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Bio-energy with CCS (BECCS): Opportunities for performance improvement

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cep

Centre for Process Systems Engineering

9th May 2017

EPSRC
Engineering and Physical Sciences Research Council

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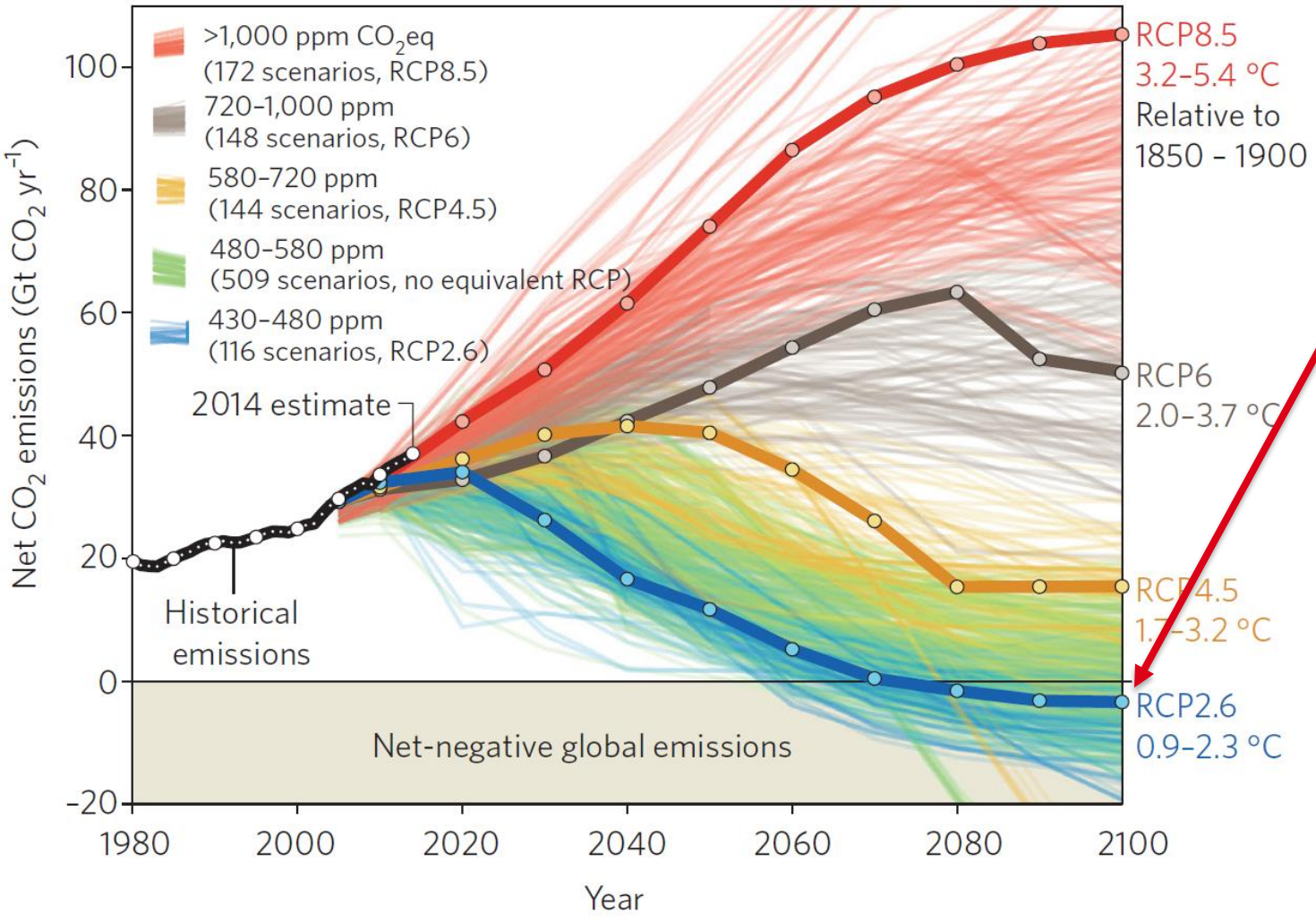
Meeting the 2°C IPCC and 1.5°C COP21 targets



- Mitigation costs 138% more without CCS
- Without CCS, <50% of IAM models solve the problem
- Most feasible solutions use BioEnergy + CCS substantially

→ BECCS is a key negative emissions technology

IPCC Fifth Assessment Synthesis Report November 2014, Fuss, S., et al. (2014). Nature Climate Change, 4(10), 850–853

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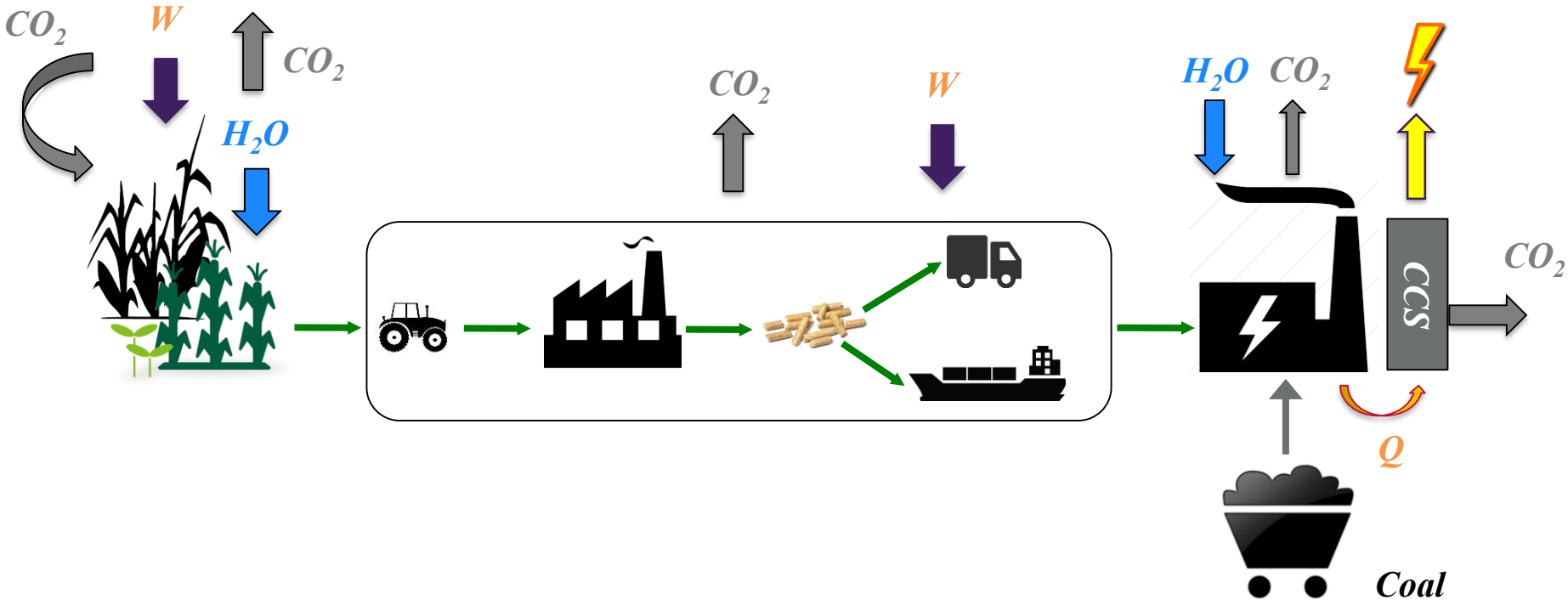
Negative emissions technology: BECCS

Atmospheric CO_2 is captured and permanently stored → Negative CO_2 balance



Reference: Fajardy, M., Daggash, H., Mac Dowell, N. (2017) Comparing BECCS and DACS potential for climate mitigation. MaGNET Workshop, International Institute for Applied Systems Analysis, Laxenburgh, Austria, 2-3 May 2017.

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Fuel properties and composition

Property	Coal	Wood	Herbaceous biomass
Ash content (wt% dry)	8.5–10.9	0.4–4.0	5–7.5
Moisture content (wt% wet)	6–10	5–60	15–25
Lower heating value, LHV (MJ/kg)	26.0–28.3	18.4–20.0	17.1–17.5
C (wt% dry)	76–87	47–52	45–47
H (wt% dry)	3.5–5.5	5.8–6.7	5.7–6.0
O (wt% dry)	2.8–11.3	38–46	40–46
Cl (wt% dry)	<0.1	0.01–0.05	0.09–0.97
S (wt% dry)	0.5–3.1	0.02–0.10	0.05–0.2
N (wt% dry)	0.8–1.5	0.1–0.8	0.4–1.04

Reference: Bui, M., Fajardy, M. & Mac Dowell, N. (2017). Bio-Energy with CCS (BECCS) performance evaluation: Efficiency enhancement and emissions reduction. Applied Energy, 195, 289–302.

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Efficiency penalty due to: Biomass (moisture & low heating value)
+ CO_2 capture process requires heat

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SO_X and NO_X emissions

Reference: Bui, M., Fajardy, M. & Mac Dowell, N. (2017). Bio-Energy with CCS (BECCS) performance evaluation: Efficiency enhancement and emissions reduction. Applied Energy, 195, 289–302.

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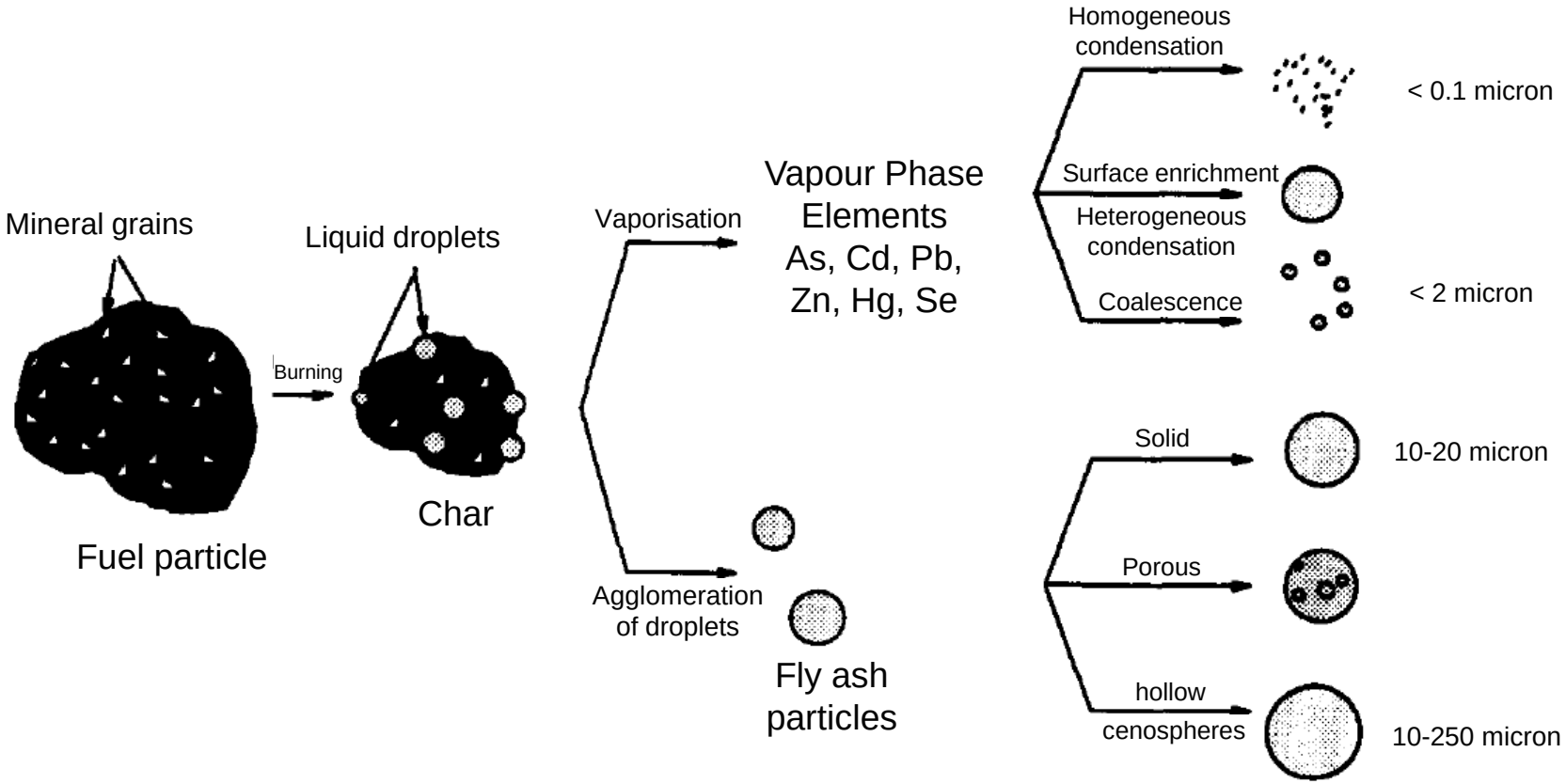
Potential emissions from a power plant



Flue gas composition and properties can be determined through:

- **Experimental measurements**
- **Detailed models (validated against data) to provide predictions**

Image reference: Ratafia-Brown, J. A. (1994). Fuel Processing Technology, 39 (1), 139–157.

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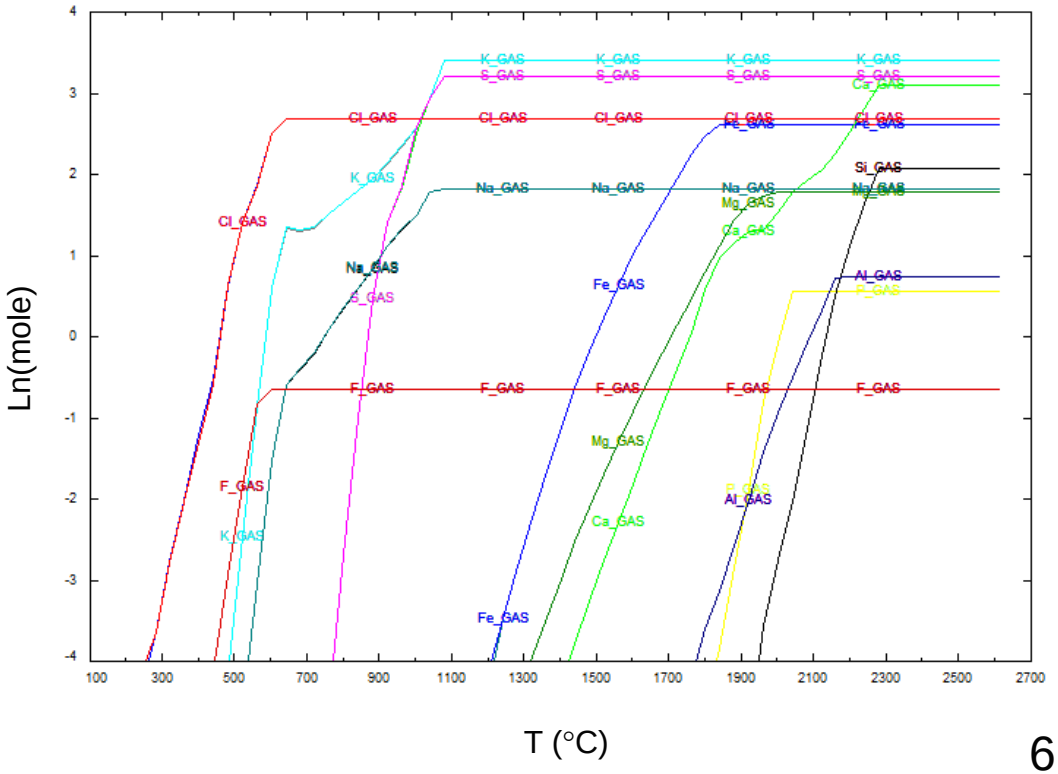
Modelling fuel combustion: Factsage

- FactSage 7.0 is a thermo-chemical modelling tool
- It uses thermodynamic data from the FACT and SGTE databases
- FactSage calculates the species present at equilibrium based on specified:
  - Temperature
  - Pressure
  - Elemental fuel composition
  - Air amount
- Can be used to:
  - Determine equilibrium distribution of elements
  - Find potential stable chemical species
  - Interpret of reaction mechanisms



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Heating and condensation of gas phase

Solids and liquids formed at various stages

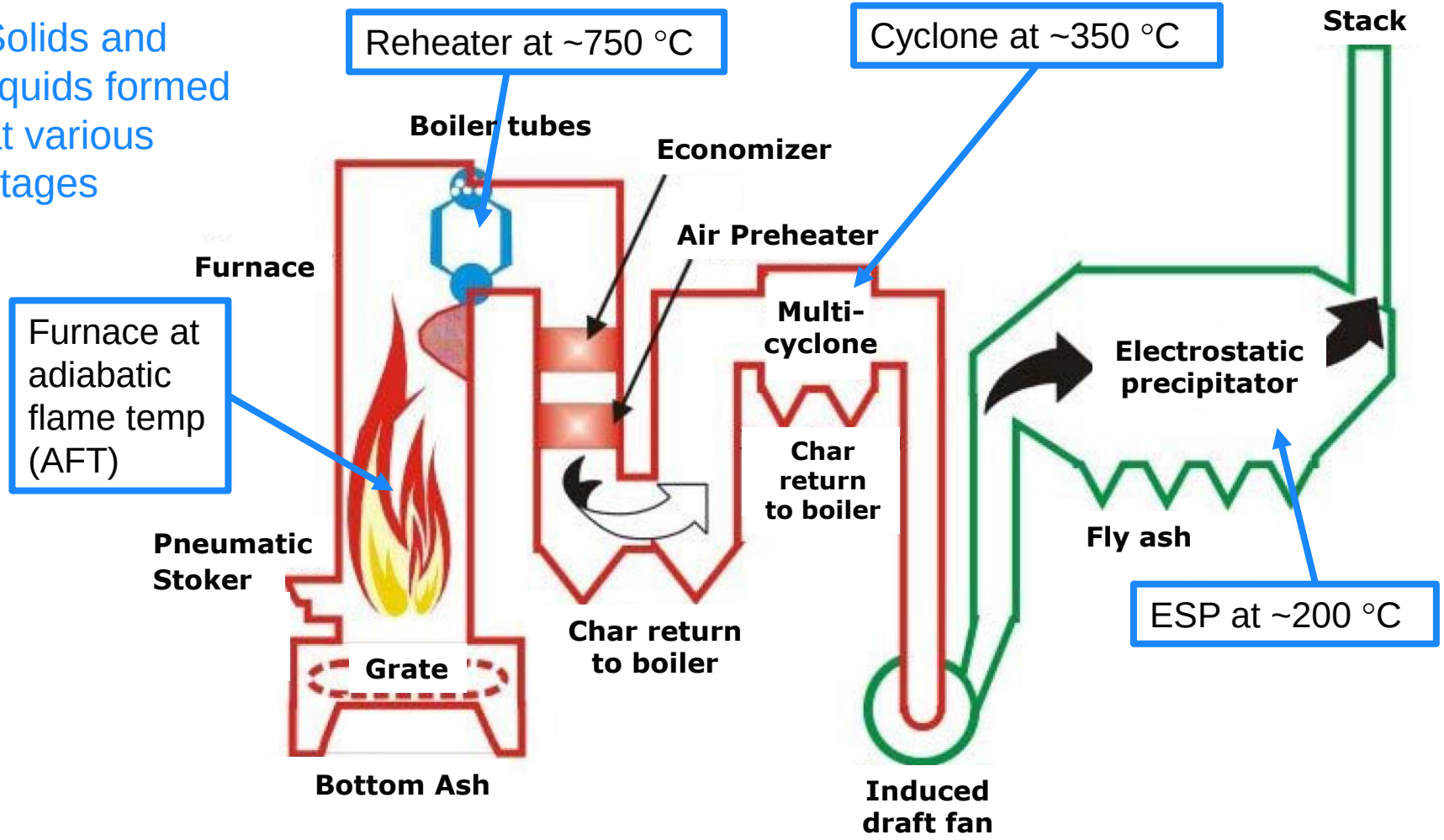

Image: Overend, Ralph P. Direct combustion of biomass, Encyclopedia of Life Support Systems

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Flue gas condensation in a power plant

Unit	Temperature (°C)	Solid/liquid removed (%)	Solid/liquid carried to next step (%)
Furnace[1]	AFT	80	20
Reheater[2]	750	15 (fouling)	85
Multi-cyclone[3]	350	80	20
ESP[4]	200	99	1

[1] Biomass combustion ash is typically 80% bottom ash, 20% fly ash (Jensen et al., 2013; Hansen et al., 2014)

[2] Biomass ash fouling at ~750 °C based on T_{15} (varies with Cl & K content) (Mansikkasalo et al., 2014)

[3] Multi-cyclones: separation efficiency of 80-95% (US EPA, 2016)

[4] ESP: separation efficiency of 99-99.9% (US EPA, 2016)

References: Jensen, P. A., *et al.* (2013). Characterization and quantification of deposits build up and removal in straw suspension fired boilers. Energinet.dk project no. 7217
Hansen, S. B., *et al.* (2014). Deposit probe measurements in large biomass-fired grate boilers and pulverized-fuel boilers. Energy & Fuels, 28 (6), 3539–3555.
Mansikkasalo, J., *et al.* (2014). High power generation from recovery boilers, what are the limits? [Online]. 2014 International Chemical Recovery Conference, Finland.
USEPA (2016). Air Pollution Control Technology Fact Sheets. United States Environmental Protection Agency (USEPA) Technology Transfer Network.

Automation of FactSage: Macros

Macros can be used to automate a large number of simulations:

- Incremental temp increase
- Removal of a particular phases from the reaction

Designed macros used to simulate the following:

- Combustion Process: (200°C to AFT)
- Flue gas condensation divided into:
    i. Furnace to Reheater (AFT to 750°C)
    ii. Reheater to Multi-cyclone (750°C to 400°C)
    iii. Multi-cyclone to ESP (400°C to 200°C)
    iv. ESP to Stack (200°C to 120°C)

Can observe flue gas composition changes during heating and cooling of the flue gas

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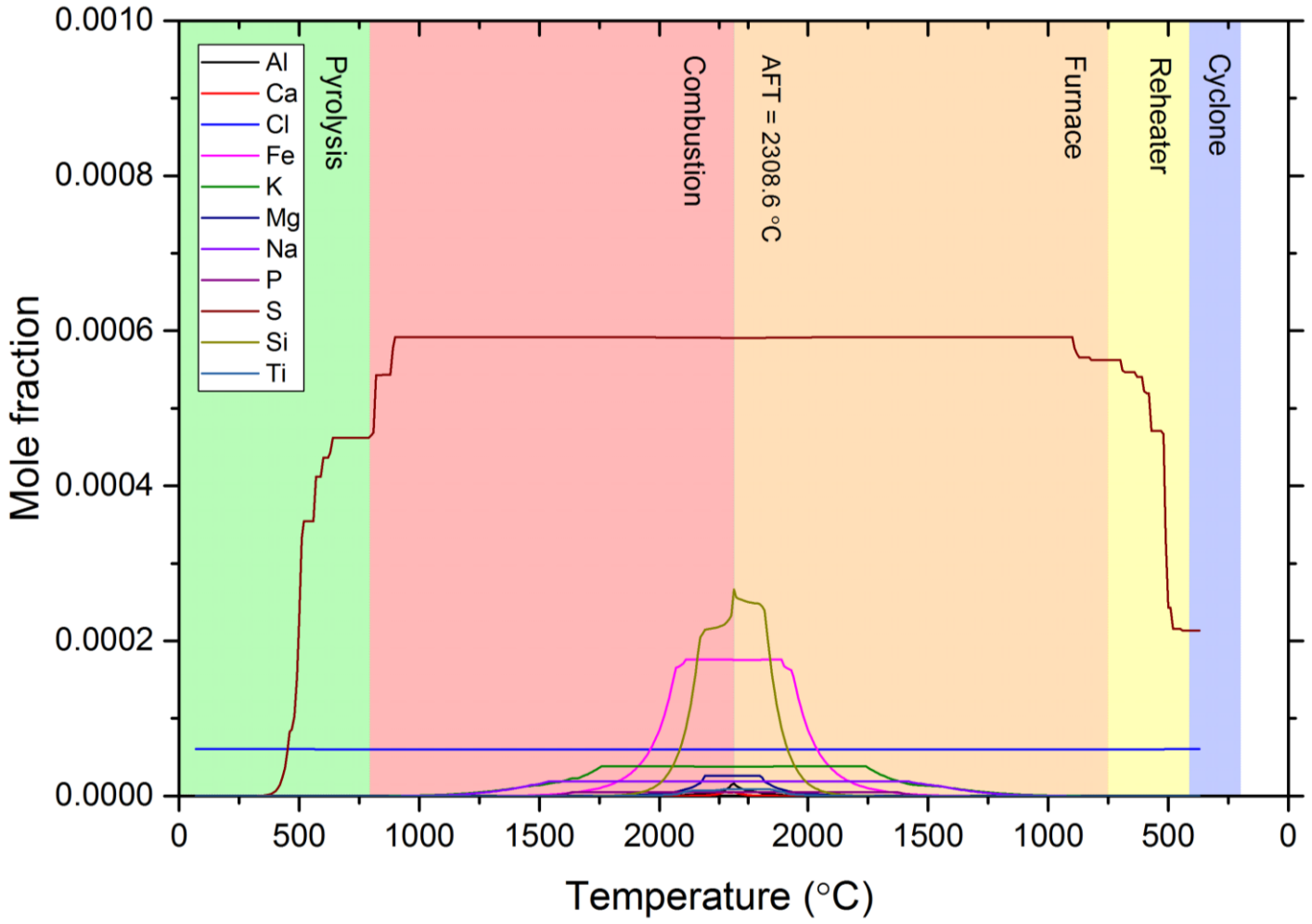
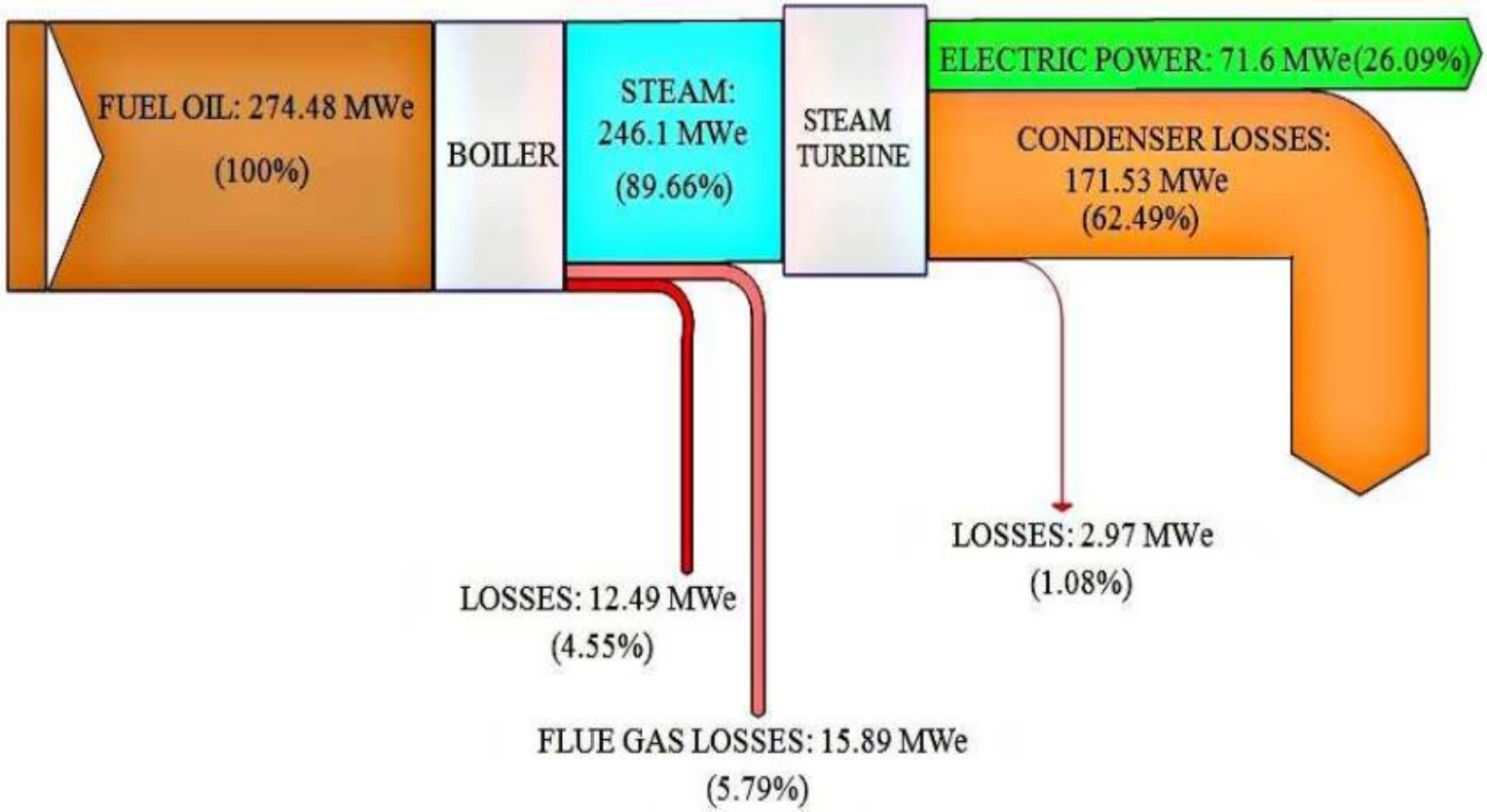
Flue gas combustion-condensation graph



Energy flow in a thermal power plant



Irrazabal Bohorquez *et al.*: Repowering: An option for refurbishment of old thermal power plants in Latin-American countries. Proceedings of ASME Turbo Expo 2010: Power for Land, Sea and Air GT2010 (June 14-18, 2010, Glasgow, UK). DOI: 10.1115/GT2010-23058
http://www.sankey-diagrams.com/tag/power-plant/

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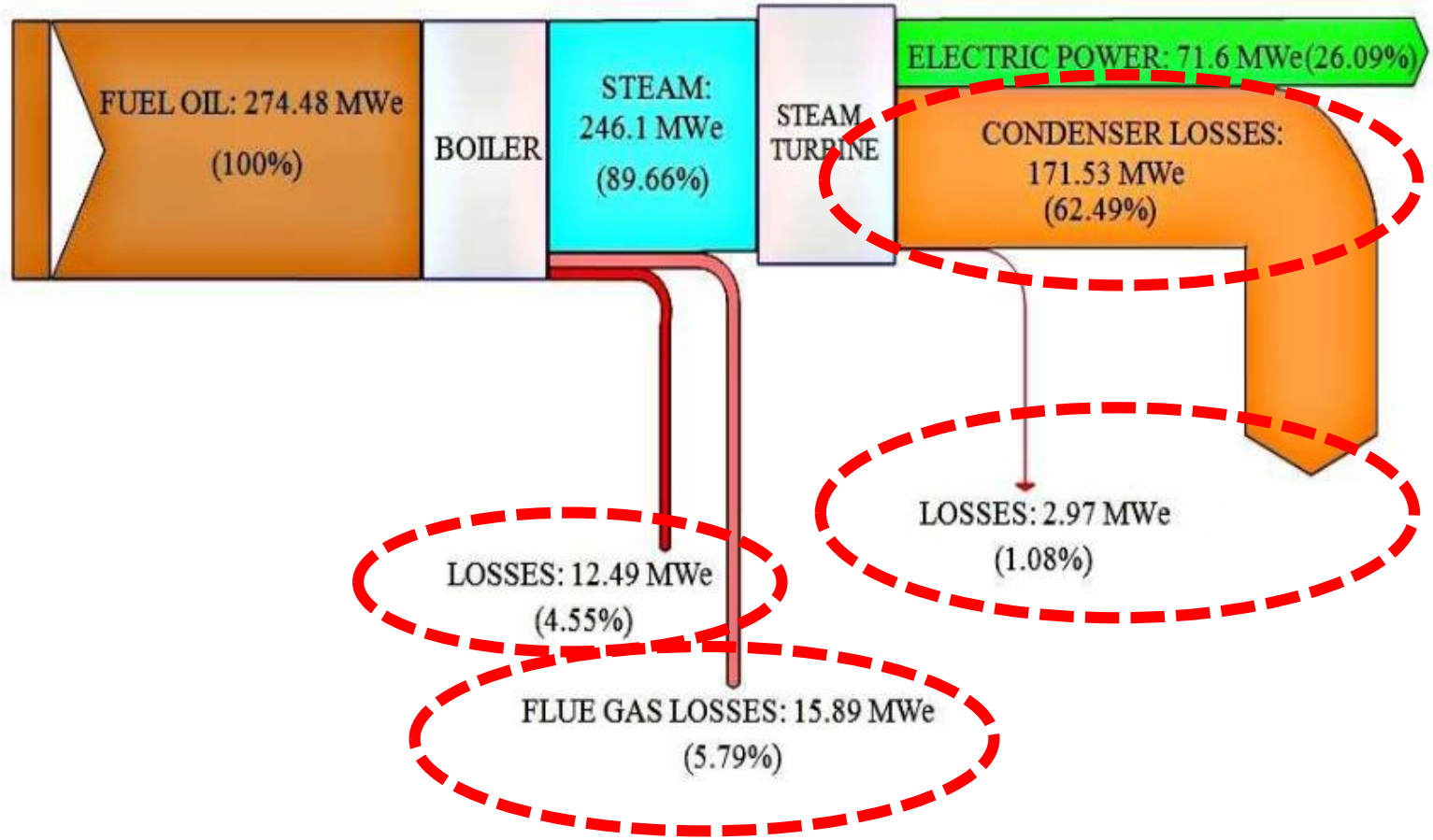
Energy flow in a thermal power plant



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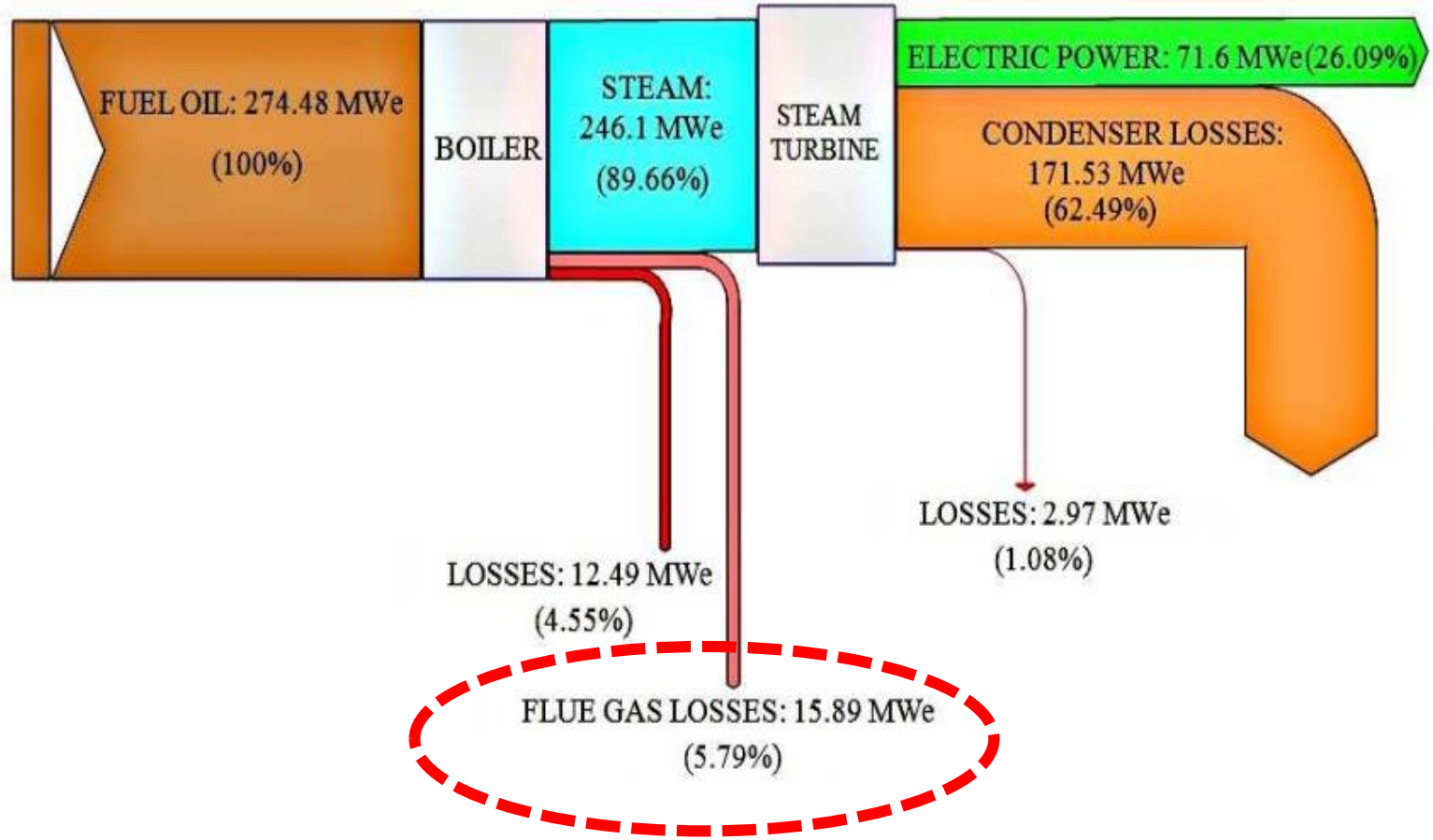

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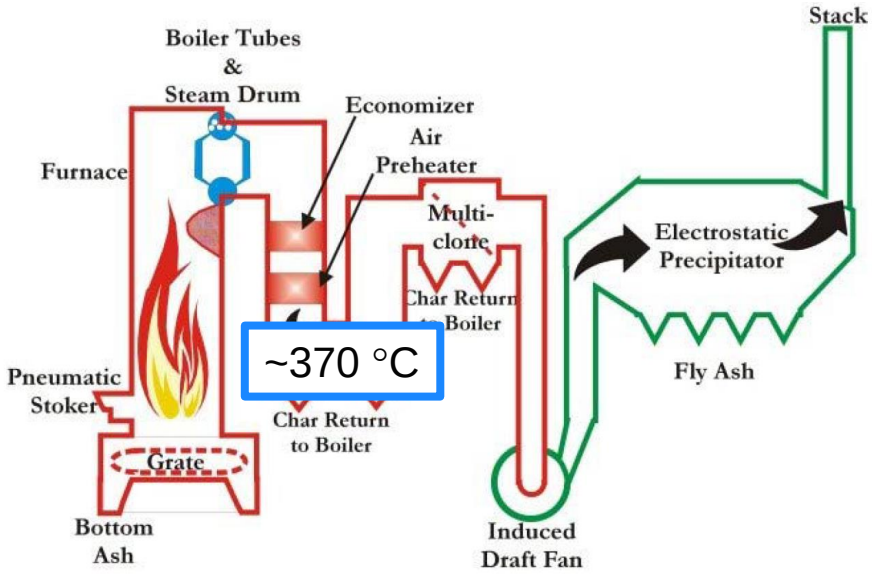
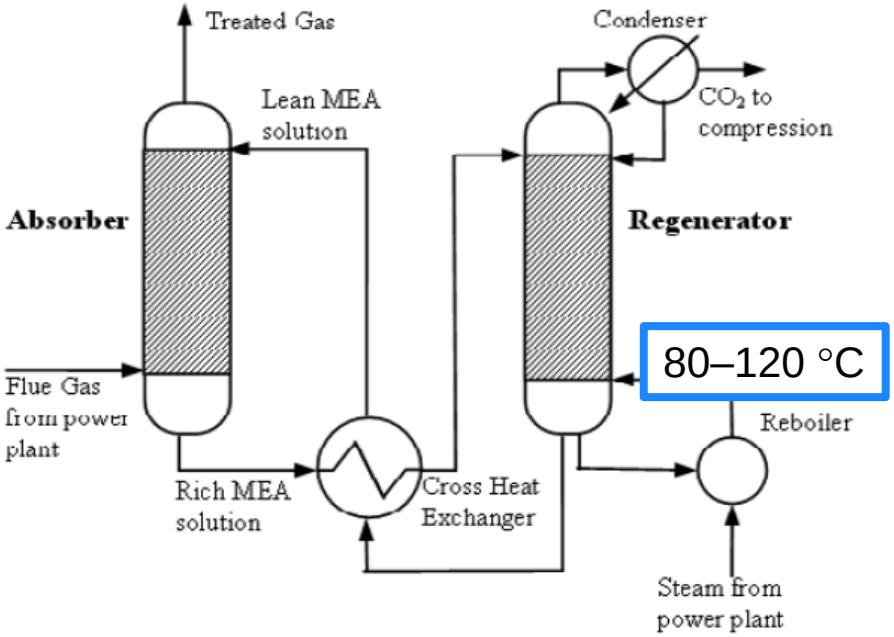
Flue gas heat recovery to improve power plant efficiency

Power Plant



CO_2 capture plant



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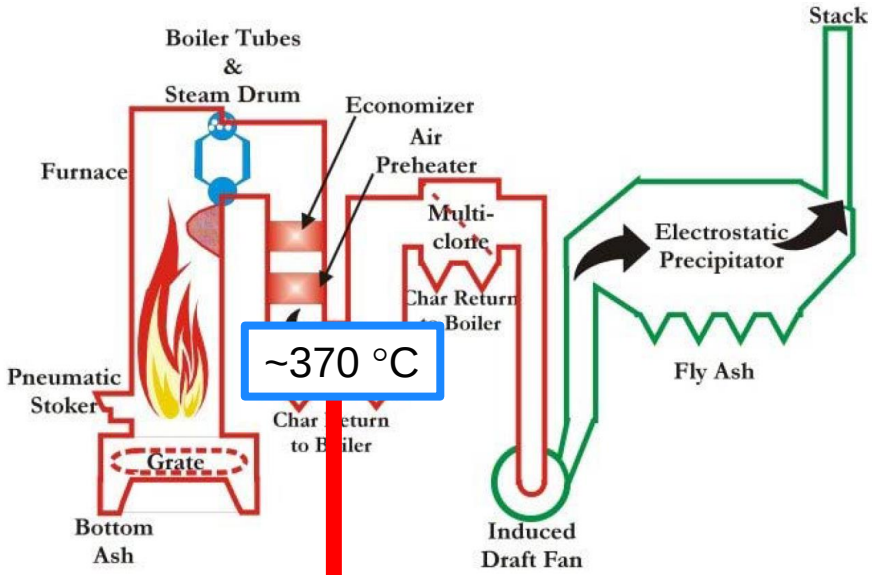

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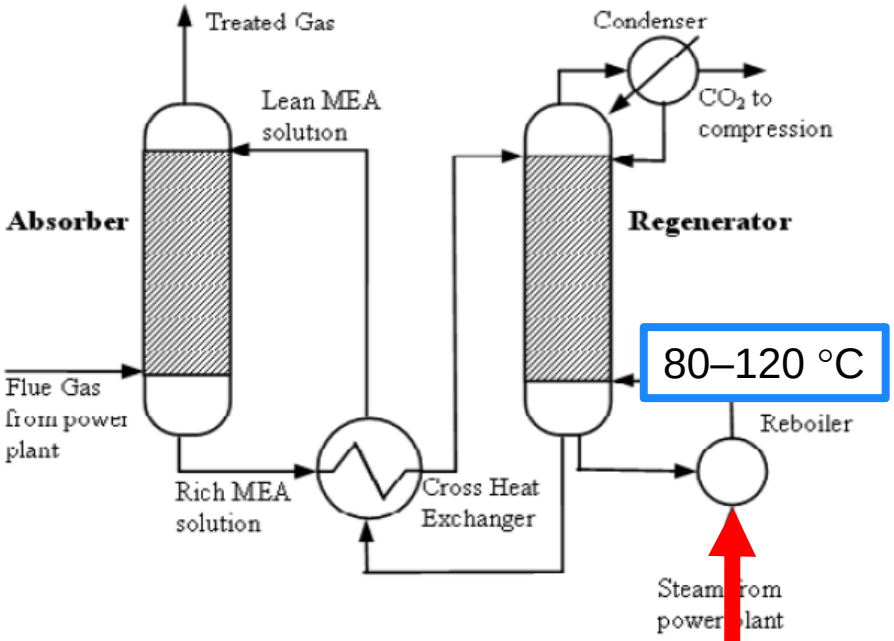

Heat recovery

Heat from boiler exhaust flue gas

To reboiler for solvent regeneration

BECCS performance evaluation study: Objectives

- Assess the performance of a BECCS system using a 500 MW ultra-supercritical pulverized fuel power plant with 90% CO_2 capture.
- The effects of the following factors were evaluated:
  i. Coal types: high sulphur 2.51 wt% and medium sulphur 0.86 wt%
  ii. Biomass type (wheat straw and clean wood chips)
  iii. Variable moisture content of the biomass (5%, 16%, 50%)
  iv. Biomass co-firing proportion %
  v. Solvent selection (MEA, Cansolv, biphasic solvents)
- Key performance indicators include:
  - Combustion adiabatic flame temperature (AFT)
  - Emissions of SO_X and NO_X
  - Recoverable heat from the flue gas
  - Energy efficiency
  - Carbon intensity

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BECCS performance evaluation study

Co-firing fuel flow rate and blended fuel data

Integrated Environmental Control Model

As %biomass increases, calculate the co-firing rate and blended fuel composition based on a 500MW power plant

Thermodynamic Equilibrium Model

FactSage

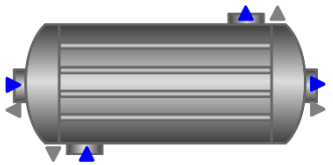
Model the combustion of biomass with coal in the power plant. Determines the flue gas composition and thermodynamic properties

Vapour-Liquid Equilibrium Model

Aspen Plus

Conduct calculations to determine the vapour-liquid-equilibrium of the exhaust gas exiting the power plant

Heat recovery calculations



Determine the influence of exhaust gas heat recovery on overall power plant efficiency

Co-firing scenarios modelled in FactSage

Scenario	Coal type	Biomass type
A	Medium sulphur coal	Wheat straw 5% moisture
B	Medium sulphur coal	Wheat straw 16% moisture
C	Medium sulphur coal	Wood chip 5% moisture
D	Medium sulphur coal	Wood chip 50% moisture
E	High sulphur coal	Wheat straw 5% moisture
F	High sulphur coal	Wheat straw 16% moisture
G	High sulphur coal	Wood chip 5% moisture
H	High sulphur coal	Wood chip 50% moisture

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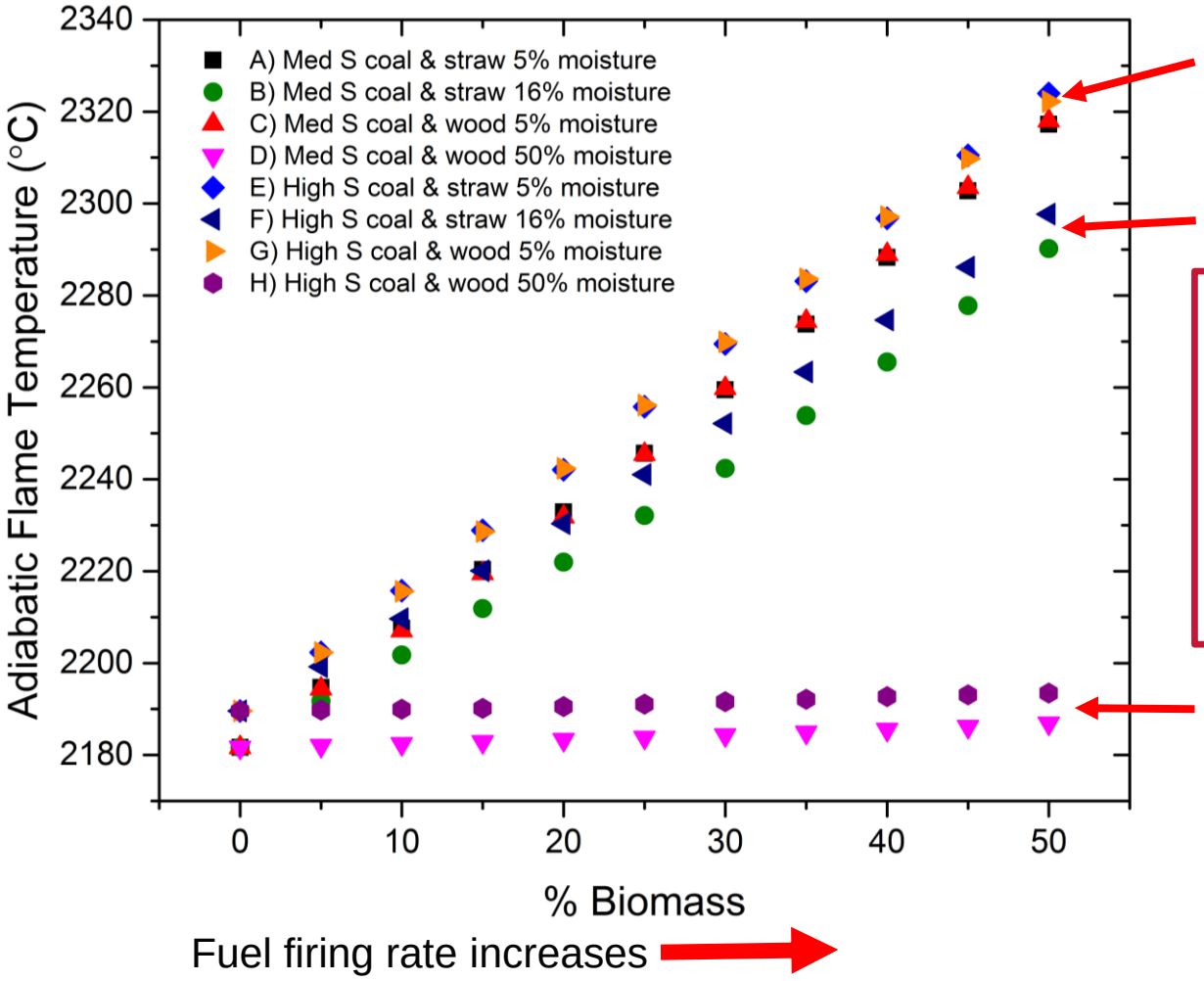
Biomass Co-firing: Adiabatic Flame Temperature (AFT)



5% moisture biomass

16% moisture straw

- AFT is slightly higher when co-firing with high S coal (< ash content)
- Co-firing with wood or straw provides similar AFTs
- More heat at higher co-firing % → enhance HR

50% moisture biomass

Reference: Bui, M., Fajardy, M. & Mac Dowell, N. (2017). Applied Energy, 195, 289–302.

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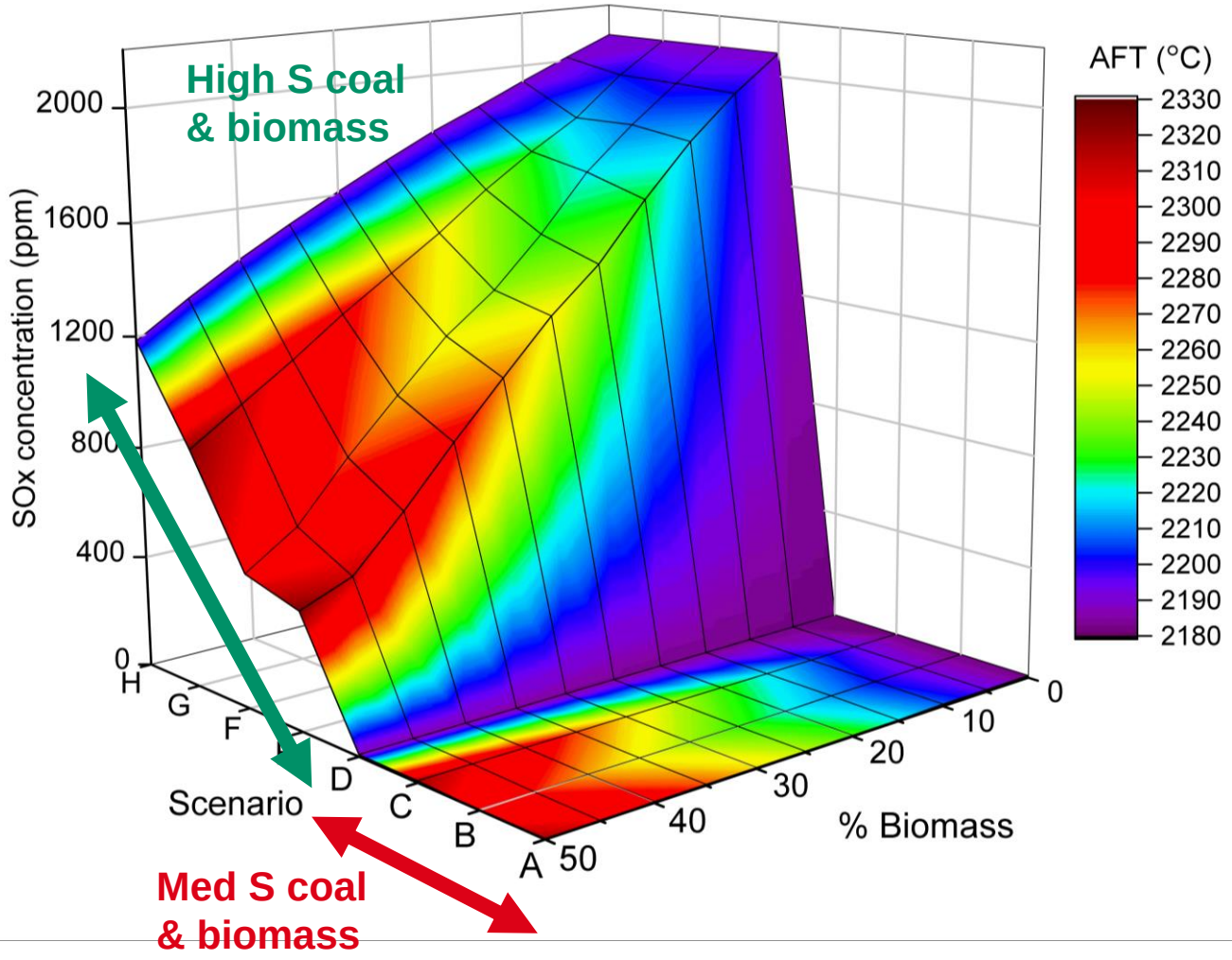
Coal co-firing with biomass : SO_x emissions



Reference: Bui, M., Fajardy, M. & Mac Dowell, N. (2017). Applied Energy, 195, 289–302.

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Coal co-firing with biomass : SO_x emissions

(1) $S + 2O_2 \rightarrow 2SO_2$

$SO_3 + H = HOSO + O$

(2) $SO_3 + O = SO_2 + O_2$

$SO_3 + SO = SO_2 + SO_2$

(3) $SO_2 + O + M = SO_3 + M$

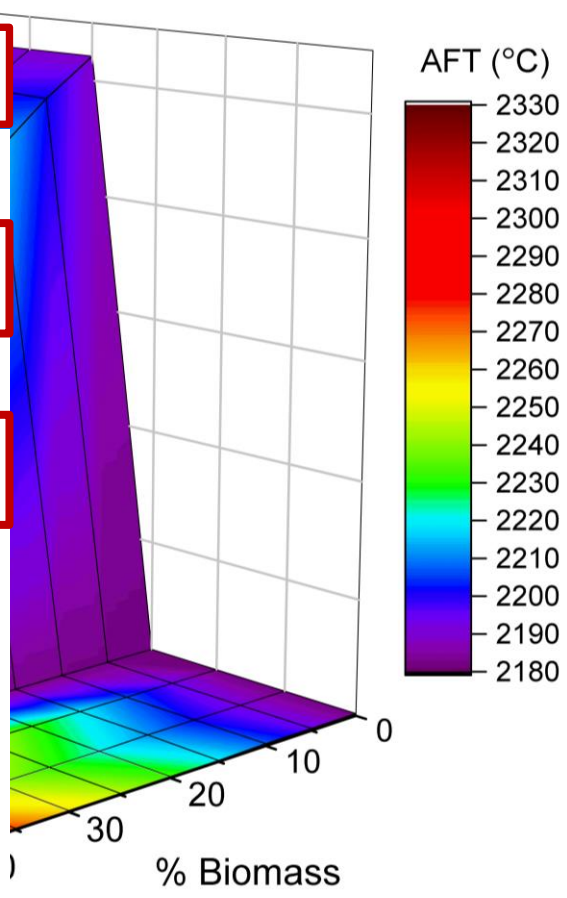
$SO_2 + OH = SO_3 + H$

$HOSO_2 = SO_3 + H$

$HOSO_2 + O = SO_3 + OH$

$HOSO_2 + OH = SO_3 + H_2O$

$HOSO_2 + O_2 = SO_3 + HO_2$



- SO_X formation mechanism involves equilibrium reactions
- SO_2 formation thermodynamically favoured
- Temperature ↓ : Equilibrium shifts towards SO_3 formation (iron oxide can catalyse reaction 2)

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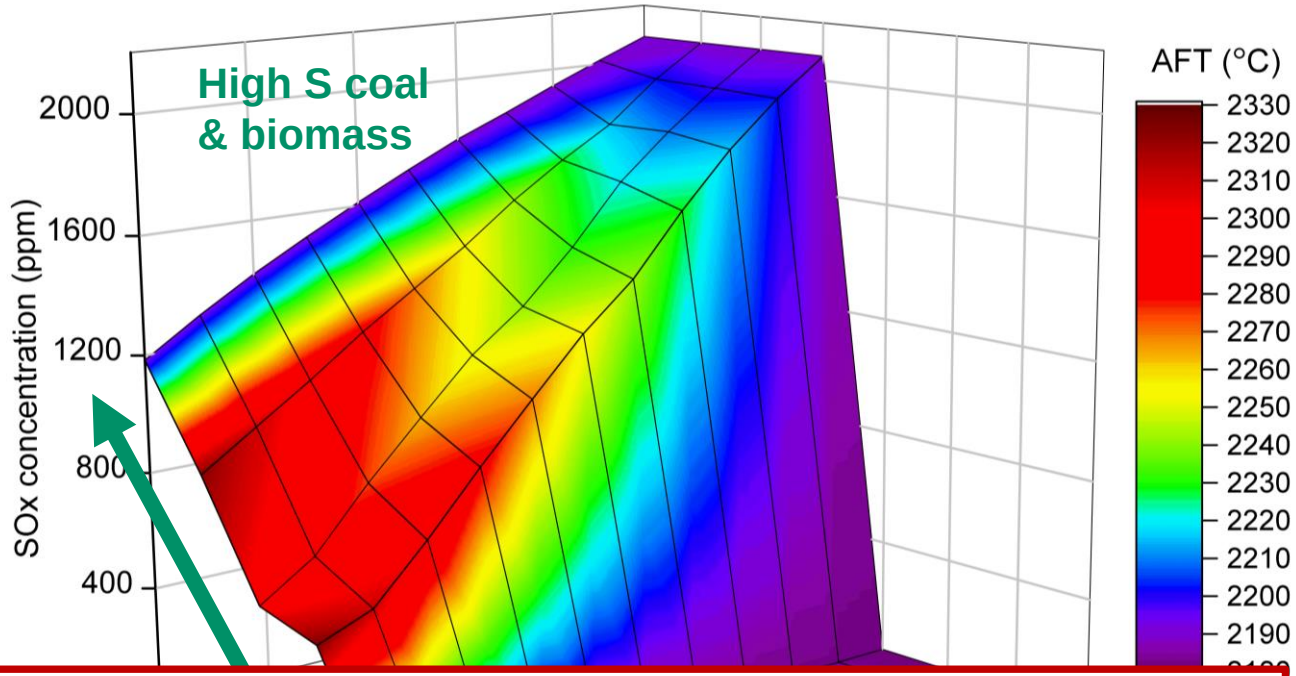
Coal co-firing with biomass : SO_x emissions



$$2CaO + 2SO_2 + O_2 \rightarrow 2CaSO_4$$

$$CaO + CO_2 \rightarrow CaCO_3$$

$$2CaCO_3 + 2SO_2 + O_2 \rightarrow 2CaSO_4 + 2CO_2$$

- SO_X formation mechanism involves equilibrium reactions
- SO_2 formation thermodynamically favoured
- Temperature ↓ : Equilibrium shifts towards SO_3 formation (iron oxide can catalyse reaction 2)
- Alkali oxides in ash capture SO_2 and SO_3

Reference: Bui, M., Fajardy, M. & Mac Dowell, N. (2017). Applied Energy, 195, 289–302.

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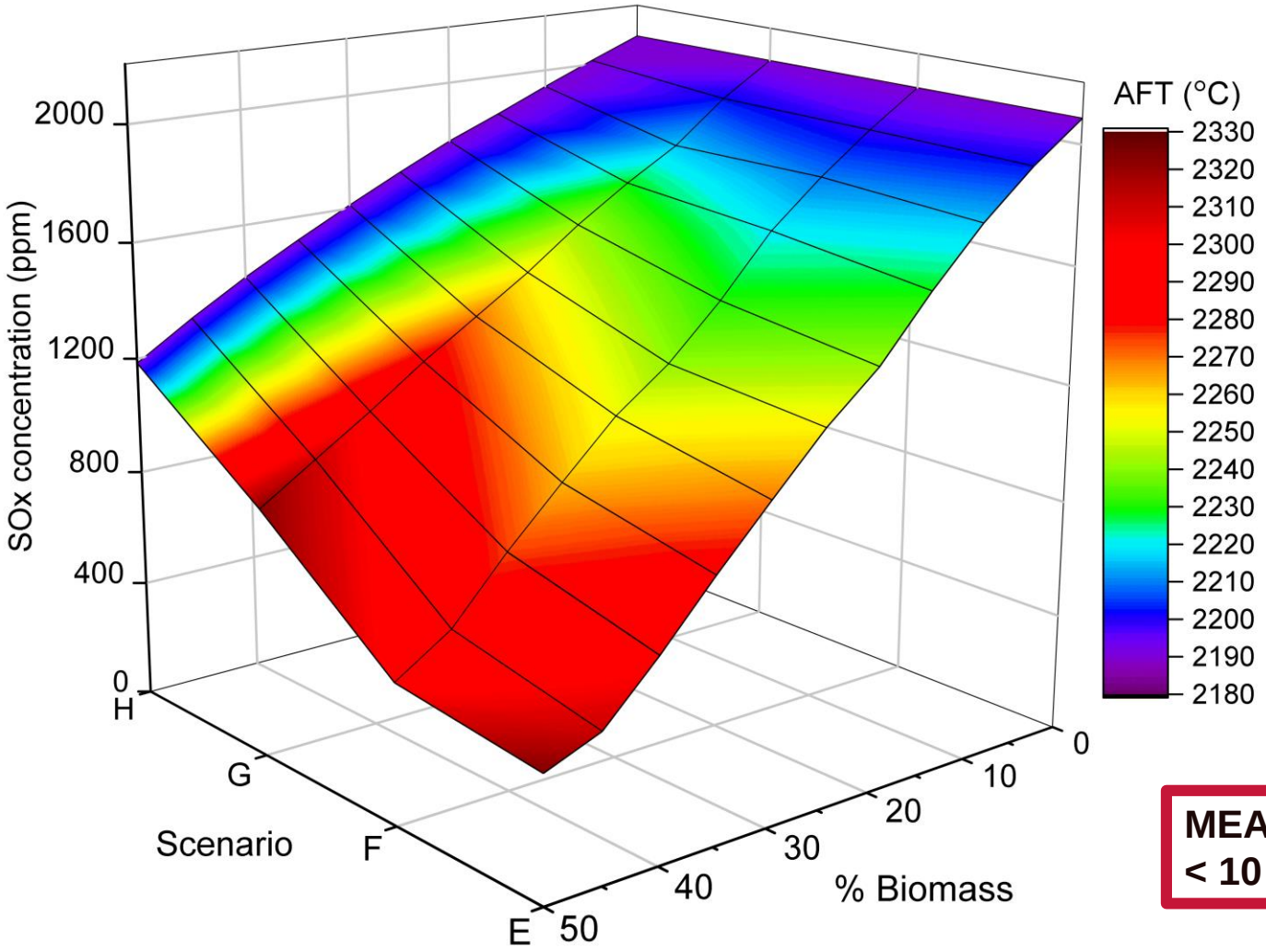
High sulphur coal & biomass: SO_x emissions



- SO_X decreases linearly with % biomass due to decreased S content

MEA tolerance to SO_X < 10 ppm

Reference: Bui, M., Fajardy, M. & Mac Dowell, N. (2017). Applied Energy, 195, 289–302.

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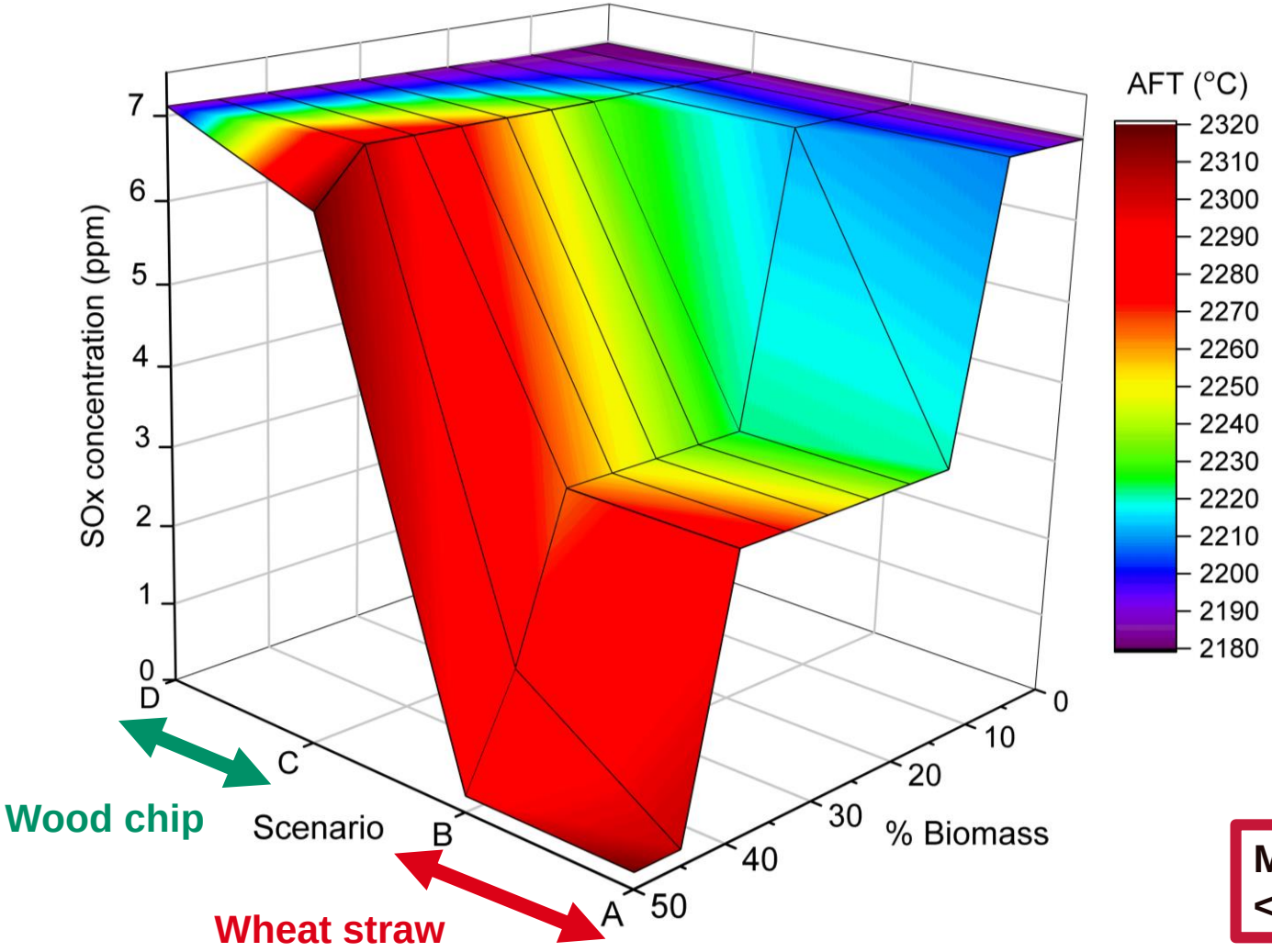
Medium sulphur coal & biomass: SO_x emissions



- CaO, MgO, Na_2O, K_2O captures SO_X
- In FactSage, Al_2O_3, Fe_2O_3 & MnO_2 also involved in SO_X ↓
- Wheat straw has higher sulphur content than the wood chip (0.1 wt% Vs 0.05 wt%)
- Wheat straw has more ash than wood chip (5.5 dry wt% Vs 2 dry wt%)
- Alkali oxides in ash → reduce SO_X emissions

MEA tolerance to SO_X < 10 ppm

Reference: Bui, M., Fajardy, M. & Mac Dowell, N. (2017). Applied Energy, 195, 289–302.

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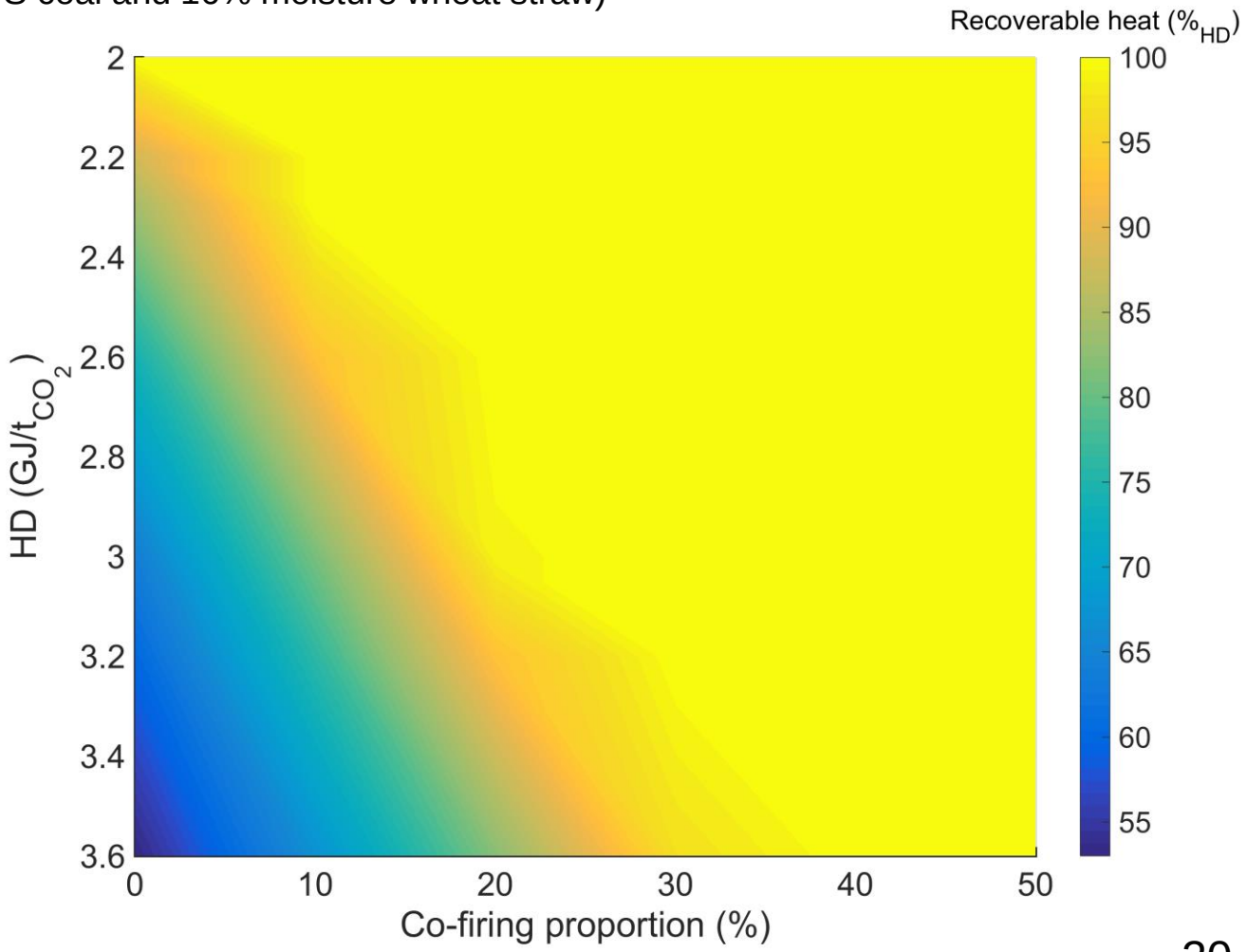
BECCS: Recoverable heat from the flue gas

Analysis of scenario F (high S coal and 16% moisture wheat straw)



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BECCS: Recoverable heat from the flue gas

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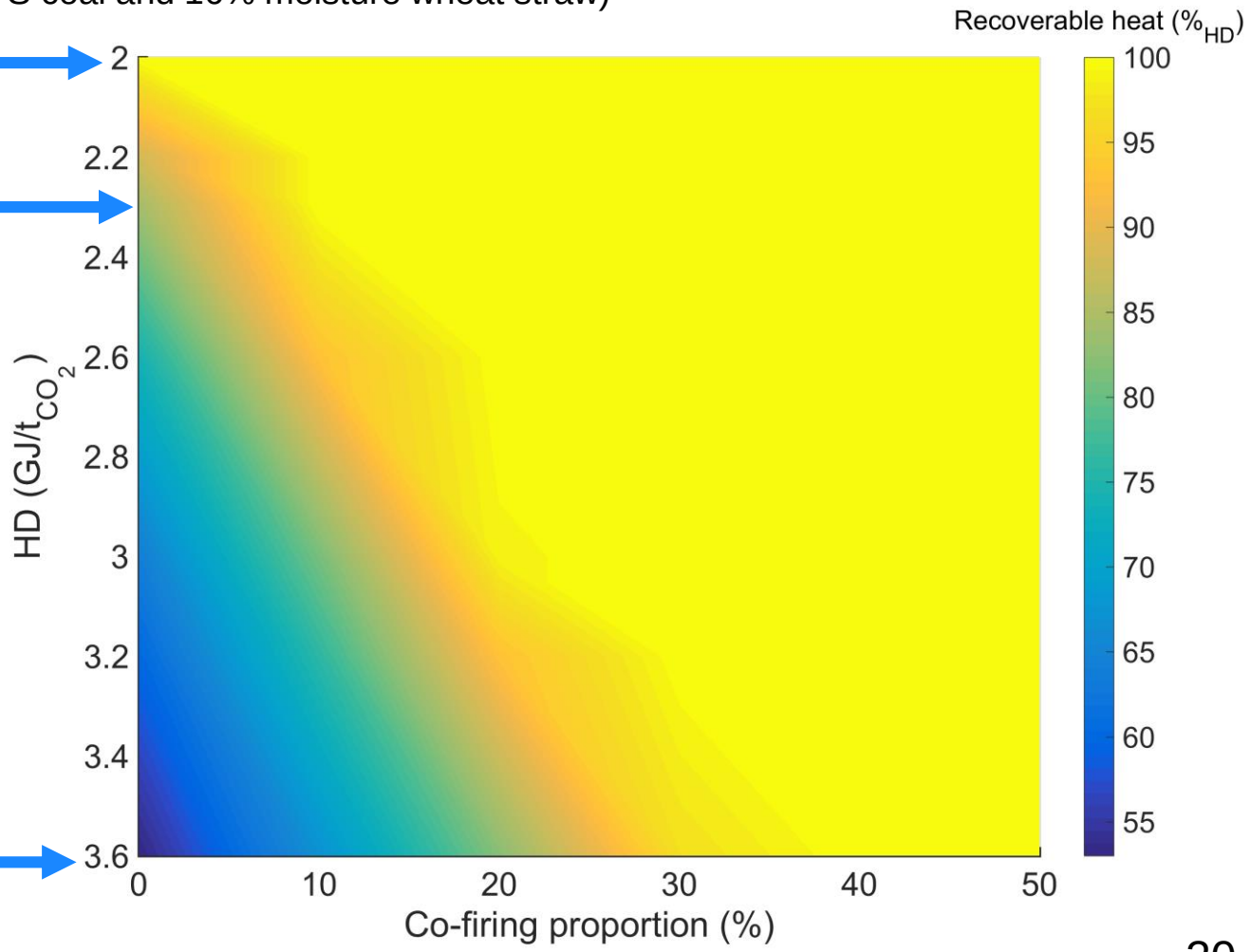
Solvent	HD (MJ/t_{CO2})	Reg T (°C)
MEA	3600	120
Cansolv	2300	120
Biphasic	2000	80

Data for biphasic solvent systems published by Ye *et al.* (2015) and Raynal *et al*. (2011)



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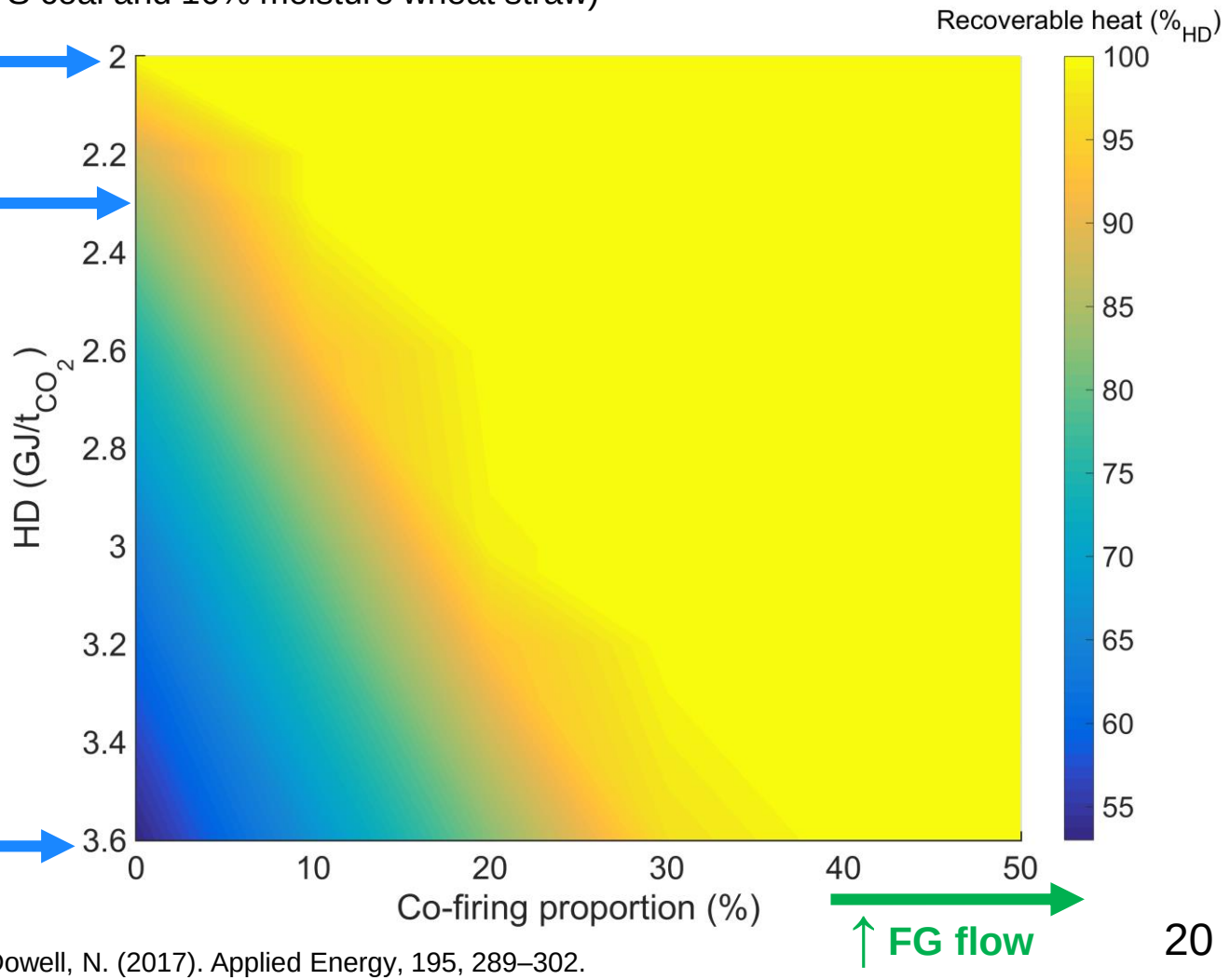

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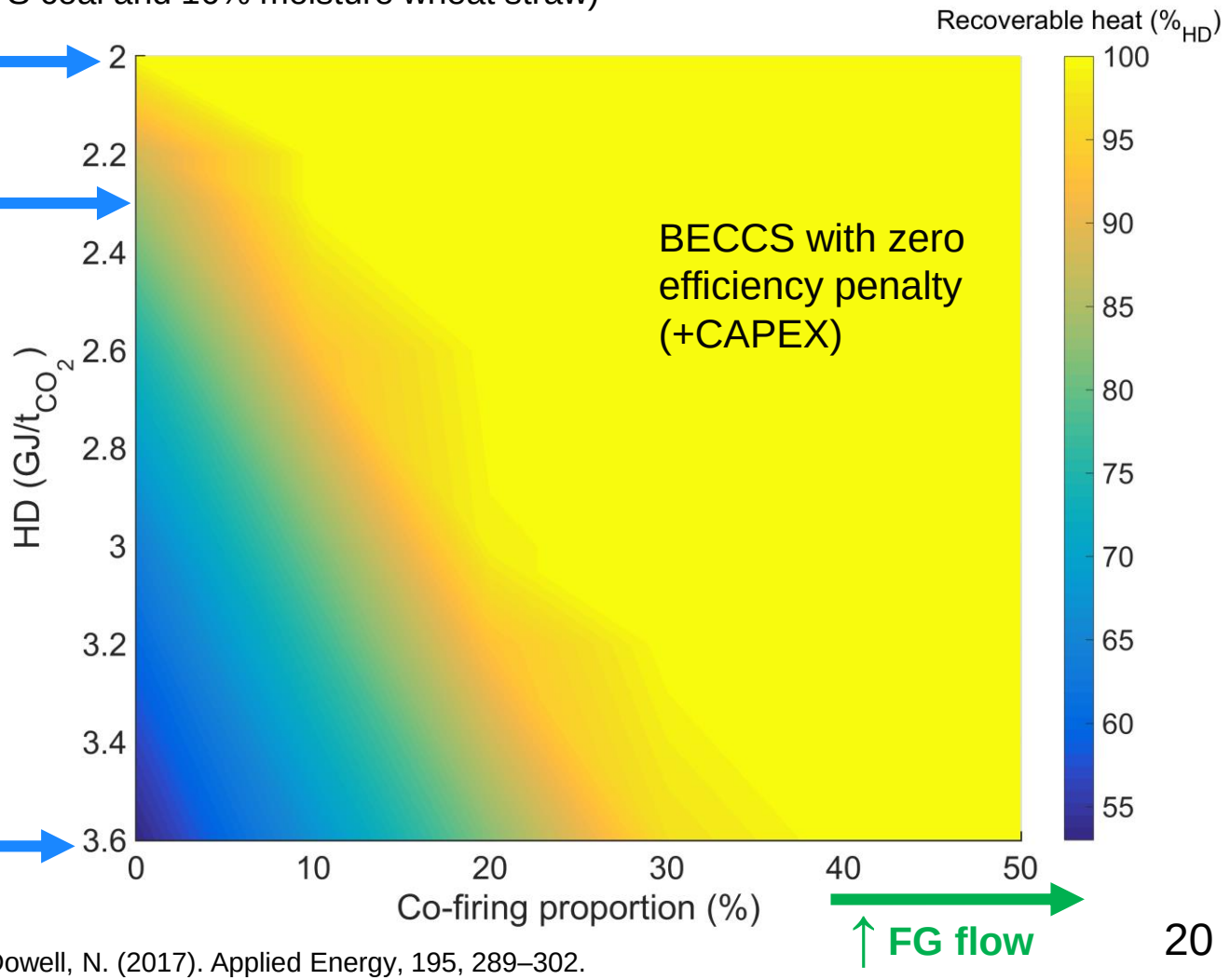

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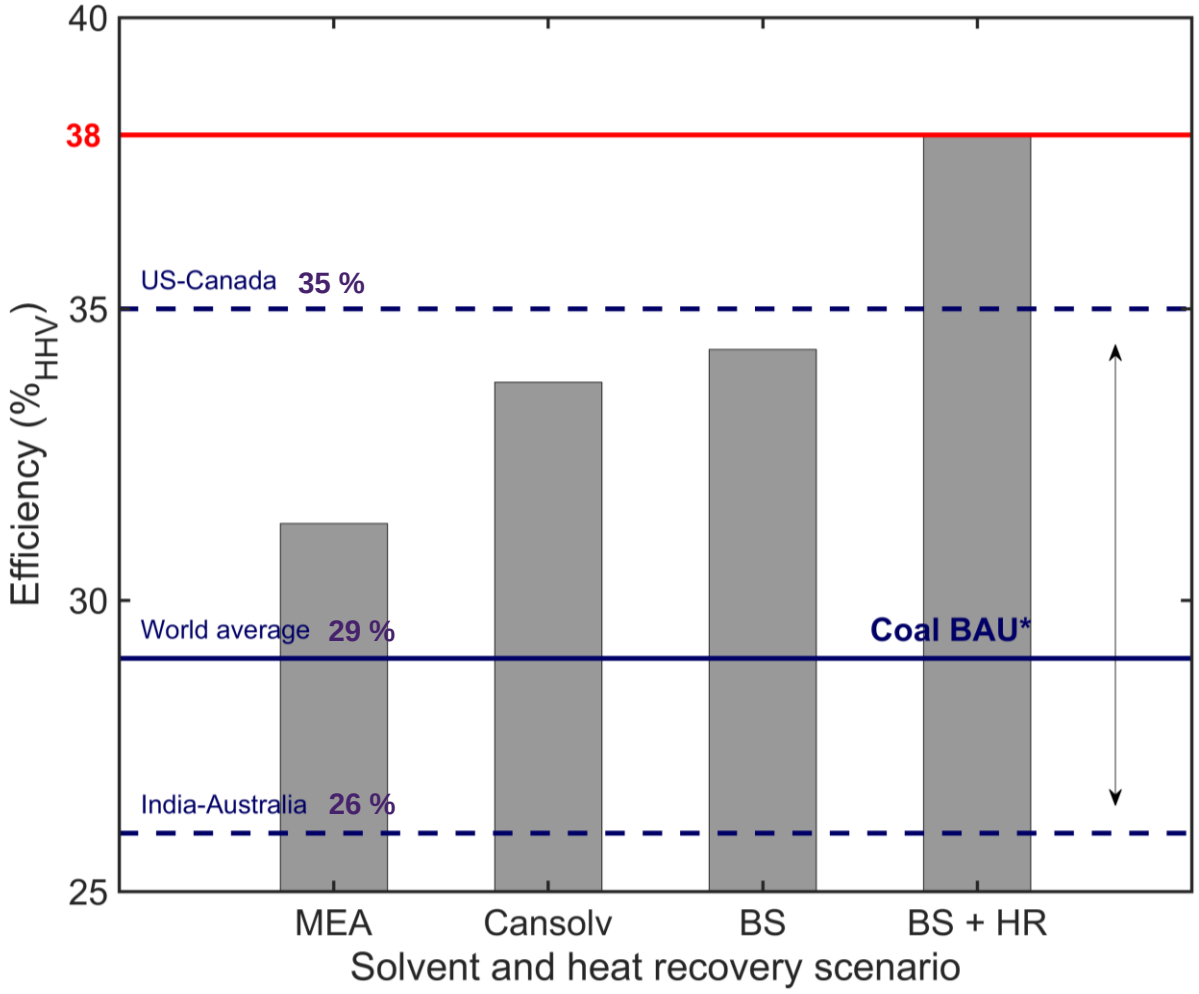
BECCS power plant efficiency improvement



- Efficiency for a 500 MW BECCS system **co-firing 50% biomass**
- Efficiency can be significantly improved by using (i) high performance solvents, (ii) heat recovery

BS = biphasic solvent

HR = heat recovery

BAU = Business As Usual (average efficiencies around the world)

Reference: Bui, M., Fajardy, M. & Mac Dowell, N. (2017). Applied Energy, 195, 289–302.

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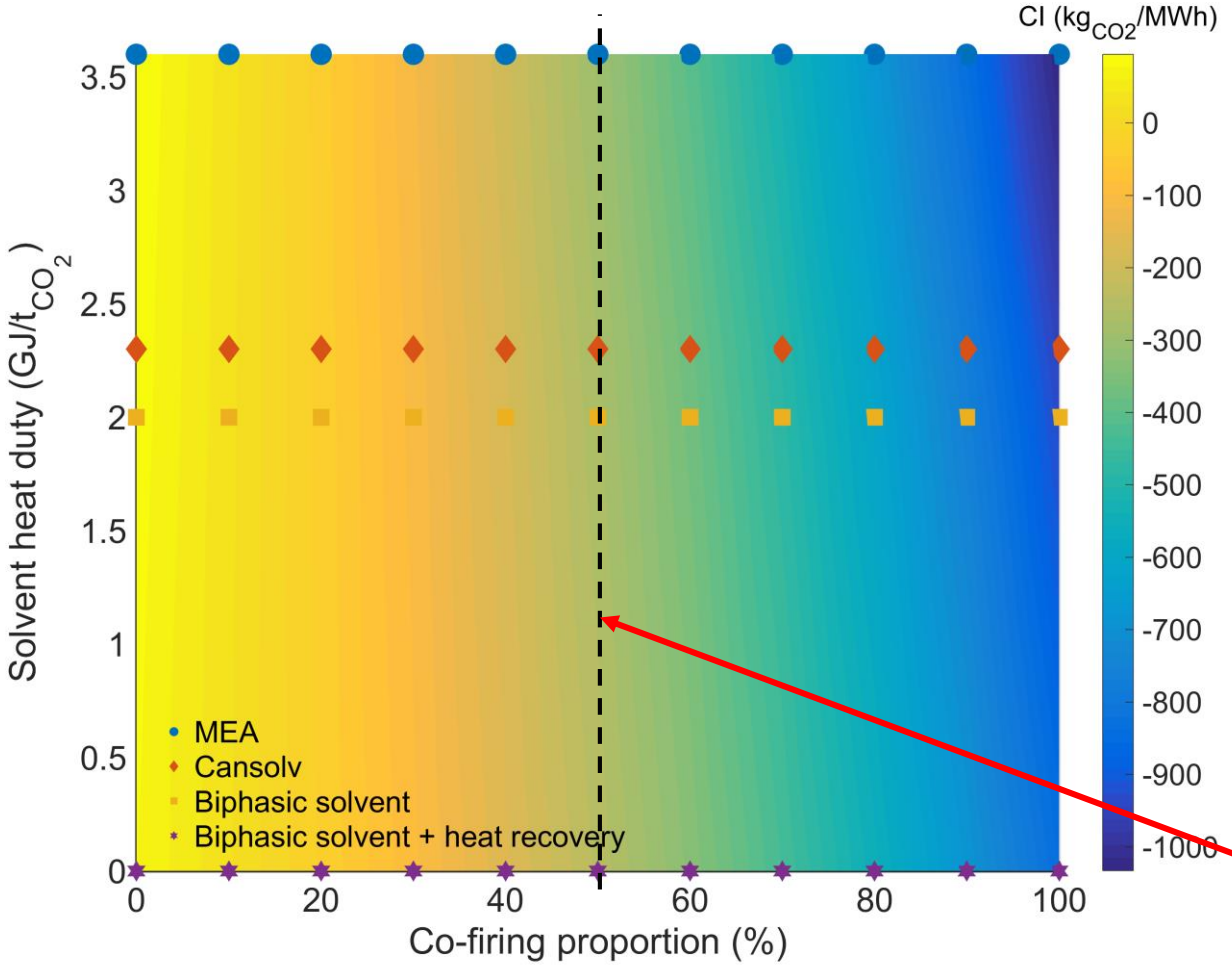
BECCS carbon intensity



As system efficiency increases, less fuel is burned per MWh produced → less CO_2 is captured per MWh of electricity generated

At 50% biomass co-firing and 90% CO_2 capture:

System	Efficiency %HHV	Carbon intensity kg CO_2/MWh
MEA	31.3	-296
Cansolv	33.7	-275
BS	34.3	-271
BS + HR	38.0	-244

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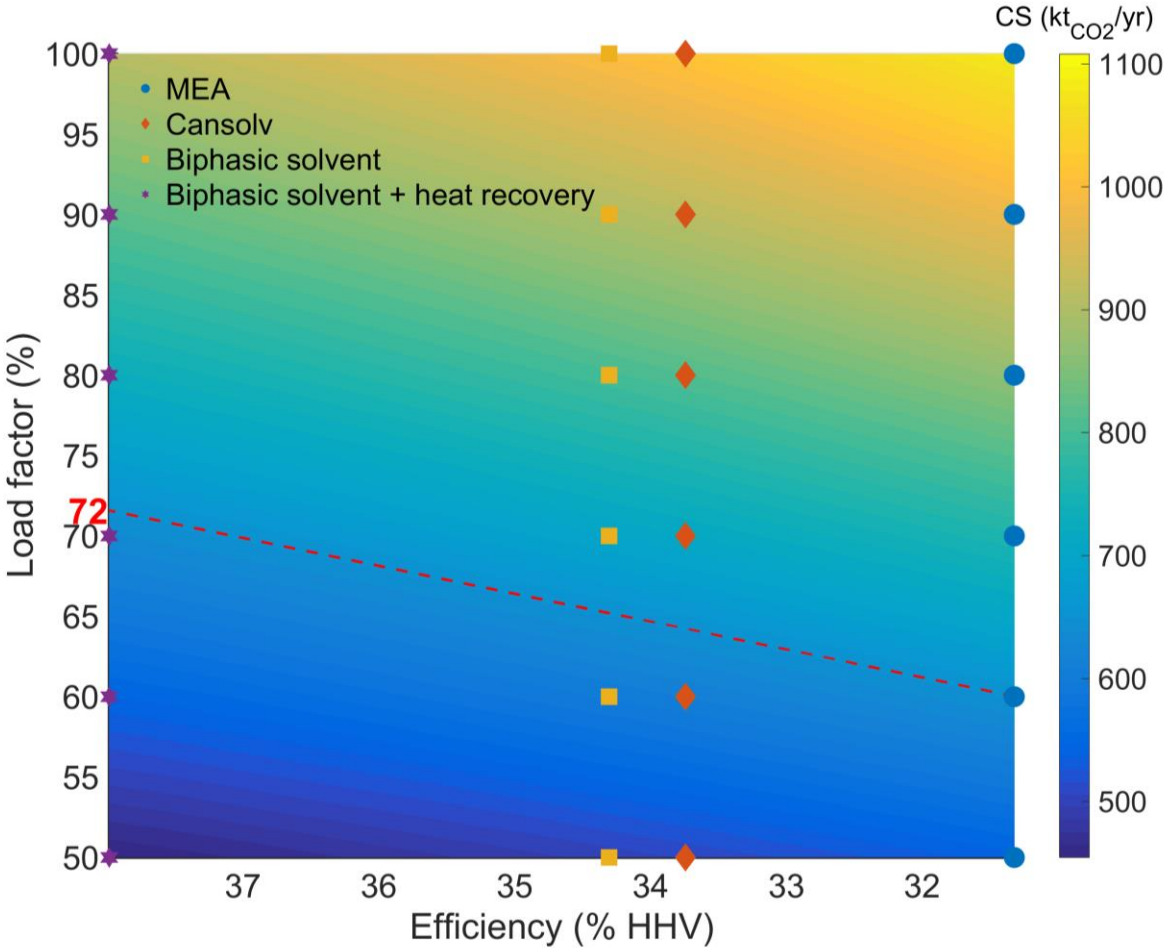
CO_2 mitigation potential of a 500 MW BECCS system



- Power plant load factor is a function of power plant efficiency.
- Improving efficiency reduces marginal costs of electricity generation, enabling operation at higher load factor (Mac Dowell & Shah, 2015; Mac Dowell & Staffell, 2016)
- The efficiency of a BECCS system will have an impact on its dispatch rate within an electricity market
  → Influences CO_2 mitigation potential

Objective: (i) more efficient at electricity generation, or (ii) more carbon negative & capture CO_2?

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Conclusion: BECSS Performance Matrix

Performance parameter	Ash content	Sulphur content	Moisture content	HHV	Biomass co-firing %	Solvent heat duty
NO_X ↓	dependent on combustion conditions					
SO_X ↓	↑	↓	↓		↑	
AFT ↑	↓		↓		↑	
Heat recovery ↑	↓		↓	↓*	↑	↓
Efficiency ↑	↓		↓	↑↓	↓	↓
CO_2 negativity ↑	↑		↑	↑	↑	↑
Exhaust gas flow rate ↑				↓	↑	

Enhance efficiency: high performance solvents (low heat duty) and higher heat recovery (higher AFT and flue gas flow rate)

Greater carbon negativity: lower efficiency systems (burn more biomass fuel, thus more CO_2 is captured and permanently stored)

Minimise pollutant emissions: Increasing biomass co-firing proportion significantly reduces SO_X emissions, fuel selection (low S, metal oxides), combustion control is required to regulate NO_X emissions.

Conclusion

- BECCS has the potential provide negative emissions, whilst providing reliable firm power generation capacity.
- Opportunities to improve energy efficiency of BECCS include enhancing heat recovery and using high performance solvents for CO_2 capture (*e.g.*, biphasic).
- Power generation efficiency increased from $31\%_{HHV}$ (MEA system) to $38\%_{HHV}$ (biphasic system with heat recovery).
- Important to consider the complex trade-offs between carbon intensity and power plant efficiency
- Inefficient BECCS → removes more CO_2 from the atmosphere
- However, inefficient systems might have lower dispatch rate compared to high efficiency systems

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Thank you

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CCT2017 Paper:

Bui, M., Fajardy, M. & Mac Dowell, N. (2017). Bio-energy with carbon capture and storage (BECCS): Opportunities for performance improvement. Fuel, submitted.

EXTRA SLIDES

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BECCS performance evaluation

	High sulphur coal	Medium sulphur coal	Clean wood chips	Wheat straw
Reference	[28]	[29]	[29]	[11, 30]
HHV ($MJ.kg^{-1}$ dry)	27.14	27.06	19.16	19.22
Fuel Composition	wt %	wt %	dry wt %	dry wt %
C	63.75	64.6	50	48.7
H	4.5	4.38	5.4	5.7
O	6.88	7.02	42.2	39.1
Cl	0.29	0.023	0.02	0.32
S	2.51	0.86	0.05	0.1
N	1.25	1.41	0.3	0.6
Moisture	11.12	9.5	-	-
Ash	9.7	12.2	2.0	5.5

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BECCS performance evaluation

Ash composition	High sulphur coal	Medium sulphur coal	Clean wood chips	Wheat straw
	% ash	% ash	% ash	% ash
SiO_2	46.8	50	43.1	56.2
Al_2O_3	18.0	30.0	8.9	1.2
Fe_2O_3	20.0	9.8	3.9	1.2
CaO	7.0	4.0	28.0	6.5
MgO	1.0	0.5	4.2	3.0
Na_2O	0.6	0.1	2.0	1.3
K_2O	1.9	0.1	5.5	23.7
TiO_2	1.0	2.0	0.4	0.06
P_2O_5	0.2	1.8	2.2	4.4
SO_3	3.5	1.7	1.8	1.1
MnO	0	0	0	1.34

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Cost of implementing heat recovery

For 500 MW BECCS, the cost of the HR heat exchangers for each scenario is as follows (USD):

MEA = $241,886

Cansolv = $103,626

NS = $83,790