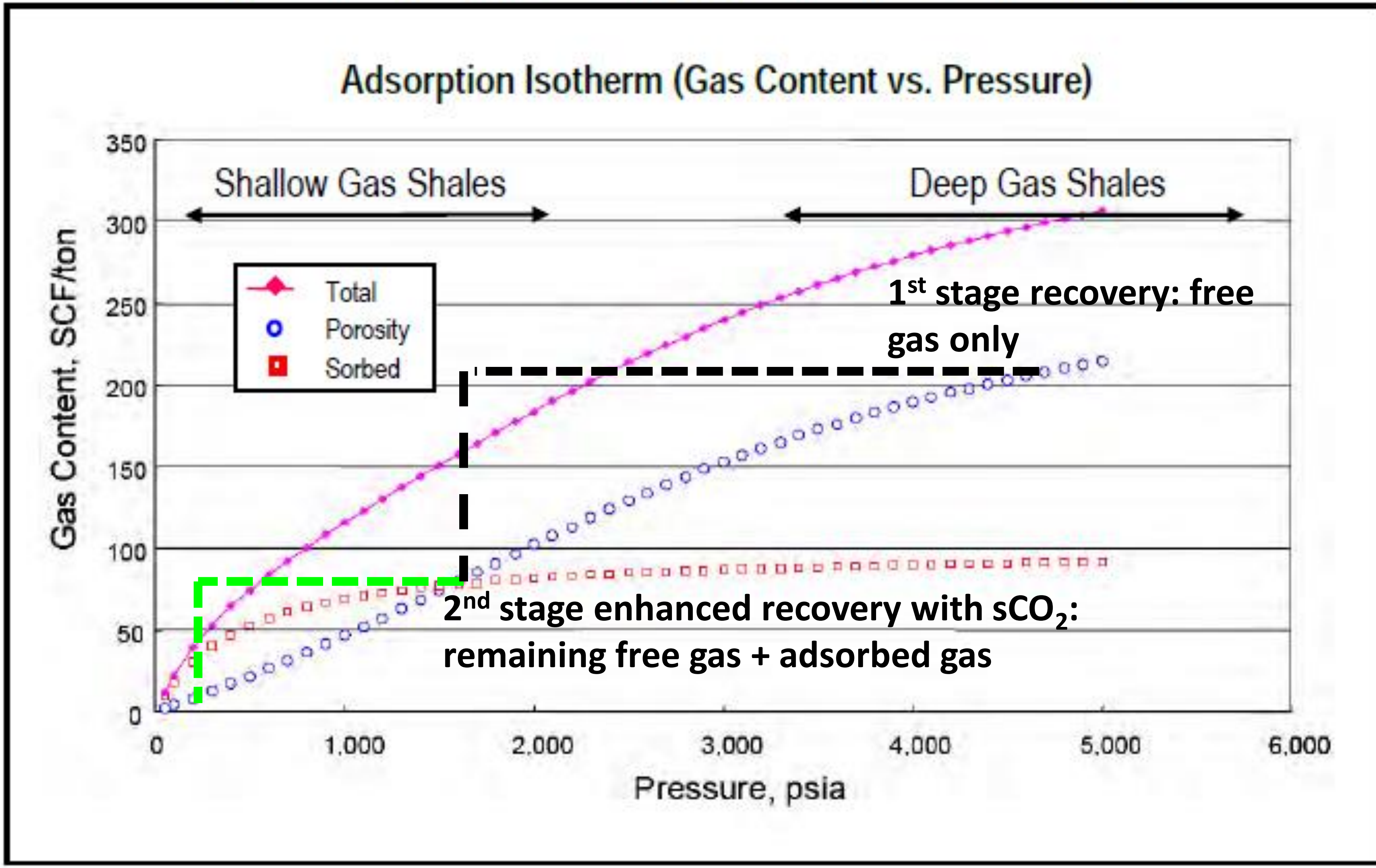
- Avoided Landfill Tax: approx £-8/GJ (2015)
- Sales of wholesale gas (60 to 65 p/therm wholesale price less 40 to 45 p/therm production cost): 15 – 20p/th
- By-products: CO_2, S, HCl, NH_3, N_2, He, Ar, Ne, vitag, fertiliser.
- Zero emissions destruction of high value hazardous wastes

VARIOUS STATUTORY INCENTIVES

- RHI for 55% biogenic carbon gas: 100p/th
- 1.8 ROC for 55% biogenic electricity (1.8 x ~£50/MWh @ 58% efficiency): 75p/th
- CfD for advanced gasification (£100 -135/MWh 'strike price' @ £65/MWh reference price ex indexation) 80 -107p/th
- GROSS PROFIT MARGIN (ex by-products/haz waste) 90 - 122p/th
- Plus benefit avoided 2030 CPF (£70/tonne) 40p/th
- Plus benefit of enhanced shale gas recovery ?????

sCO_2 INJECTION DOUBLES ESTIMATED ULTIMATE RECOVERY IN DEEP SHALES

Figure 2-10. Combining Free and Adsorbed Gas for Total Gas In-Place



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SYNERGIES: ULTRA LOW VISCOSITY SUPERCRITICAL CO_2 FOR ENHANCED SHALE OIL, GAS & CCS

- **Dry fracking. Use sCO_2 to drive drill; coiled tubing; under-balancing; enhance fracturing; improved proppant, fewer blockages. Hybrid processes.**
- **Green completions: Reduced water use; less flow-back water disposal, fewer CH_4 and CO_2 emissions.**
- **Enhanced gas recovery. 5 mols CO_2 : 1 mol CH_4 desorption ratio. Re-pressurise reservoir from bottom up @ ~80% depletion. Act as ‘sweep’ gas.**
- **Separate mixed CH_4 and CO_2. Reinject sCO_2 for EGR.**
- **CO_2 sequestration in capped depleted shale gas well. Avoided 2030 CFP £70/tonne sCO_2.**

Two main storage options

- Inject gas into formations
  - Use shales as a natural seal
  - Use fractured shales as the storage medium
- Enhanced gas recovery (EGR)
  - CO2 stored preferentially over methane by 3:1

- **Natural Gas worth ~£340/tonne @ 67 p/th**
- **CH_4 mol wt = 16; CO_2 mol wt = 44.**
- **3:1 CO_2: CH_4 volume ratio = 8.25 tonnes CO_2 injected per tonne additional CH_4 recovered.**
- **Delivered well head value of sCO_2 ~£40/tonne. Assume £5/tonne transport costs. sCO_2 plant gate value ~£35/tonne.**
- **128 tonnes/hour sCO_2 produced per $1GWhr_{LCG.}$**
- **£4480 value of sCO_2 per $3600GJ_{LCG}$ = 13 p/th**

The economics of shale gas in the UK

UK Shale Gas Development Costs

Costs are almost as high as North Sea costs but should reduce with time

Drilling Capex	**20 p/therm**	£6 million cost and 3 bcf gas per well or lateral
Facilities Capex	**2.5 p/therm**	£30 million for single drillpad for 120 bcf gas
Opex	**22.5 p/therm**	£0.5 million/bcf and 2.5% capex per year
Appraisal	**2 p/therm**	
Restoration	**3 p/therm**	
Sub total	**50 p/therm**	
Gas Price (NBP 2014)	**67 p/therm**	

A multiwell production site

17 p/therm for profit , tax, financing costs, ROI, etc

A profitable development if gas prices stay on average above 50 p/therm.

A worthwhile investment if gas prices average 60 p/therm.

LCG AND ESGR: 2030 REVENUE STREAMS

- **Avoided Landfill Tax: approx £-8/GJ (2015):**
- **Gas sales (60-65 p/th less 40 to 45 p/th production cost) 20p/th**
- **By-products: CO_2, S, HCl, NH_3, N_2, He, Ar, Ne, aggregate, fertiliser.**
- **Zero emissions destruction of high value hazardous wastes**

VARIOUS STATUTORY INCENTIVES

- **RHI for 55% biogenic carbon gas: 100p/th**
- **1.8 ROC for 55% biogenic electricity @ 58% efficiency: 75p/th**
- **CfD (£100/MWh indexed 'strike price' @ £65/MWh ref price): 80p/th**
- **PROFIT MARGIN (Inc CfD ex by-products/haz waste): 100p/th**
- **Benefit avoided 2030 shale gas CPF (75% x £70/tonne CO_2): 30p/th**
- **Benefit reduced capital cost of shale gas: 10-11p/th**
- **Benefit of enhanced shale gas recovery: 13p/th**
- **GROSS PROFIT (Inc CfD & ESGR ex by-products/haz waste): 150p/th**

THANK YOU