Refereed Proceedings

The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering

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PRESENTATION SLIDES: Fluidized Bed Combustion for Clean Energy

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FLUIDIZED BED COMBUSTION FOR CLEAN ENERGY

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Fluidization XII - New Horizons in Fluidization Engineering – May 13-18, 2007

Structure of presentation

- Introduction - energy market
  - Climate change
  - Boiler market
  - Example of FB related bridging technologies
- The FBC market
- FBC and fluidization
  - Flow characteristics
  - R&D need
- New concepts
- Conclusions

Large investments required in the energy sector over the next decades:

- battle climate change

- maintain security of supply

- maintain competitiveness

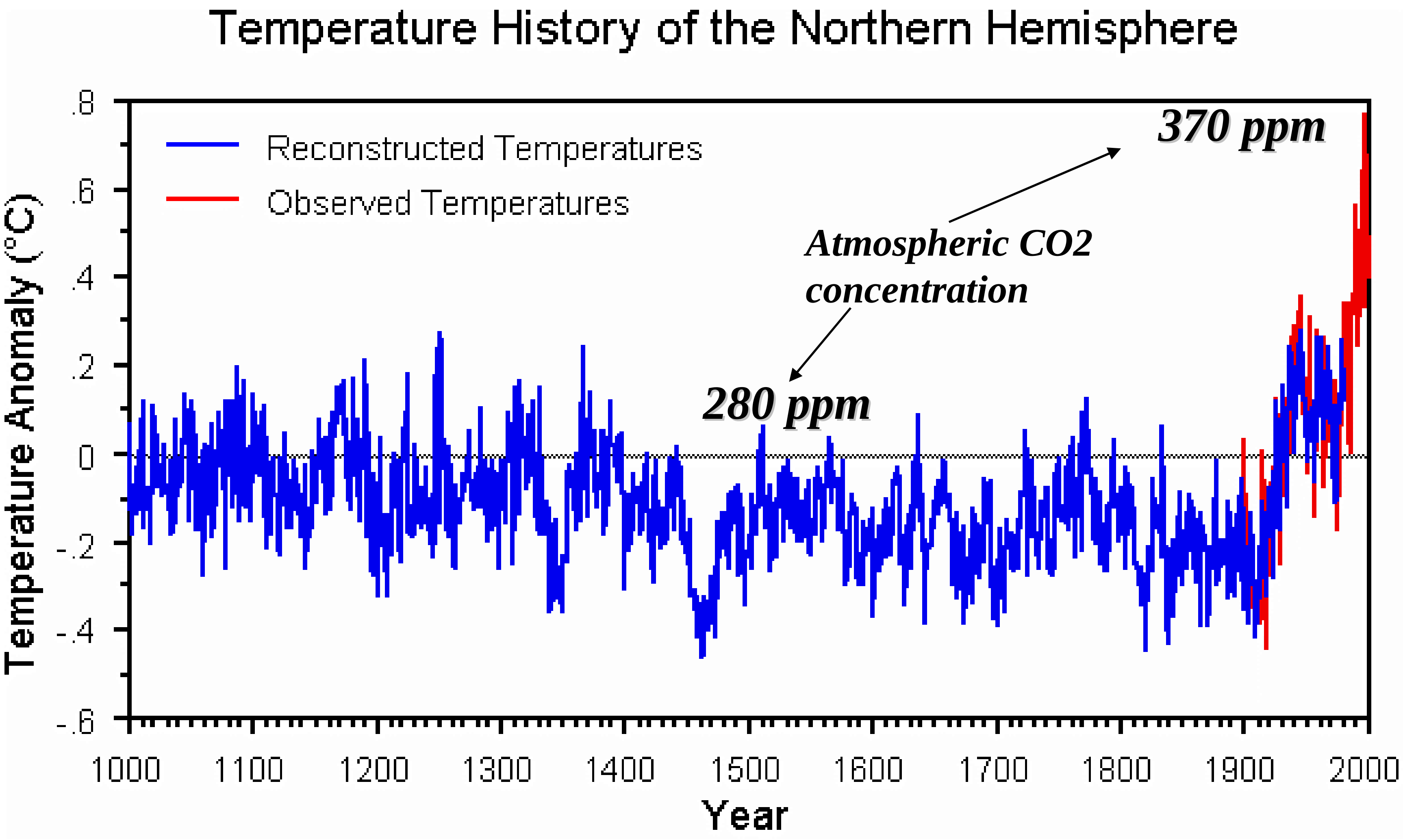
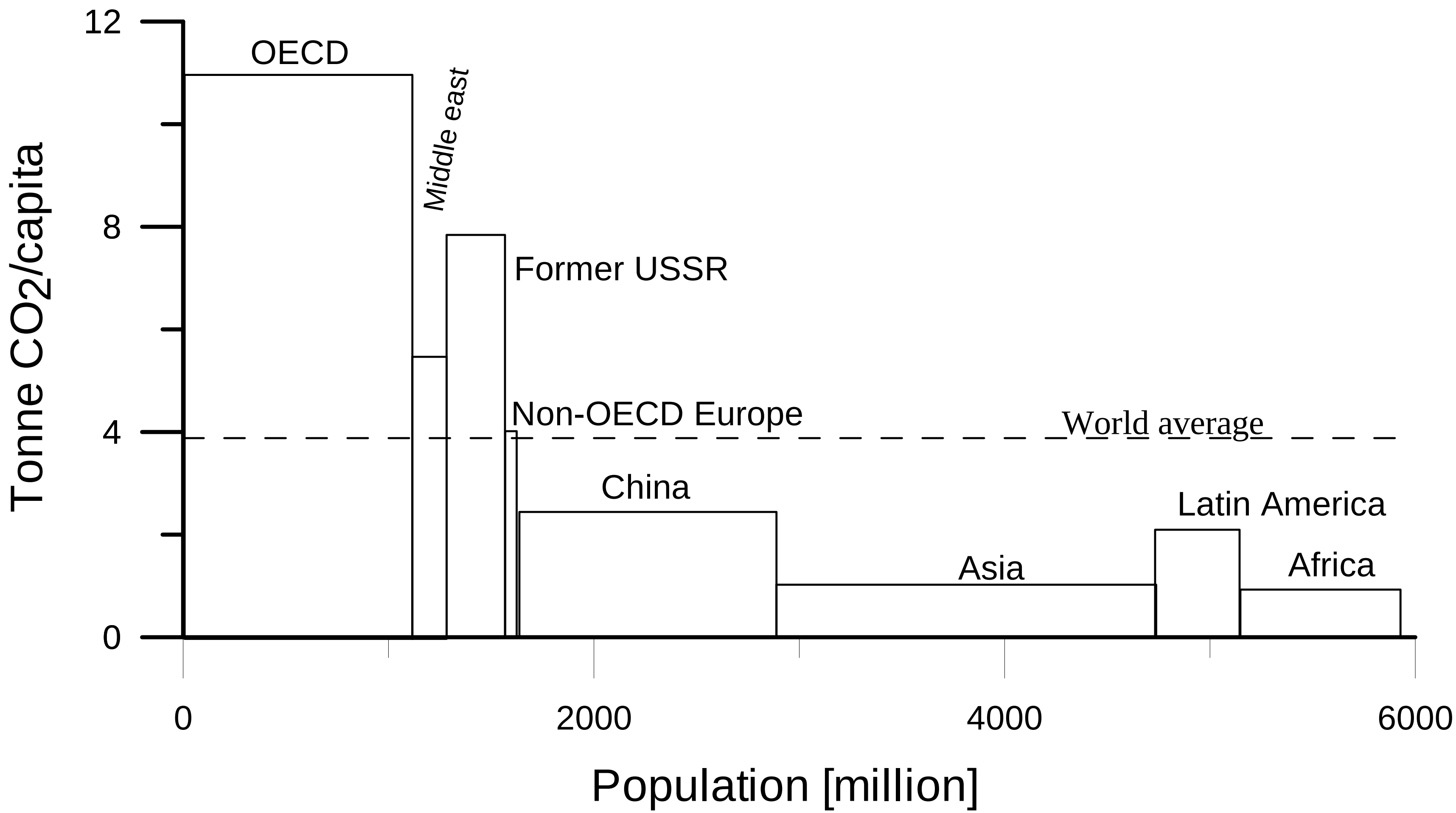

Temperature History of the Northern Hemisphere
Reconstructed Temperatures
Observed Temperatures
370 ppm
Atmospheric CO2 concentration
280 ppm
Temperature Anomaly (°C)
.8
.6
.4
.2
0
-.2
-.4
-.6
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Year

Table SPM.5: Characteristics of post-TAR stabilization scenarios [Table TS 2, 3.10][37]

Category	Radiative Forcing	CO_2 Concentration[39]	CO_2-eq Concentration[39]	Global mean temperature increase above pre-industrial at equilibrium, using "best estimate" climate sensitivity[38, 39]	Peaking year for CO_2 emissions[40]	Change in global CO_2 emissions in 2050 (% of 2000 emissions)[40]	No. of assessed scenarios
	W/m²	ppm	ppm	ºC	Year	percent	
A1	2.5 – 3.0	350 – 400	445 – 490	2.0 – 2.4	2000 - 2015	-85 to -50	6
A2	3.0 – 3.5	400 – 440	490 – 535	2.4 – 2.8	2000 - 2020	-60 to -30	18
B	3.5 – 4.0	440 – 485	535 – 590	2.8 – 3.2	2010 - 2030	-30 to +5	21
C	4.0 – 5.0	485 – 570	590 – 710	3.2 – 4.0	2020 - 2060	+10 to +60	118
D	5.0 – 6.0	570 – 660	710 – 855	4.0 – 4.9	2050 - 2080	+25 to +85	9
E	6.0 – 7.5	660 – 790	855 – 1130	4.9 – 6.1	2060 - 2090	+90 to +140	5
Total							177

Summary for Policymakers, IPCC Fourth Assessment Report, Working Group III, (Draft May 5, 2007)

Per Capita CO_2 Emissions



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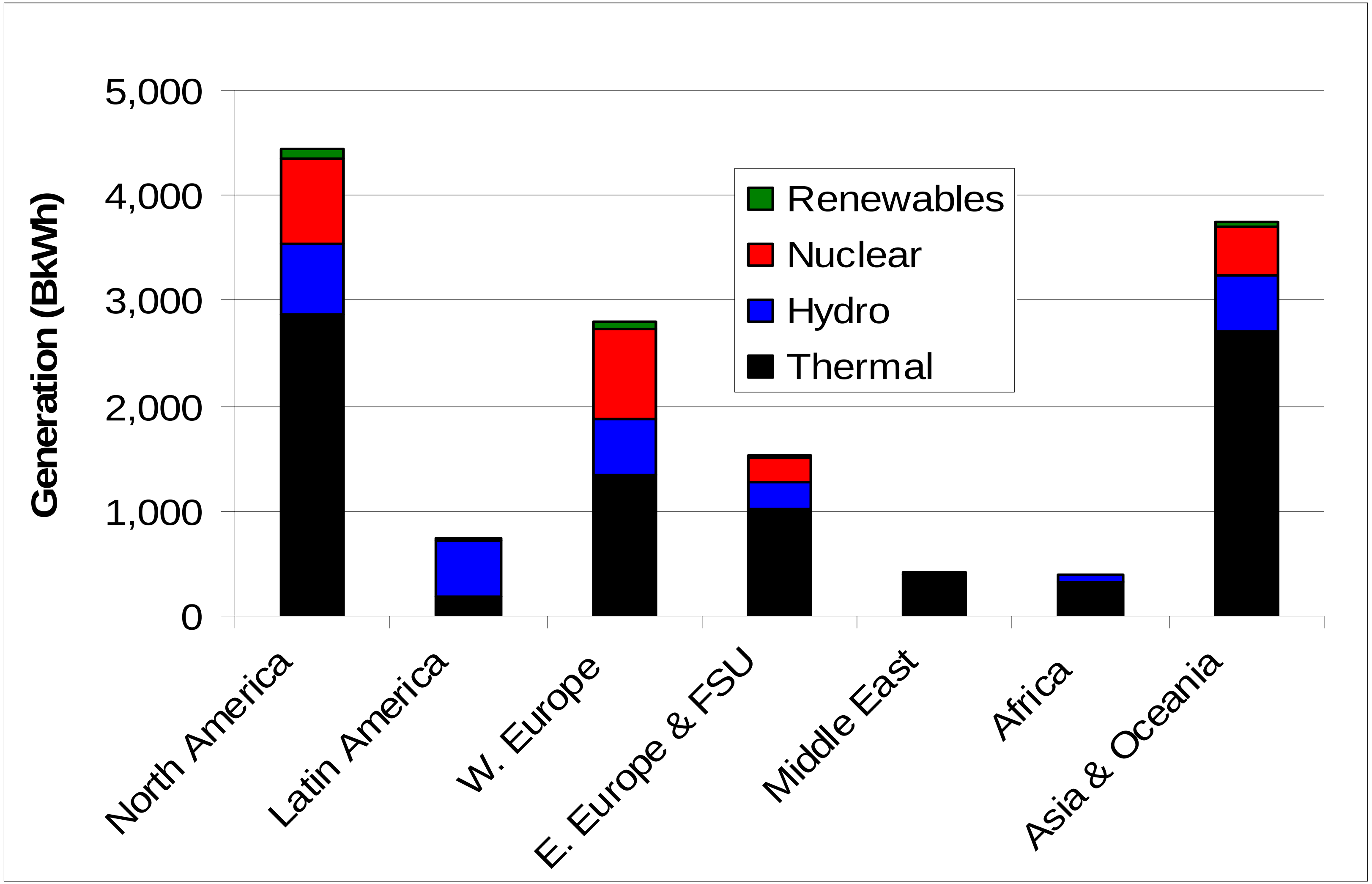
Global Power Generation by Fuel



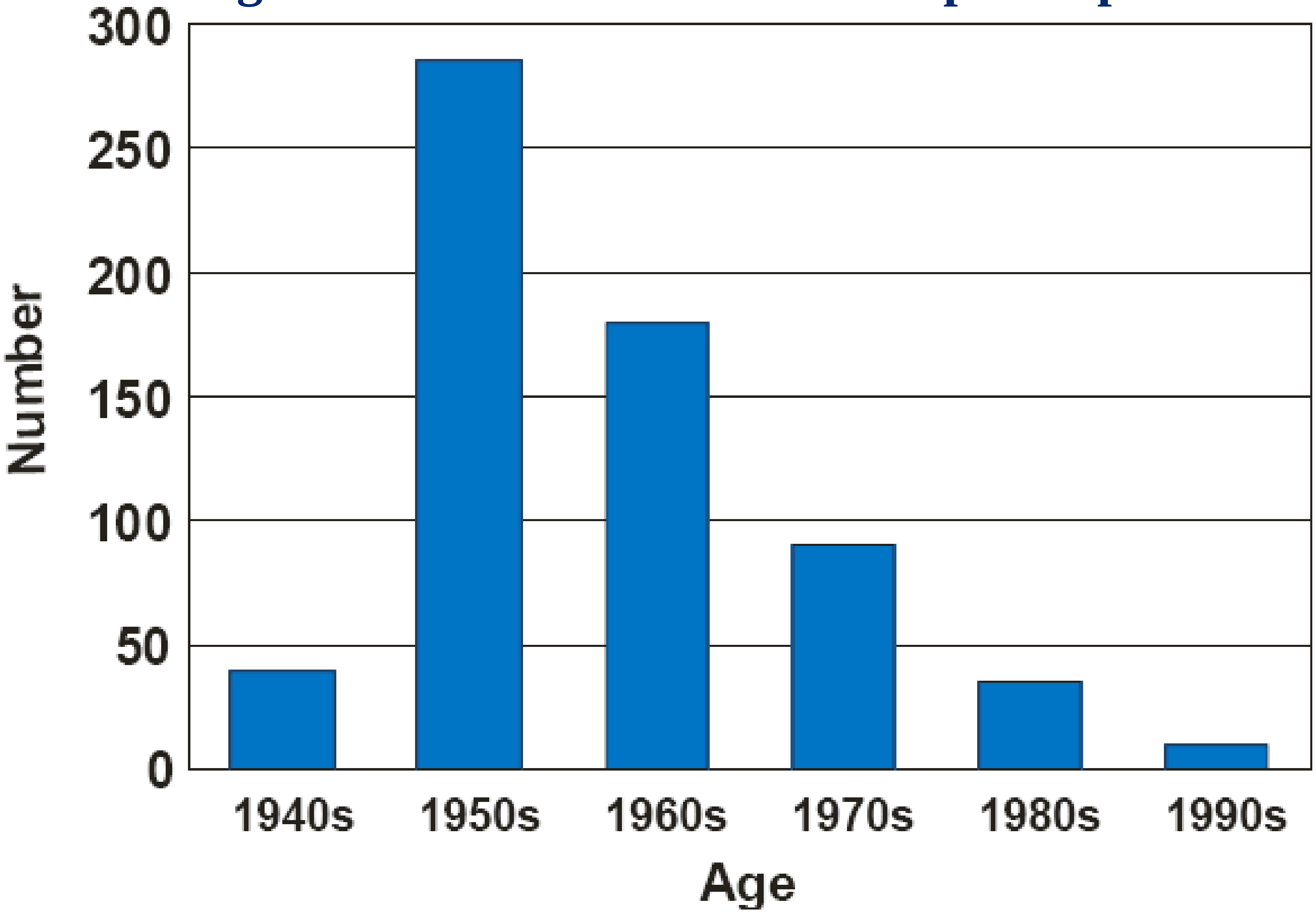
Alternatives towards Sustainable Energy Systems - General

- To use less energy
  - Population
  - Technology
  - affluence and life style
  - efficiency measures
- To shift fuel
  - Renewable energy
  - Nuclear
  - Coal to gas
- To Capture and Store CO_2
  - From large point sources (power plants, industry, hydrogen from fossil fuels)
  - Carbon sequestration (Land Use Change and Forestation-LUCF)

Power generation

Large need for investments in boiler capacity

Age distribution of US coal fired power plants



FOSSIL FUEL POWER GENERATION - STATE-OF-THE-ART" PowerClean Thematic Network, 2005, http://www.cleanpowernet.net/

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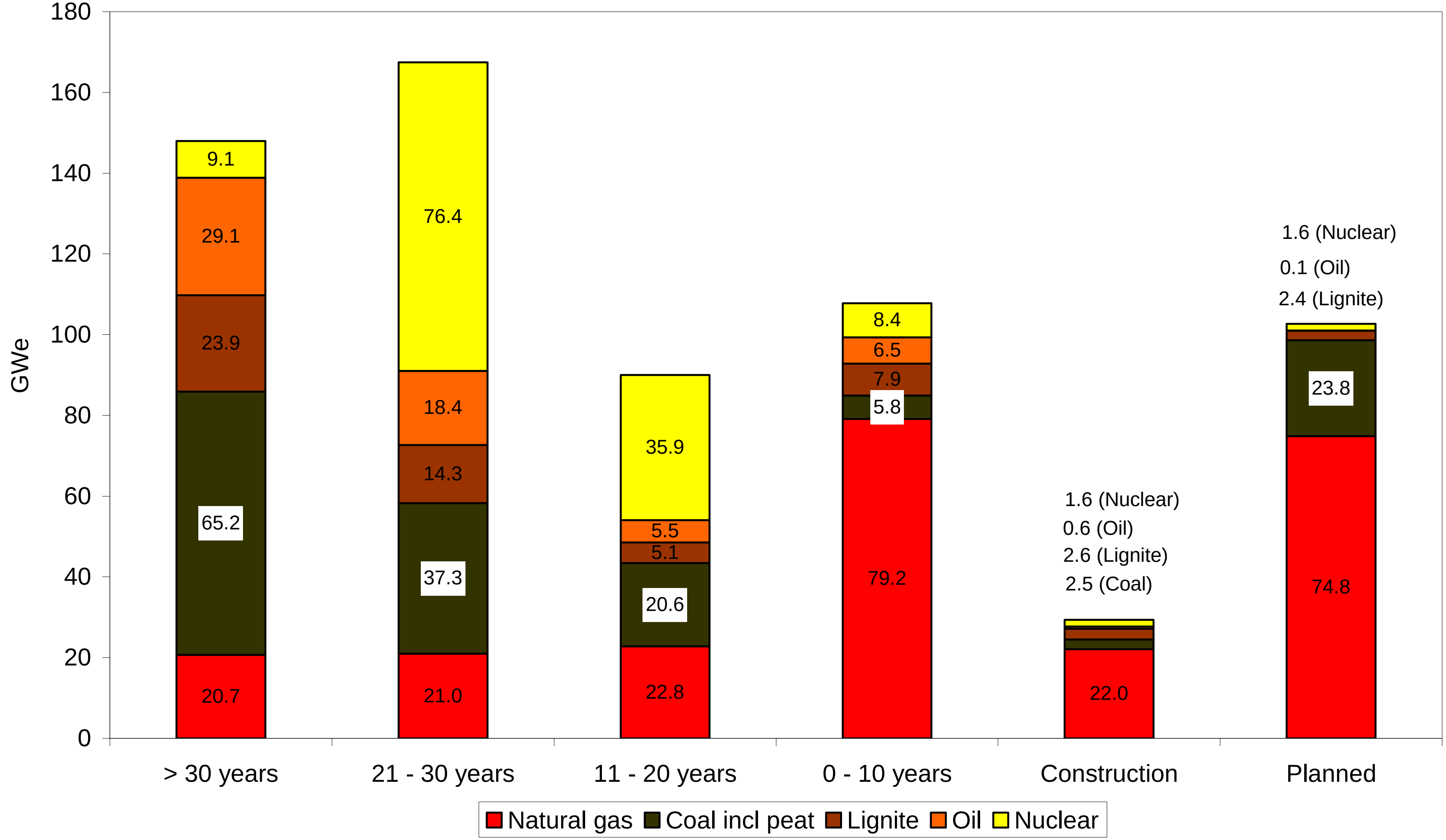
Net capacity of operating and planned thermal power plants in EU-25 distributed by fuel and age



Kjärstad, J., Johnsson, F., "The European power plant infrastructure—Presentation of the Chalmers energy infrastructure database with applications", *Energy Policy 35*, 2007, pp3643-3664

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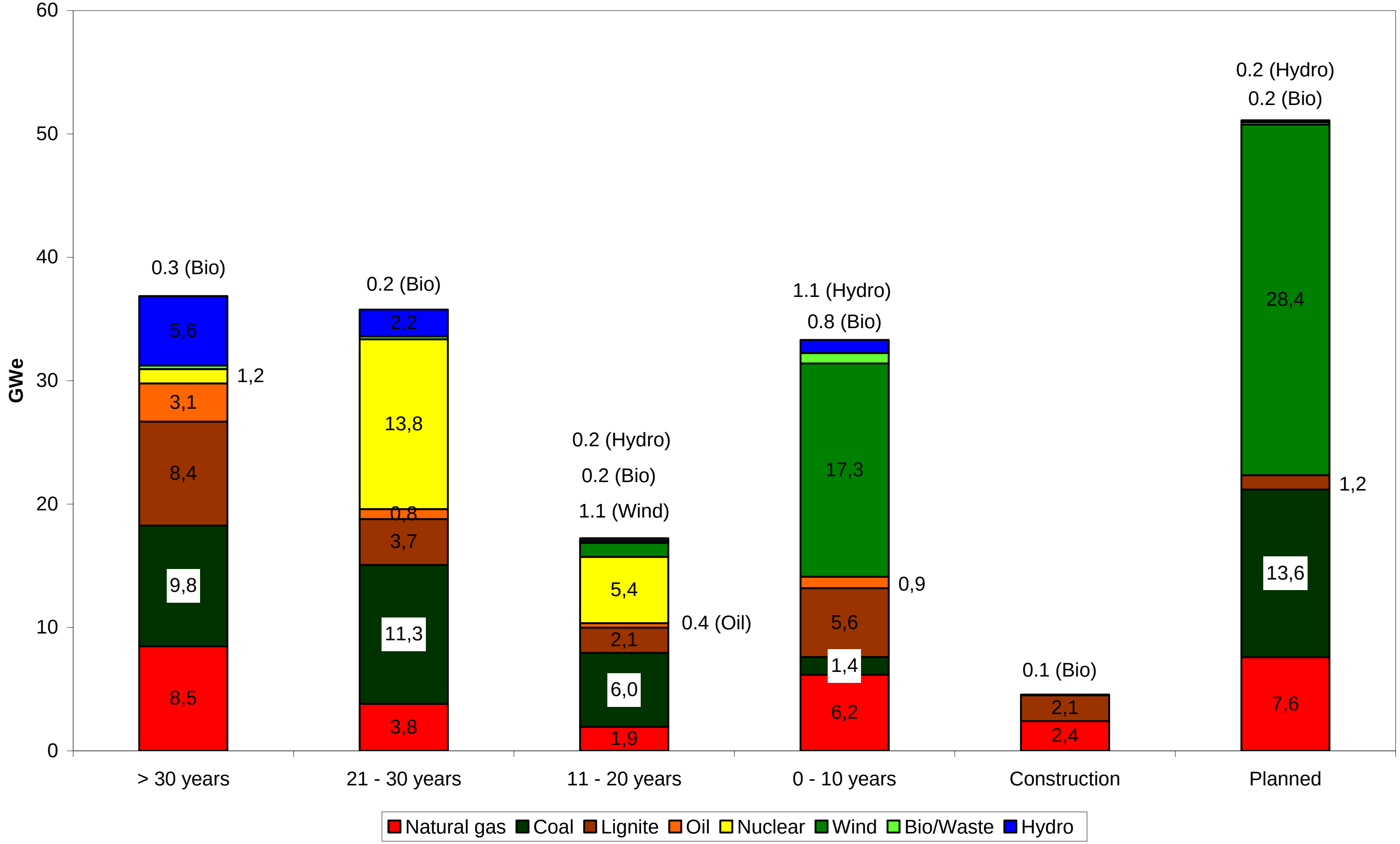
Power generation capacity - Germany



Kjärstad, J., Johnsson, F., "The European power plant infrastructure—Presentation of the Chalmers energy infrastructure database with applications", *Energy Policy 35*, 2007, pp3643-3664

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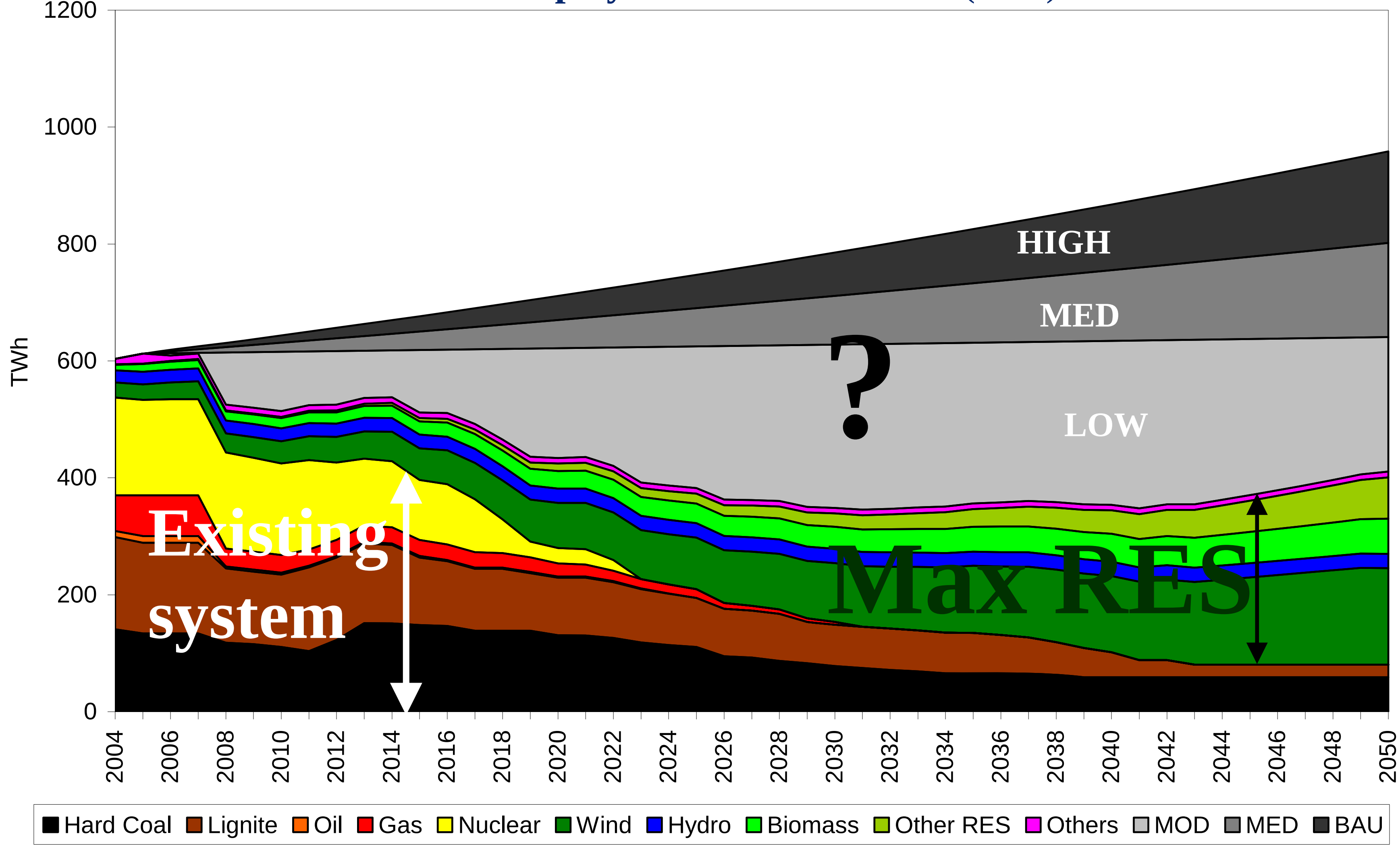
The challenge – Example Germany

Phase out of fossil and nuclear generation in Germany together with estimated “**maximum realistic deployment**” of renewables (RES) 2004-2050



Kjärstad, J., Johnsson, F., “The European power plant infrastructure—Presentation of the Chalmers energy infrastructure database with applications”, *Energy Policy 35*, 2007, pp3643-3664

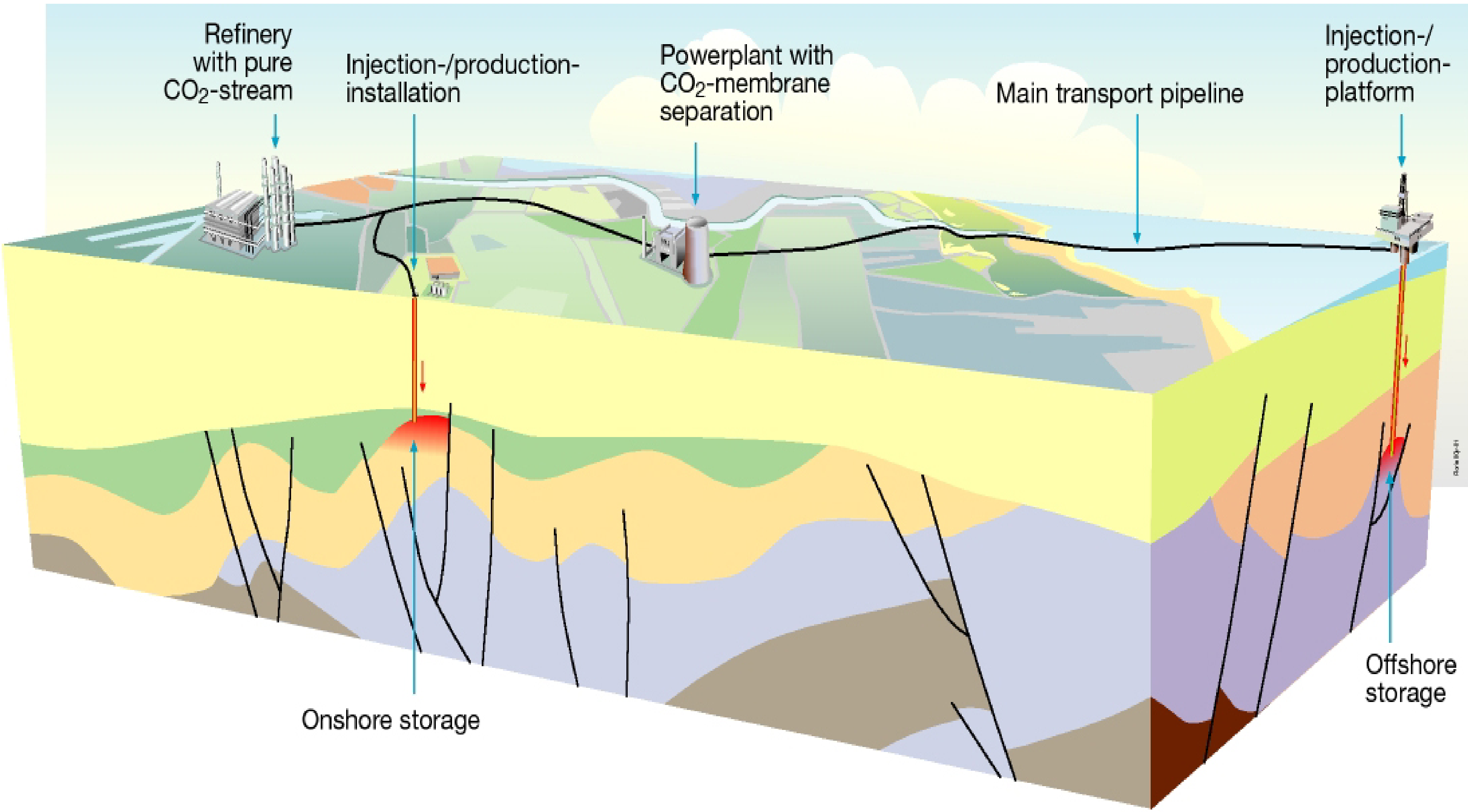
RES and Energy efficiency not likely to be sufficient
We need bridging technologies:

1. Nuclear (life time extensions + new installations)
2. Fossil with CO2 capture
3. Co-firing biomass with coal
4. Coal to gas (but feasible?)
5. CHP with waste as fuel (increased use of DH)

- 2, 3 and 5 are possible markets for FBC together with biomass and waste in CHP with FBC technology

- CO_2 Capture and Storage as a bridging technology

CO_2 Capture, Transport & Storage (CCS)



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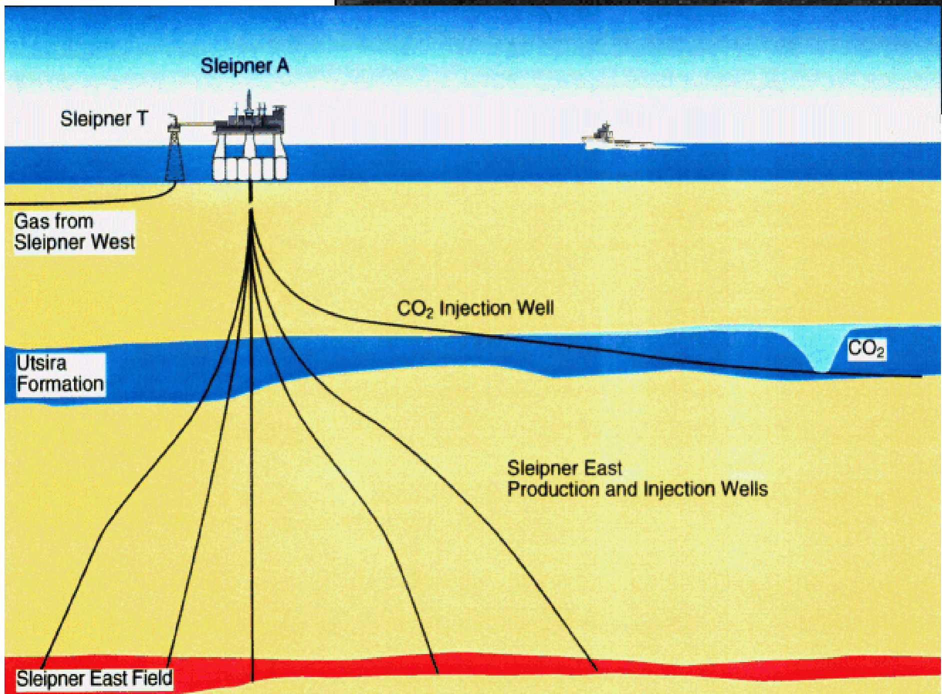
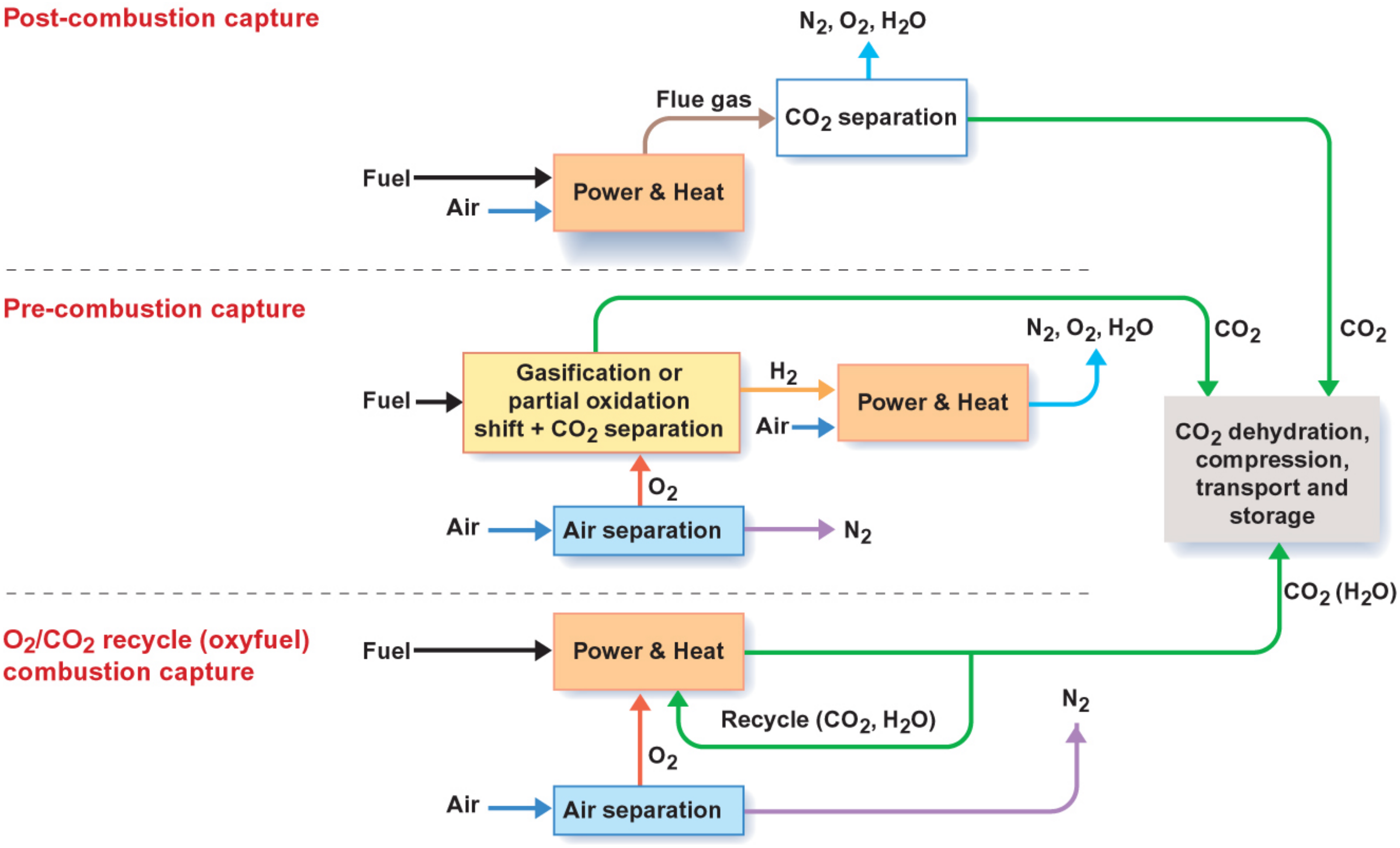


Storage

1 Mt/year – pilot project in the North See since 1996

CO2 Capture – main technologies



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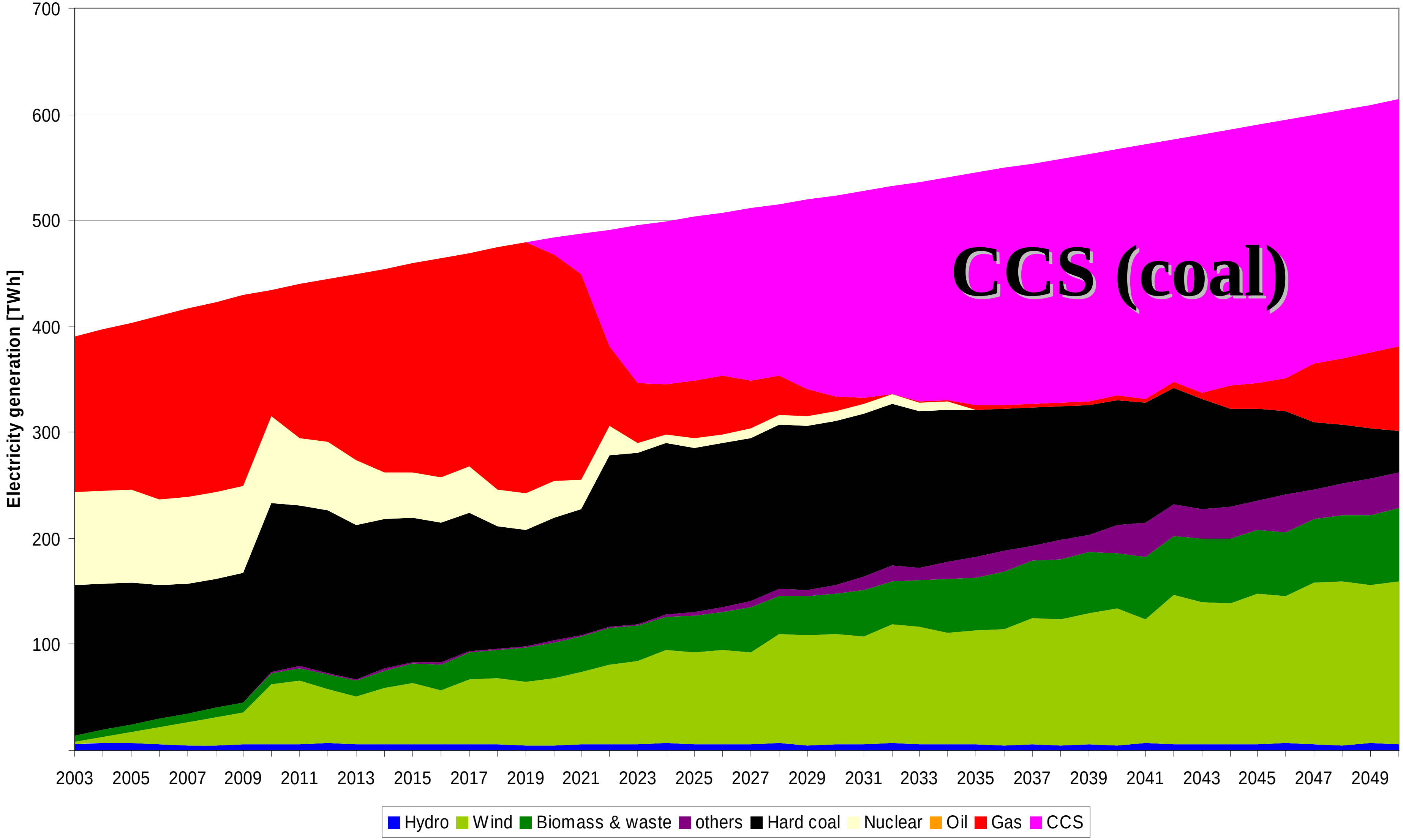
Example UK

60% CO2 reduction by 2050, Fuel costs and demand from EU Energy & Transport Trends 2030 (2005 edition), extrapolated to 2050



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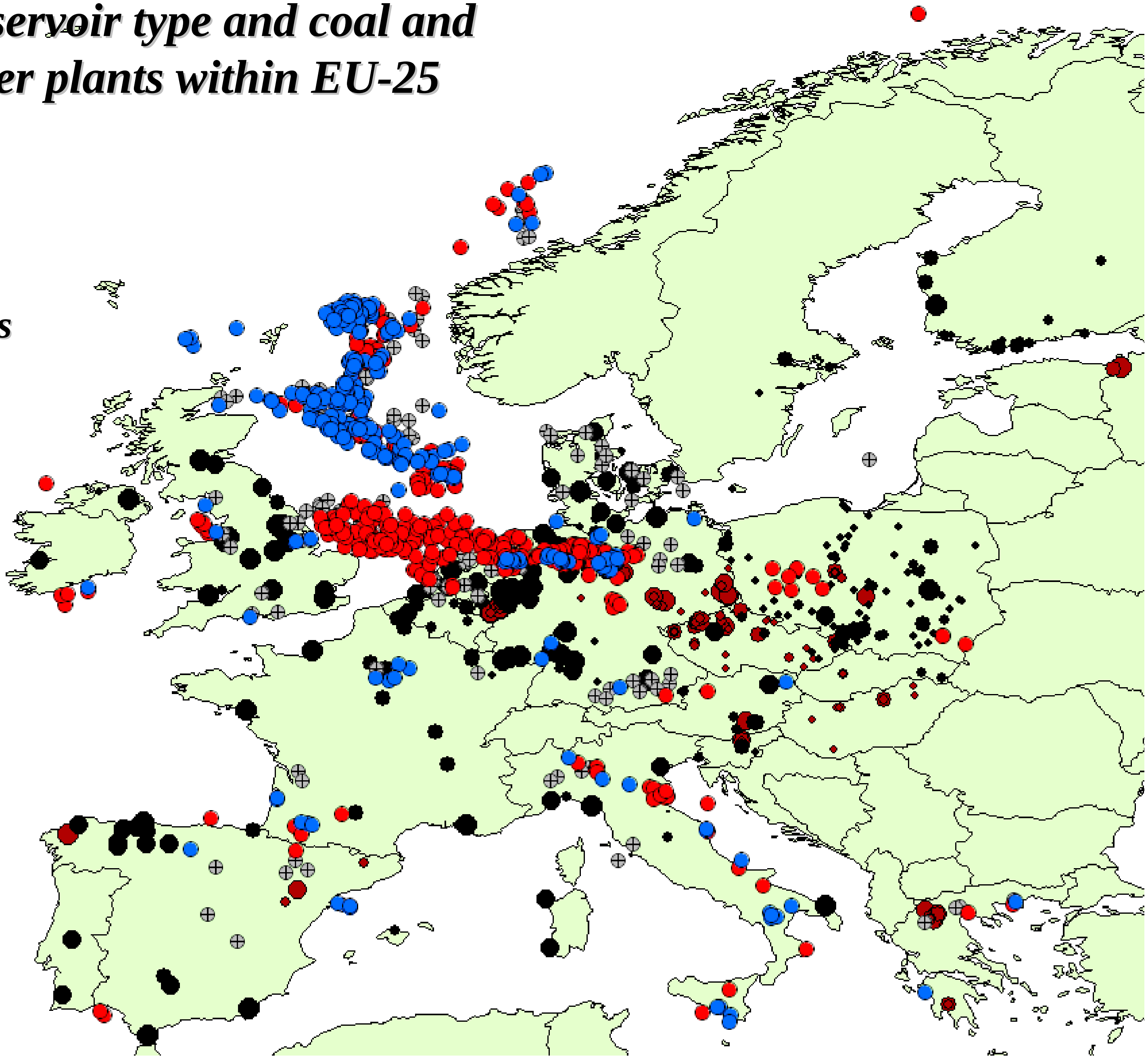
Storage sites by reservoir type and coal and lignite fuelled power plants within EU-25 plus Norway

Blue = oil fields
Red = gas fields
Crossed grey = aquifers

Black = coal plants
Brown = lignite plants



- Co-firing as a bridging technology

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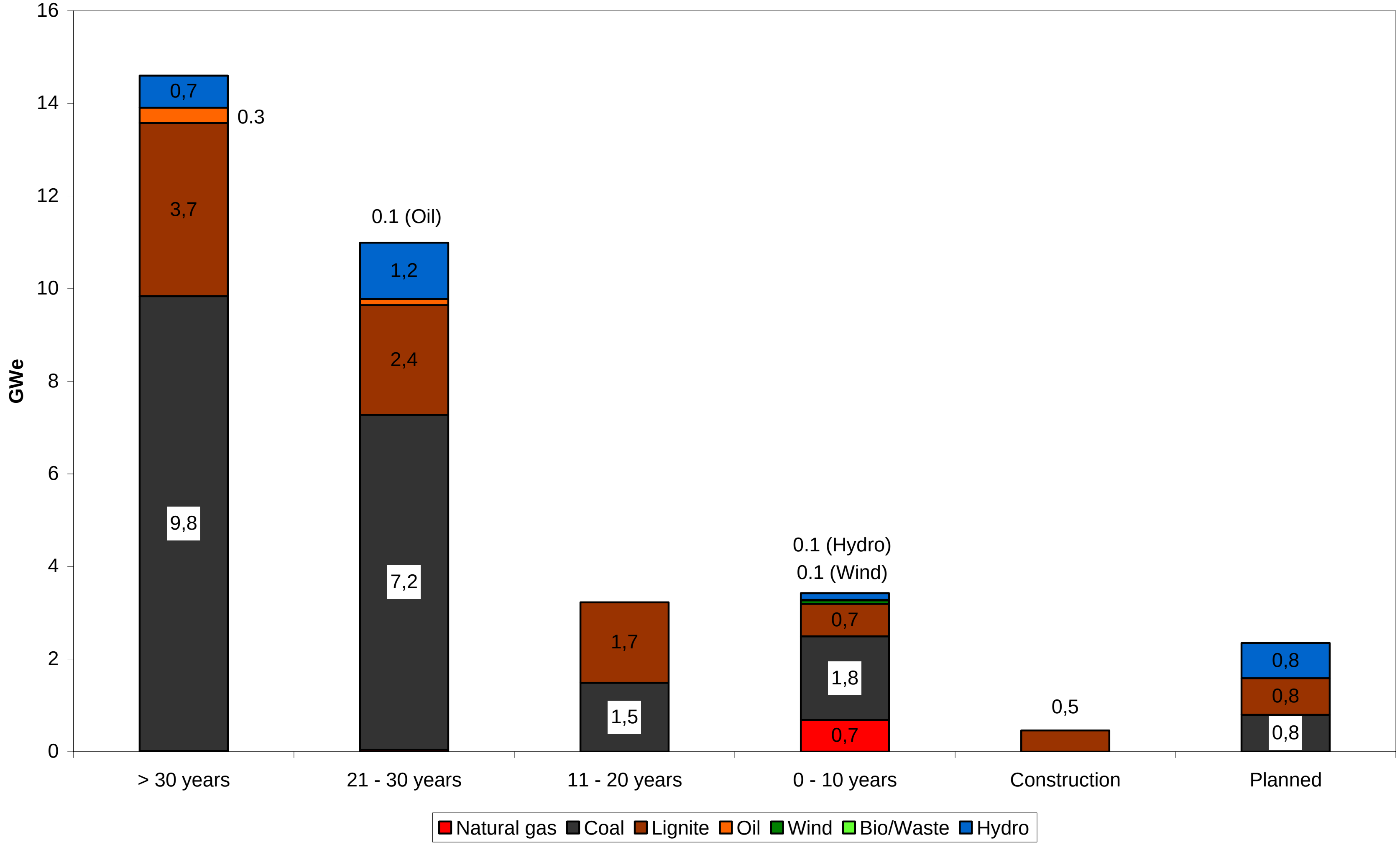
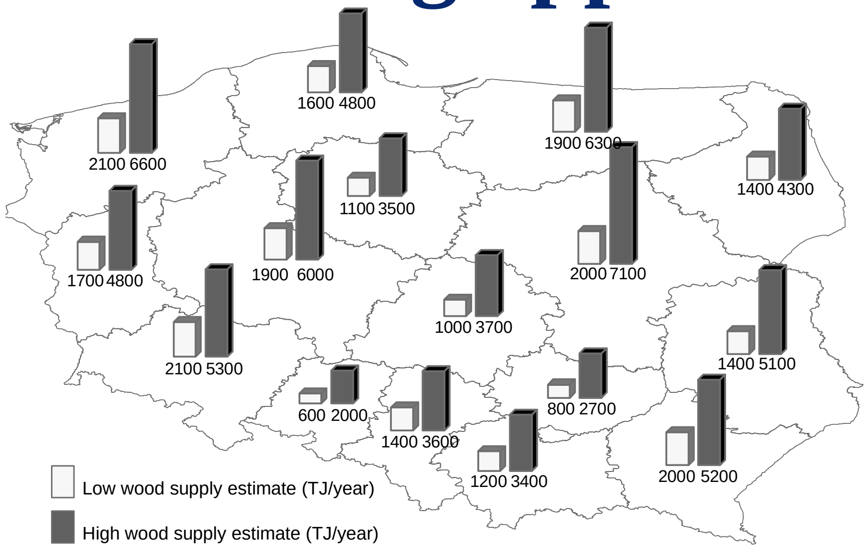
Power generation capacity - Poland

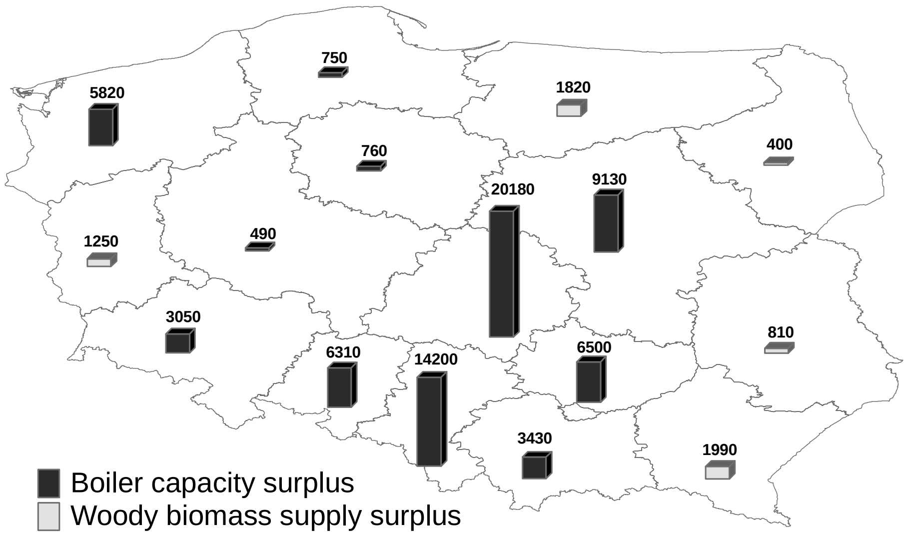


Kjärstad, J., Johnsson, F., Chalmers power plant database

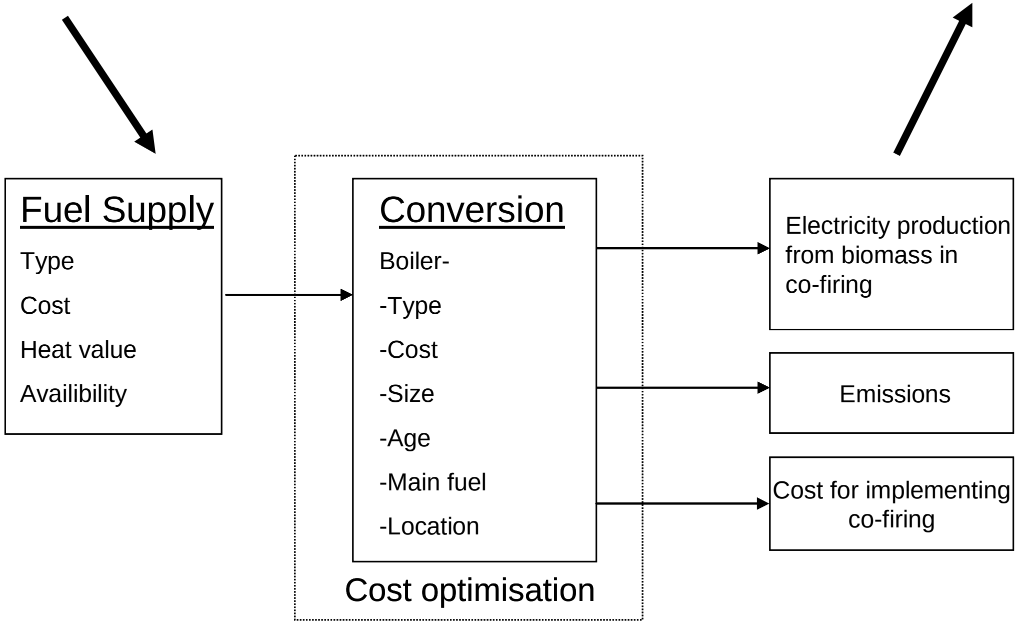
Example of repowered power plant - FB boilers in Turow (Bogatynia)

Co-firing opportunities in 2010 and 2020





Poland



Low-cost CO_2 avoidance option

Johnsson, F., Berndes, G., Berggren, M., *World Bioenergy Conference & Exhibition, 30 May-1 June 2006, Jönköping*

- The FBC market

Fluidized Bed Combustion

- Originates from the need to burn difficult low grade fuels of varying quality
- Ability to burn various fuels in the same unit
- Good load following characteristics
- Possibility for in-bed sulphur removal and low NOx emissions (low combustion temperature) and that without any need for special DeSOx or DeNOx equipment

For reviews on history of the FBC development see Banales and Norberg-Bohm (*Energy Policy 30*, 2002, p 1173) and Koornneef et al. (*Prog. Energy and Combustion Science 33*, 2007, p 19)

For FBC reviews see e.g. Leckner (*Prog. Energy and Combustion Sci. 24*, 1998, p 31) and previous Proc of *Fluidization conf*, *FBC conf* and *CFB conf.*

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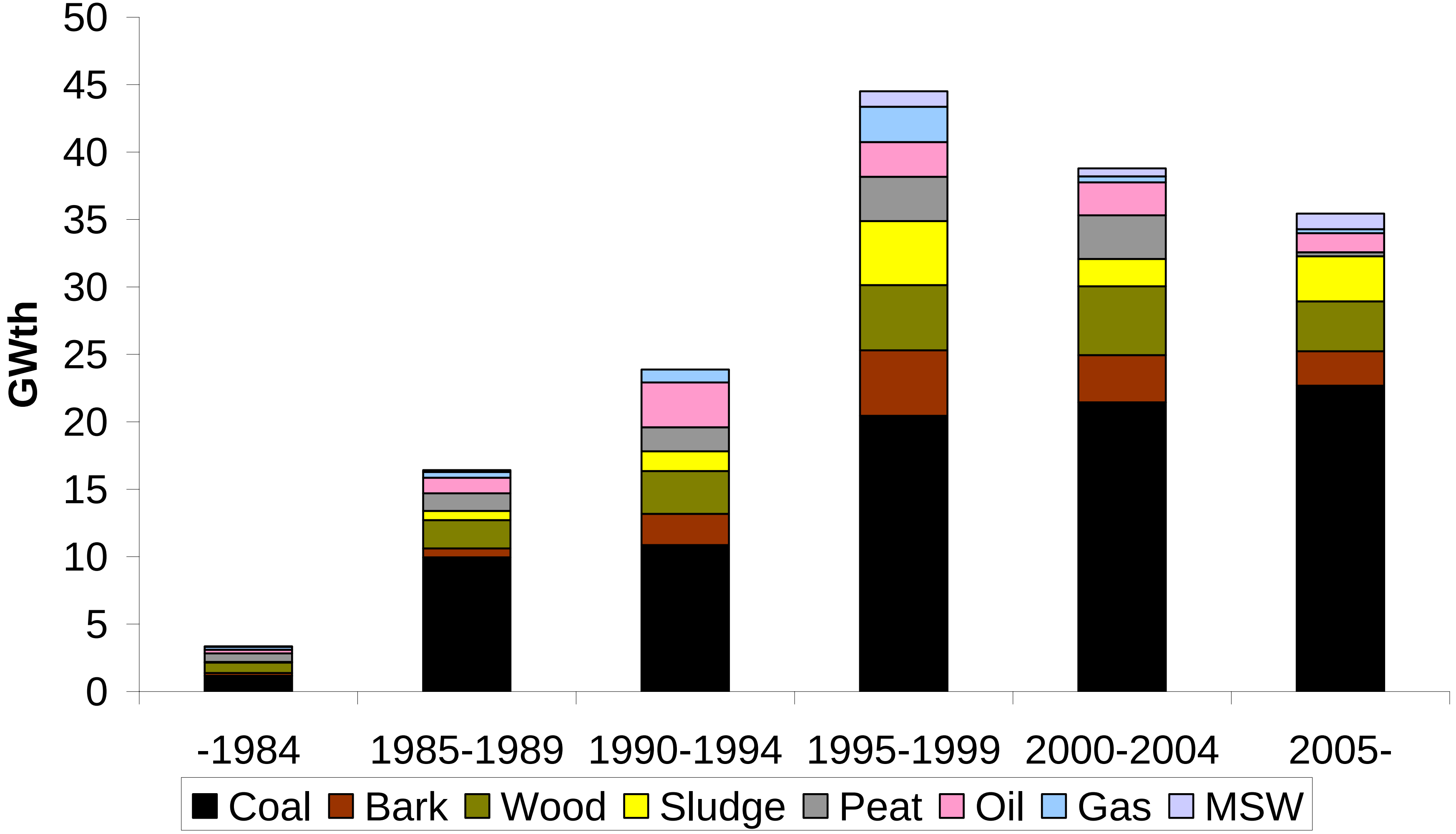
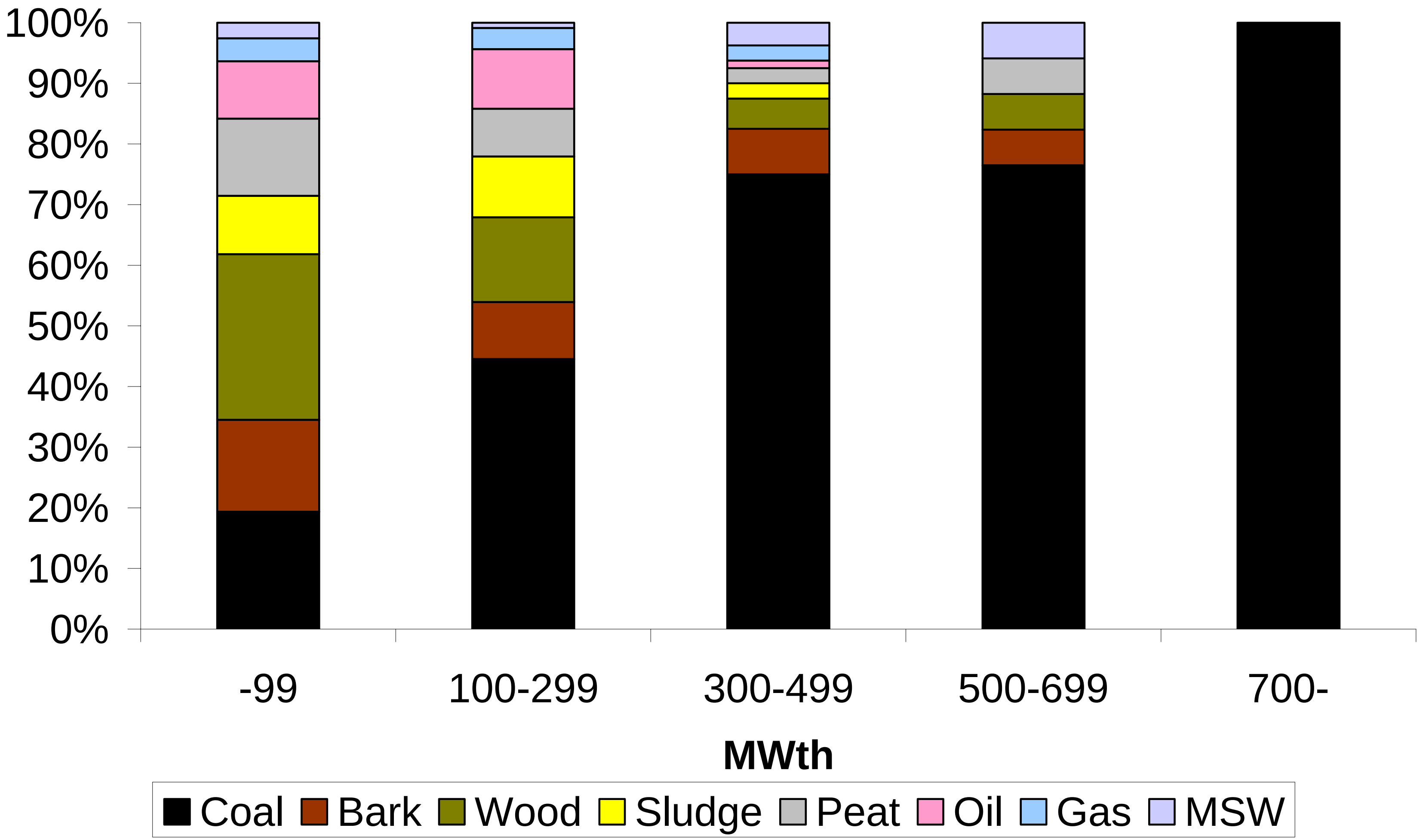
FBC installations (year of commissioning and fuel)

FBC reference lists from Alstom, Foster Wheeler and Metso Power



FBC installations (thermal rating and fuel)

FBC reference lists from Alstom, Foster Wheeler and Metso Power



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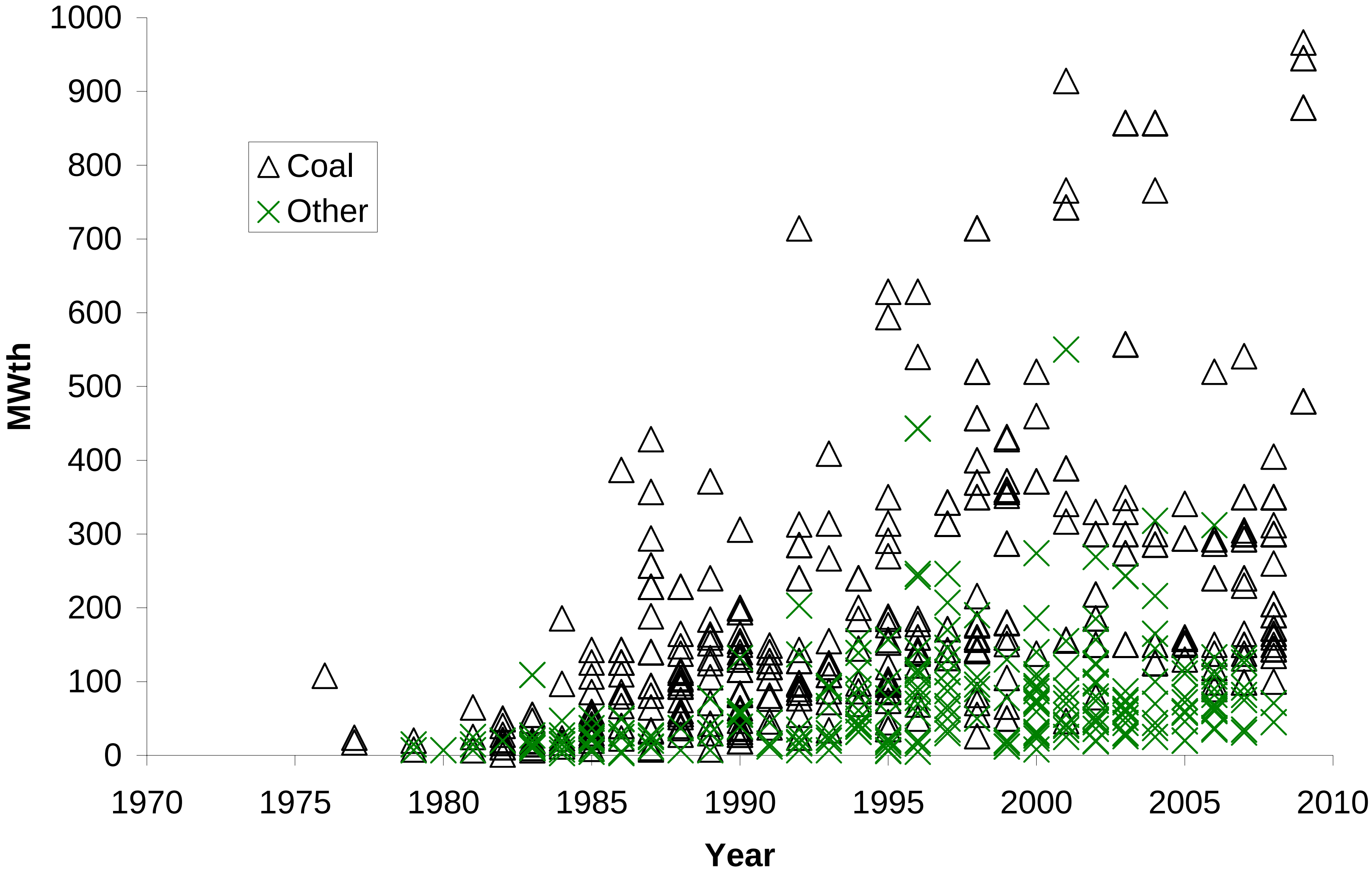
FBC installations (thermal rating, year and fuel)

FBC reference lists from Alstom, Foster Wheeler and Metso Power



FBC market

- Boilers of a capacity of less than ~ 100 MW_{th} burning waste derived fuels, including biomass, typically operating in CHP schemes (or as heat only boilers, mainly in Sweden)
  - Competing technology – grate fired boilers
- Large power boilers (up to ~1,000 MW_{th} mainly burning coal (bituminous coal or lignite),
  - Competing technology – PC boilers

Fuel flexibility will be increasingly important?

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Future of FBC technology in a CO_2 constrained world

- If climate target to be met, coal plants must be equipped with CO_2 capture!
- Current EU target is that all new coal fired plants should have capture from 2020 and on (even stricter target is required if to meet new IPCC target for max 2 ºC temperature increase)

⇒ Also FBC power boilers must be with capture!

⇒ Increase in biomass and waste combustion and CHP schemes can be expected

⇒ Development of new concepts such as CLC

⇒ New FB gasification concepts (biomass, coal with biomass)

FBC and fluidization

- Flow characteristics
- R&D need *related to Fludization*

FBC characteristics

- A height to diameter (aspect) ratio of the riser (H_0 / D_{eq}) of the order of or less than 10
- A ratio of settled bed height (the bed formed if the solids are not fluidized) to riser diameter of less than 1 ($H_{b,settled} / D_{eq} < 1$)
- Fluidized solids belonging to group B in the Geldart classification
- For CFB units a solids net flux ($G_{s,net}$) typically ranging from 0.5 to 20 kg/m^{2}s
  - $G_{s,net}$ not known and should not be input in CFBC models
- Primary operational parameters of the furnace (with respect to fluid dynamics) are the riser pressure drop and the gas flows (i.e. fluidization velocity, secondary gas injection)

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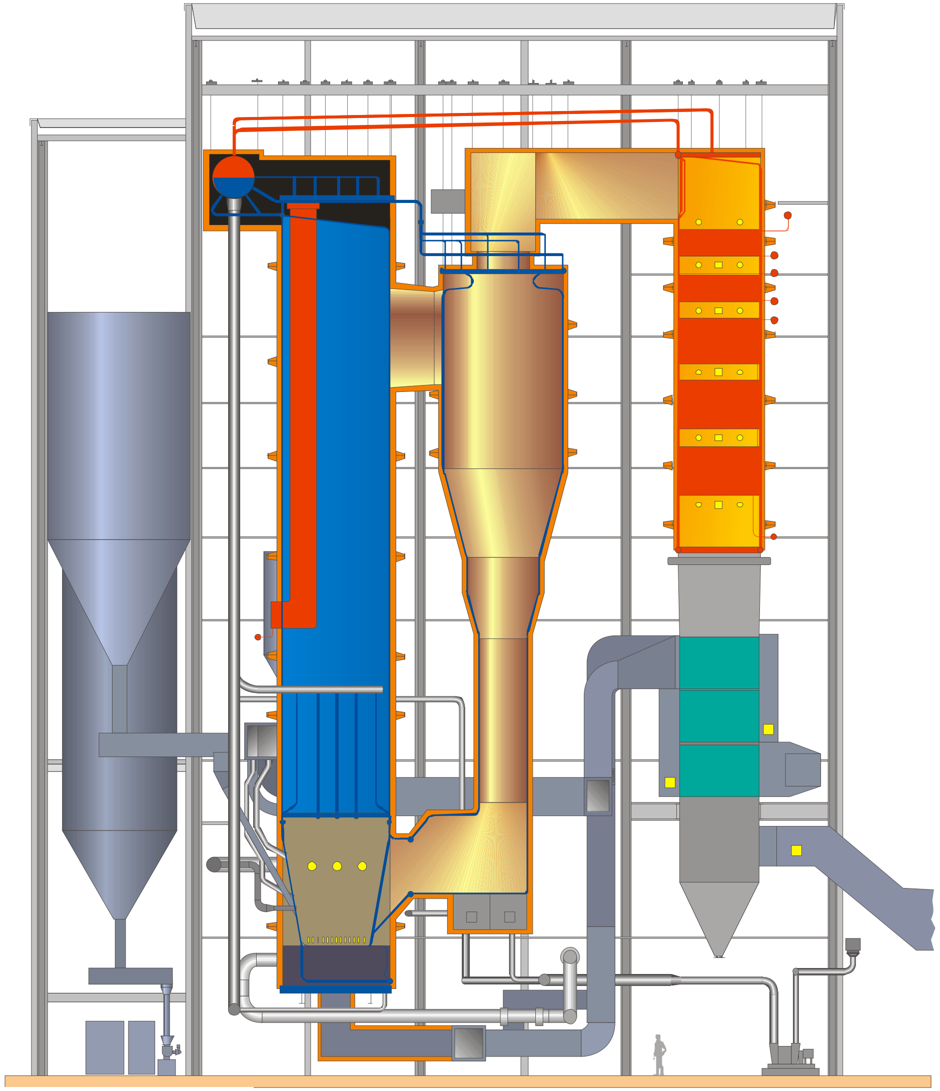
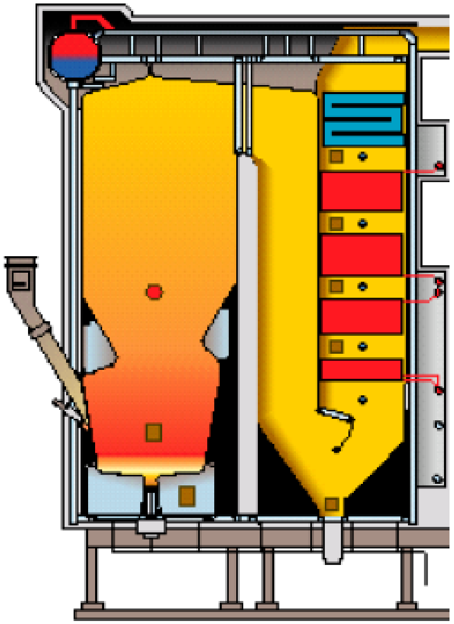
Circulating FBC



Bubbling FBC



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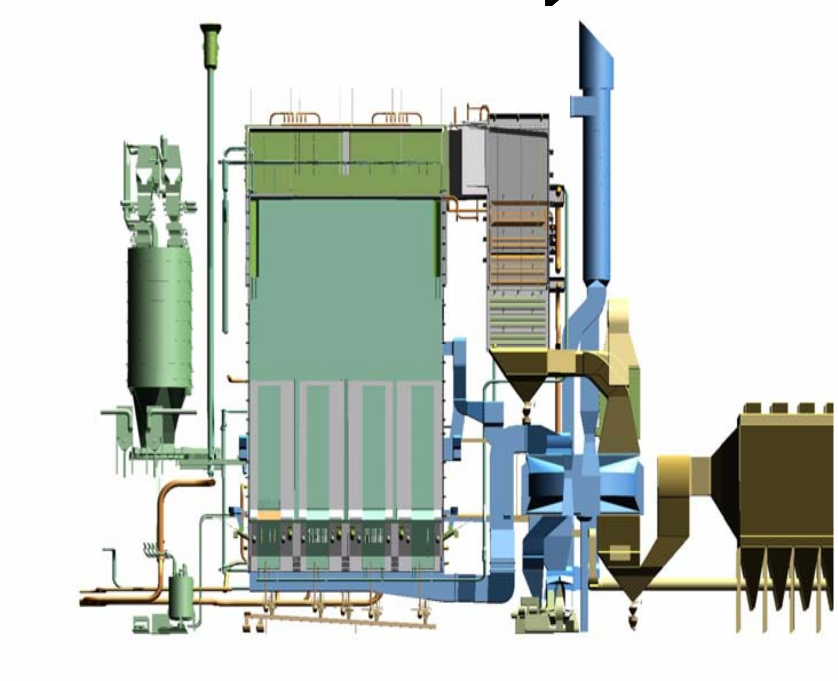
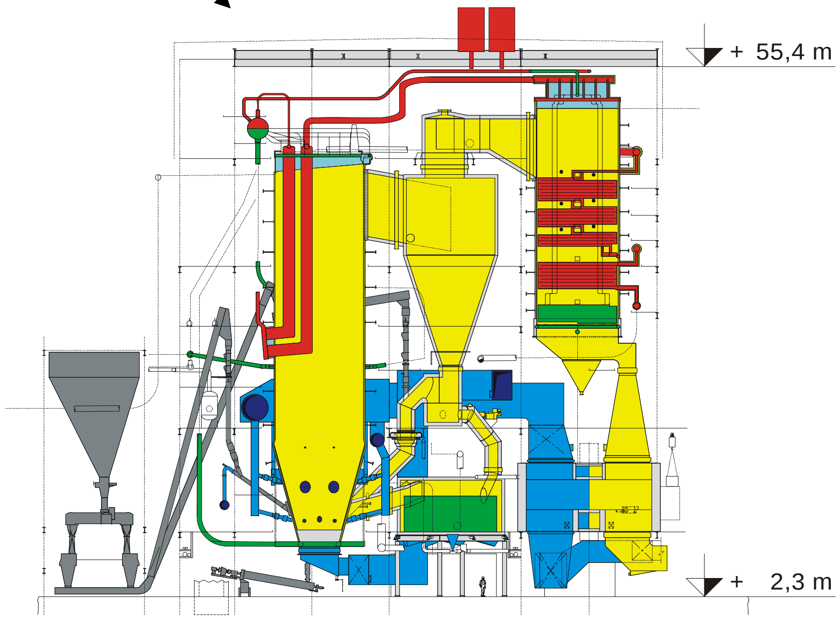
Without and with EHE



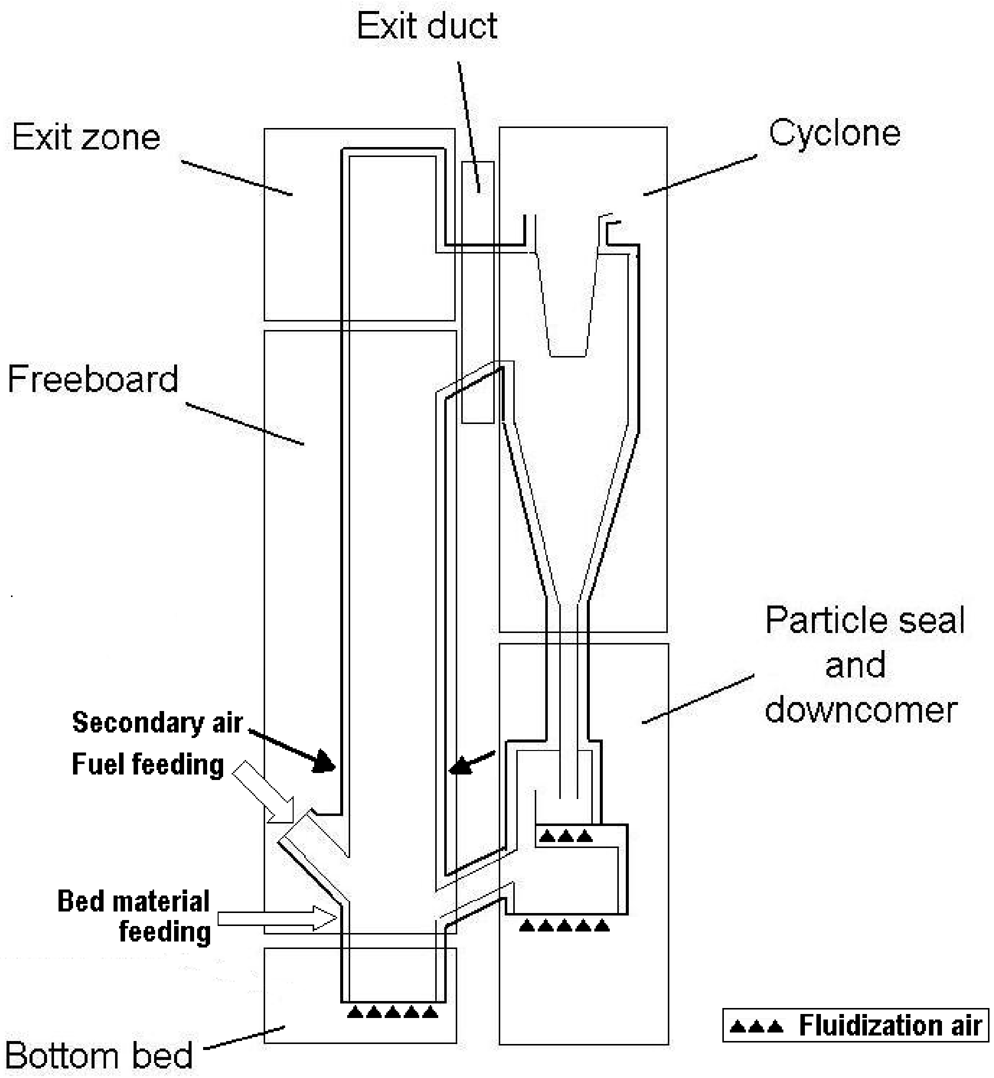


FOSTER WHEELER

ALSTOM

Flow characteristics

- Bottom bed with exploding bubbles
  - High through flow
  - High fluctuations in gas flow
  - Interaction with air plenum
  - Reducing conditions
- Freeboard
  - Splash zone with strong solids back mixing (cluster phase dominates)
  - Transport zone with backmixing at furnace walls (disperse phase flow dominates)
- Solids segregation
  - Freeboard
  - Exit
  - Exit duct
  - Cyclone



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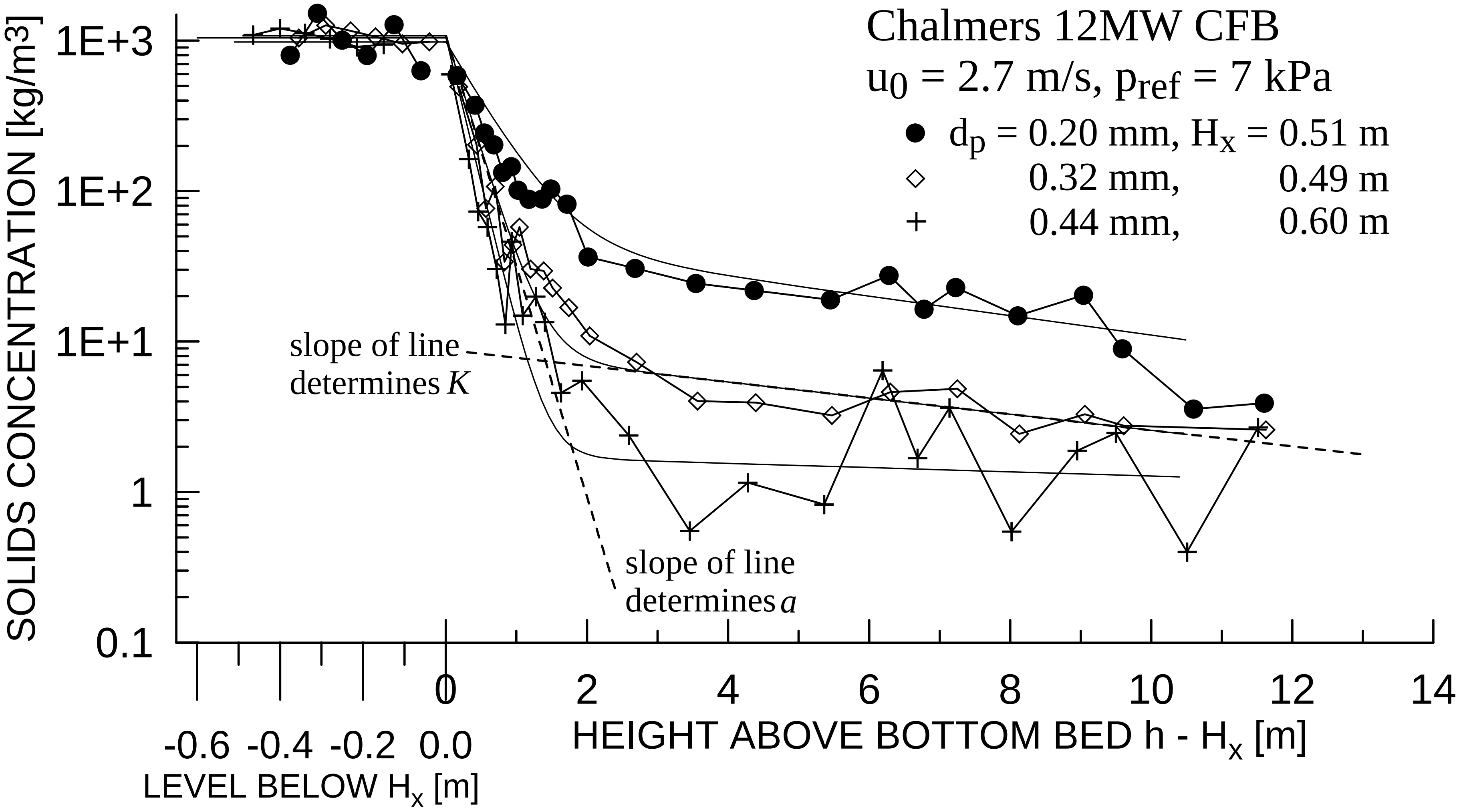
Application of Johnsson & Leckner (1995) freeboard model (with *a* and *K* decay factors)



(From Johnsson & Leckner, 1995)

Exploding bubble in bottom bed

Primary gas flow varies with time and with spatial location

Air distributor

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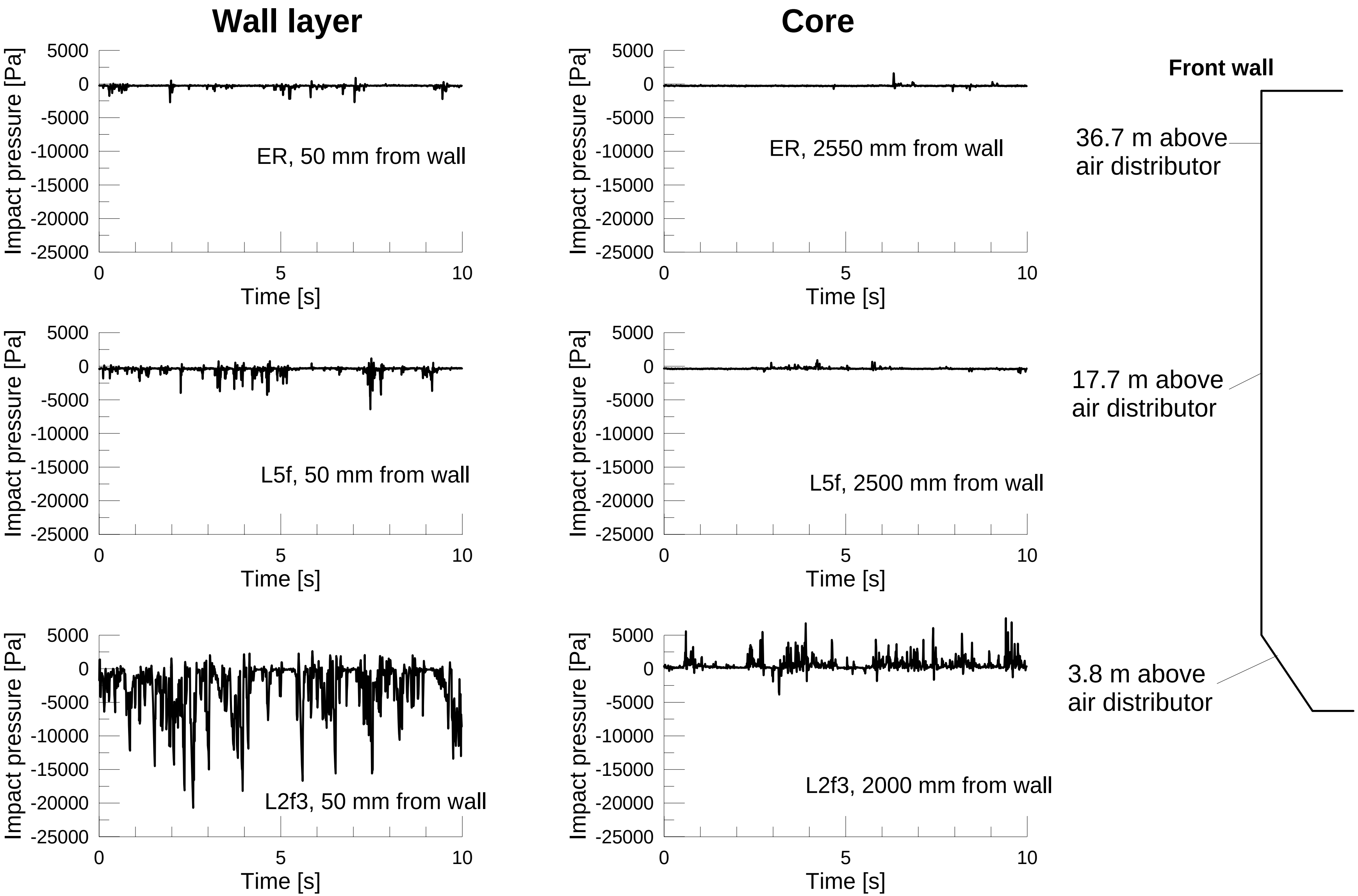
Momentum probe signals from three elevations in the Turow CFB boiler



- Need for FBC research related to fluidization

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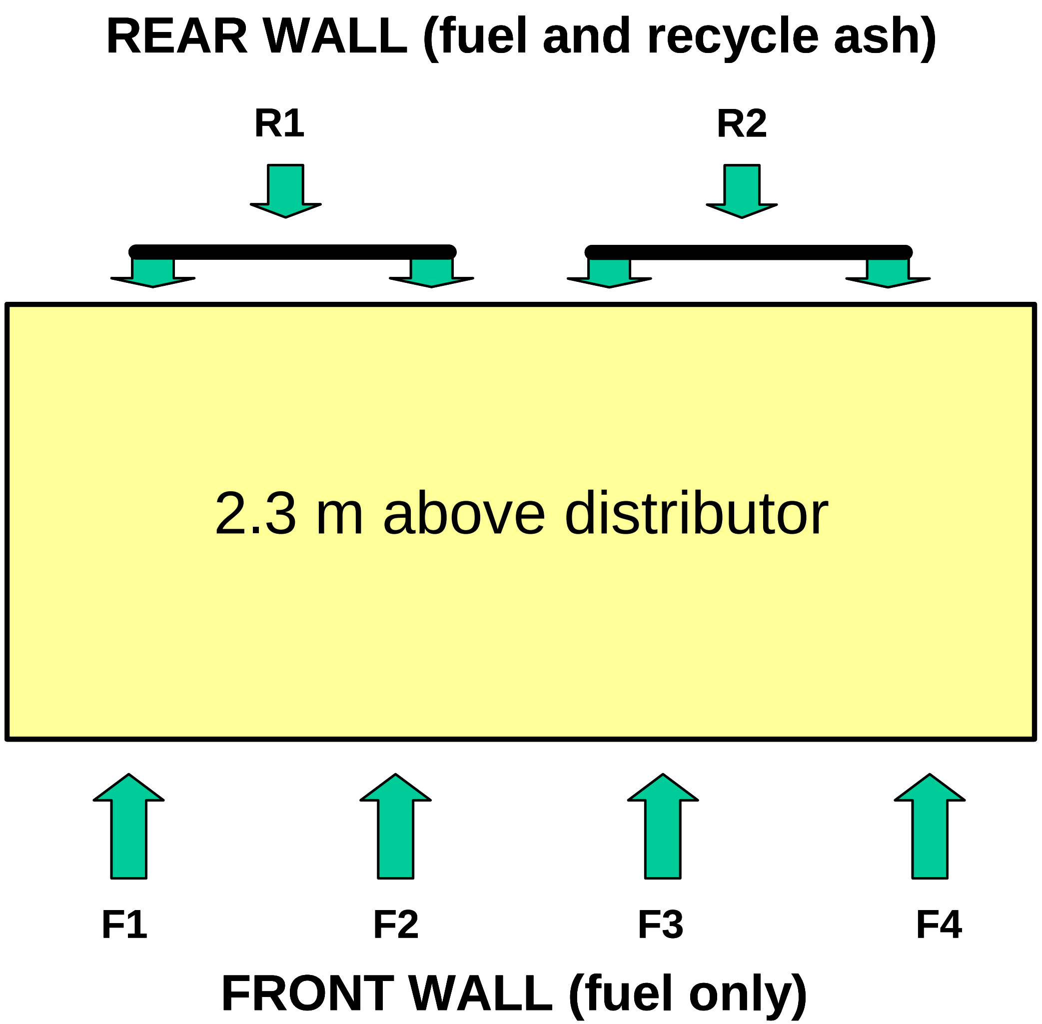
Bottom bed and Freeboard

- To increase the knowledge and modeling capabilities for prediction of mixing of fuel and combustion air
- Depends on the fuel conversion time and the characteristic mixing length. Comparison of the characteristic times for fuel dispersion and conversion:

$$Da = \frac{\tau_{dispersion}}{\tau_{conversion}} = \frac{L^{*}/r_{dispersion}}{\tau_{conversion}}$$

$\tau_{dispersion}$ = characteristic time for fuel dispersion, $r_{dispersion}$ = mixing rate, $\tau_{conversion}$ = characteristic time for fuel conversion, L^{*} = characteristic mixing length

Fuel feed distribution (Turow 235 MW_e)



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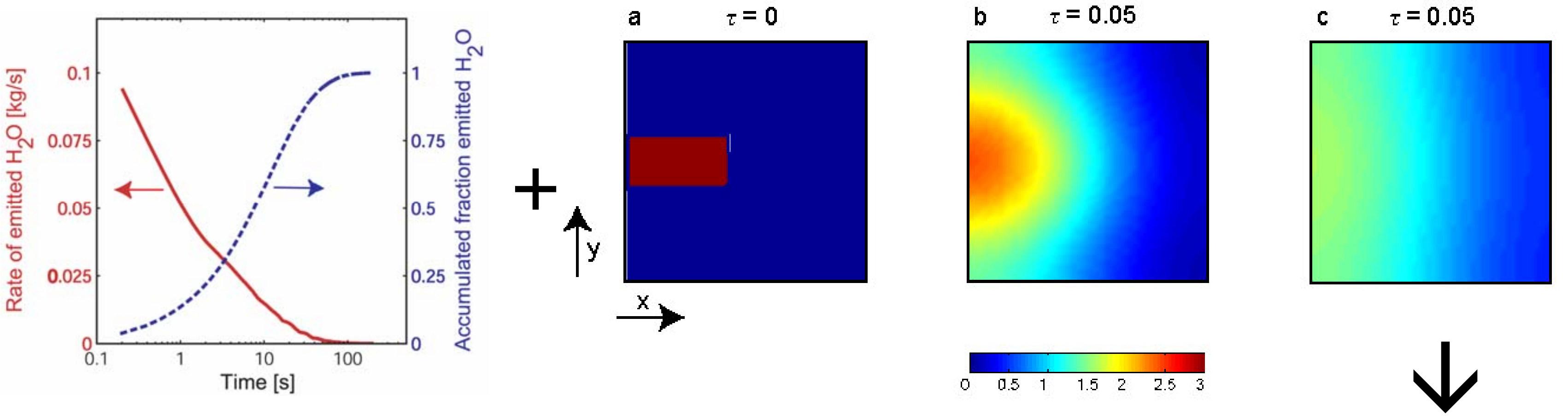
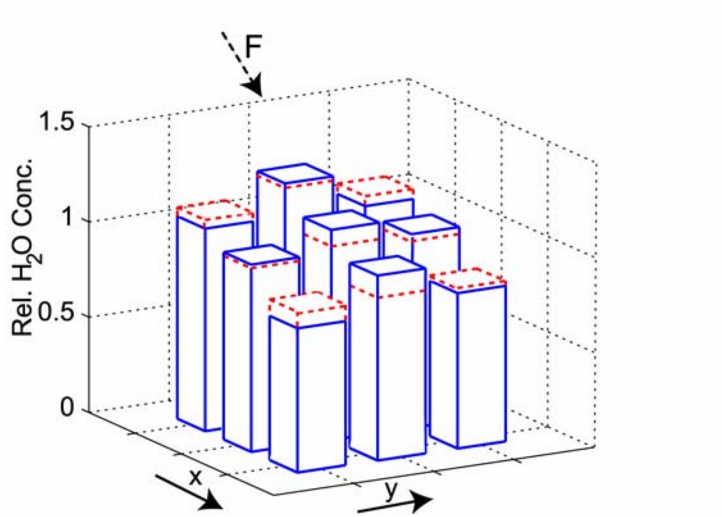
D_{sr} from modeled drying rate of fuel and measured concentrations of H_2O above the bed



Drying rate + Dispersion of fuel → Distribution of H_2O above the bed

Comparison between modeled and measured concentrations of H_2O gives best fit for $D_{sr} \approx 0.1\ m^2/s$

- **Most measurements from narrow units ⇒ lower dispersion rates**
- **Not a dispersion process**



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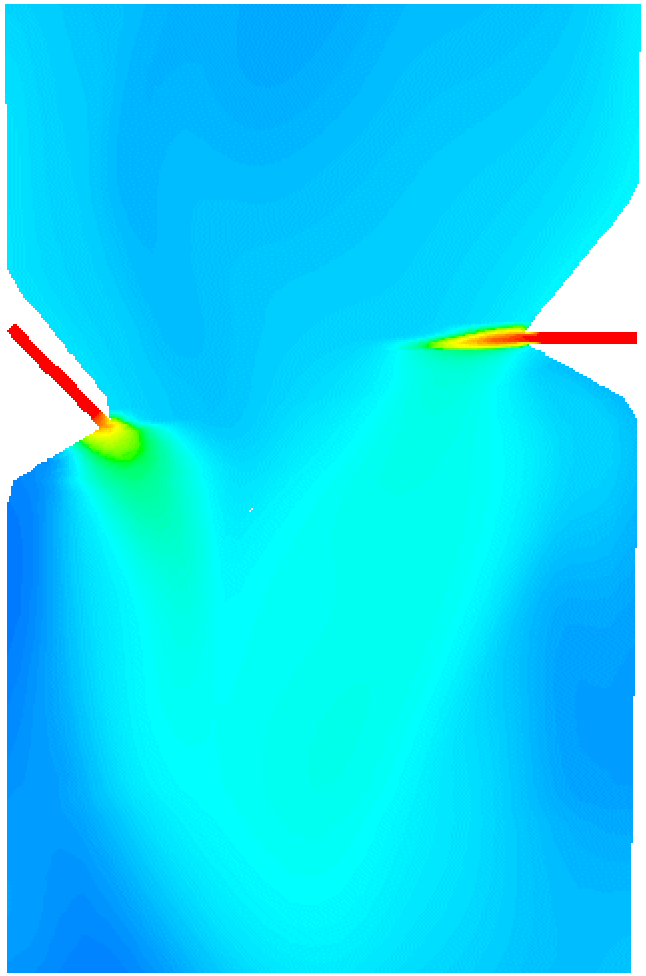
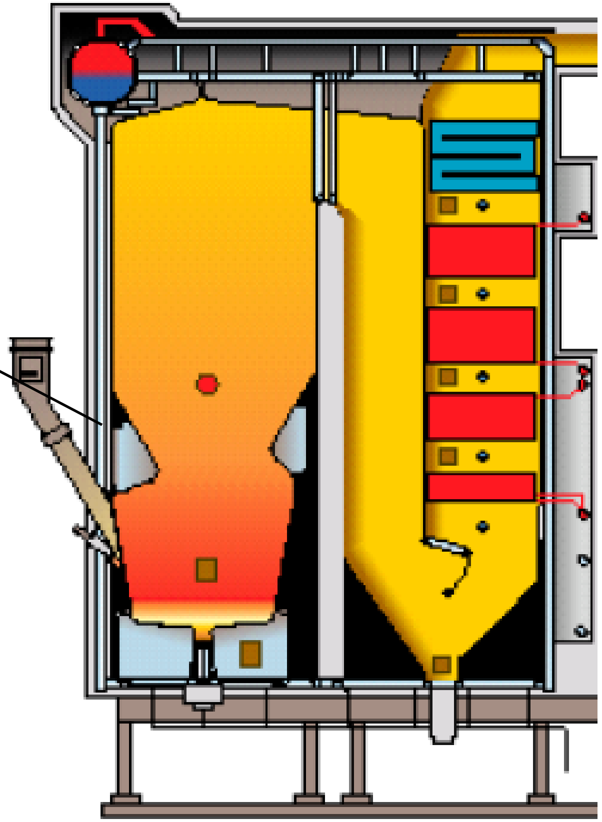
Influence of bottom bed fluctuations on freeboard mixing flow





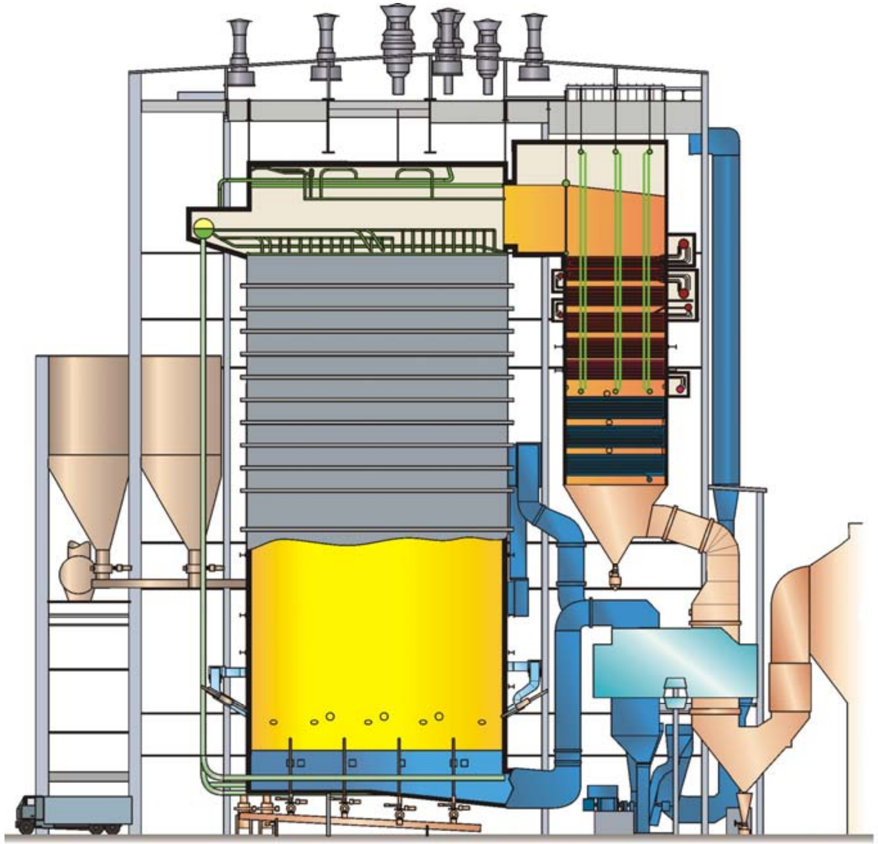
Bed surface

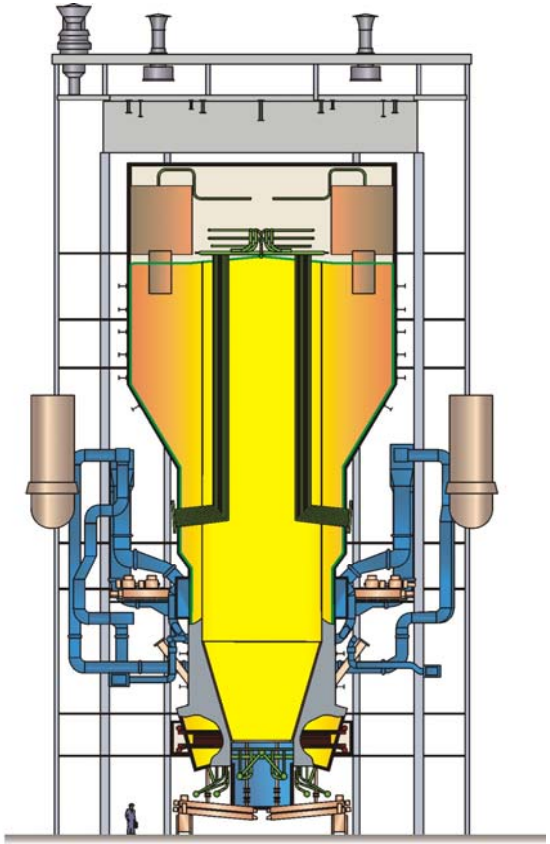
Exit zone and exit duct

- To model the ratio of the solids which leave the furnace and the solids which are internally recirculated, i.e. the back-flow ratio
- For conditions corresponding to those in boilers, it seems as if the exit geometry has little influence on the back-mixing ratio, but that is not to say that the net solids flux can be predicted

Cyclone

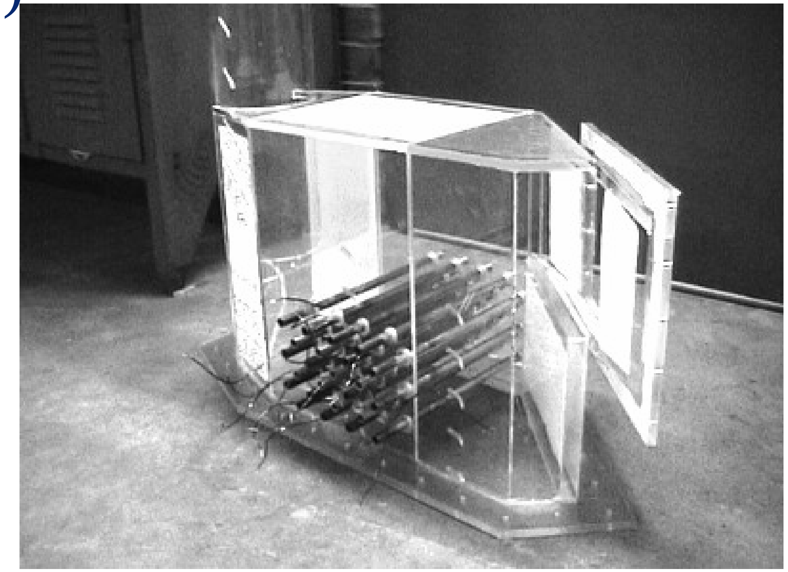
- To find primary particle separation systems with a more compact design (e.g. integrated with furnace, U-beam separators)





Particle seal and downcomer

- To integrate a external heat exchanger (EHE) in the loop seal is advantageous due to the high in-bed heat transfer and the CFB loop will provide a self controlled power output from the EHE
- The solids flow and solid size distribution becomes crucial for the design of the heat transfer surfaces in the EHE
- EHE flow is complex. Few studies (e.g. Werderman, and Werther, *Proc. 12th Int. FBC Conf*, 1993, p 985, Johansson et al., *J. Energy Resources Technology*, *128*, 2006, p 135)



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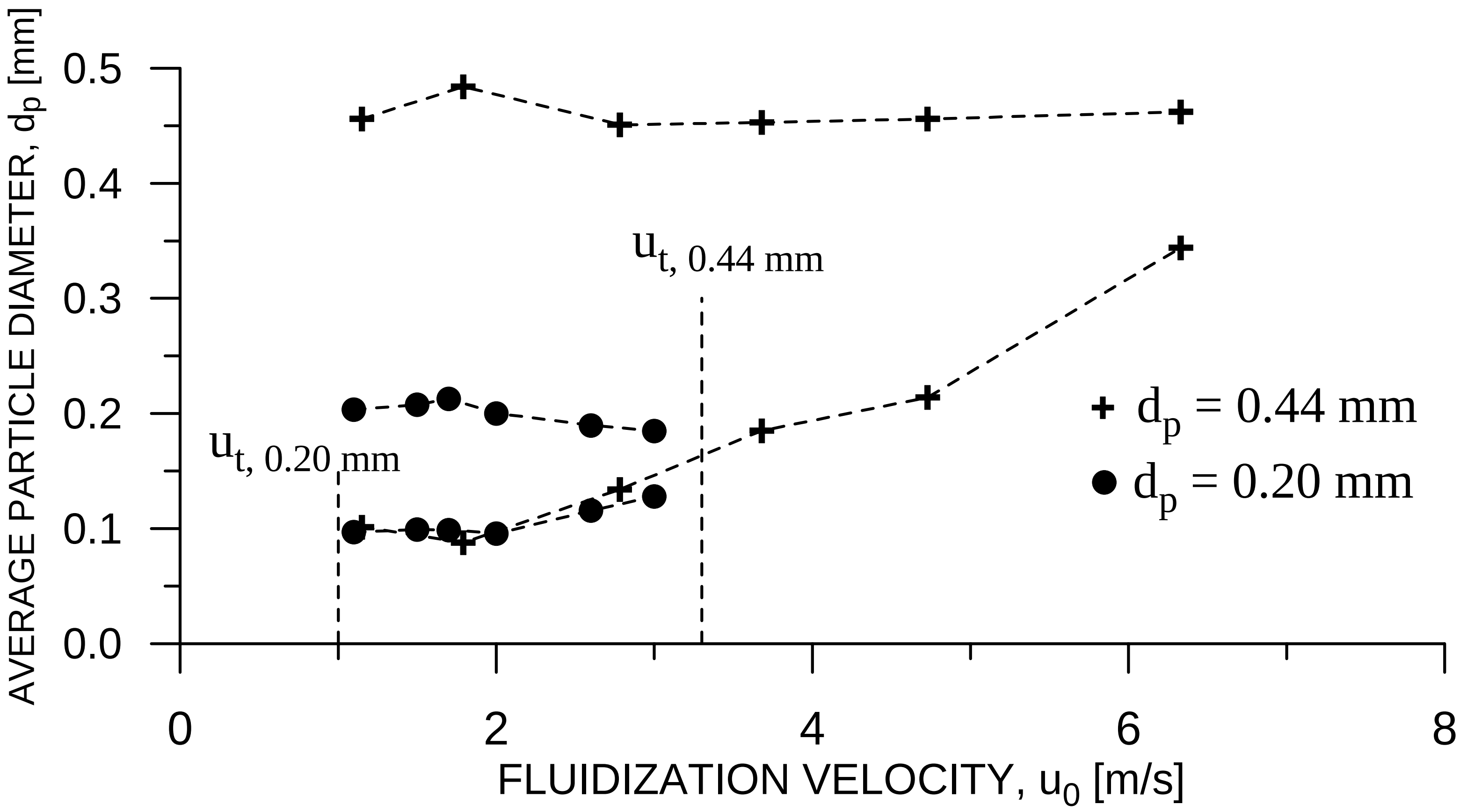
Entire loop in the case of CFB boiler

- Integrating the above zones in a model requires knowledge on the particle size segregation
- For a given set of operational parameters (pressure drop and gas velocities), particle size distribution determines:
  - internal solids backmixing
  - net solids flux
  - cyclone efficiency (i.e. the design of cyclone)
  - solids size (and size distribution) in the loop seal
- Modelling of solids size segregation may require that momentum transfer between solids of different size and weight is taken into account

Solids size segregation in CFB boiler



(From Johnsson & Leckner, 1995)

New concepts

- Oxyfuel CFB for CO2 capture
- Chemical looping combustion
- Integrated gasifier in FB boiler

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Process and cost study of a large scale lignite fired O2/CO2 PC power plant

Reference plant (current):

Lignite-fired 2x933MW_{el}

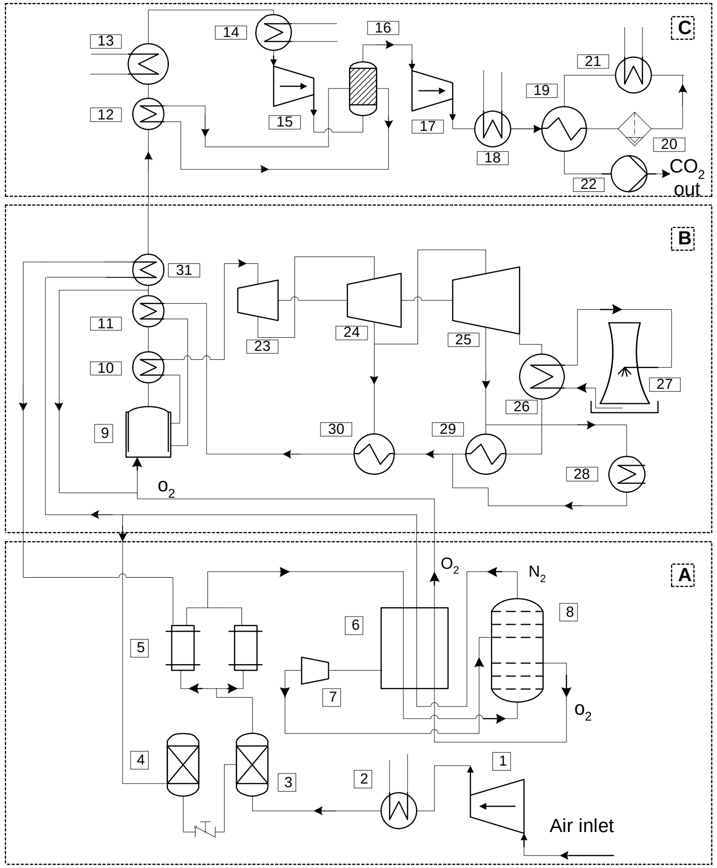
2x115MW_{heat}

Commissioned in 2000

10 million tons CO_2/year!

Proposed O2/CO2 scheme:

(99.5% reduction in CO2 emissions to the atmosphere)

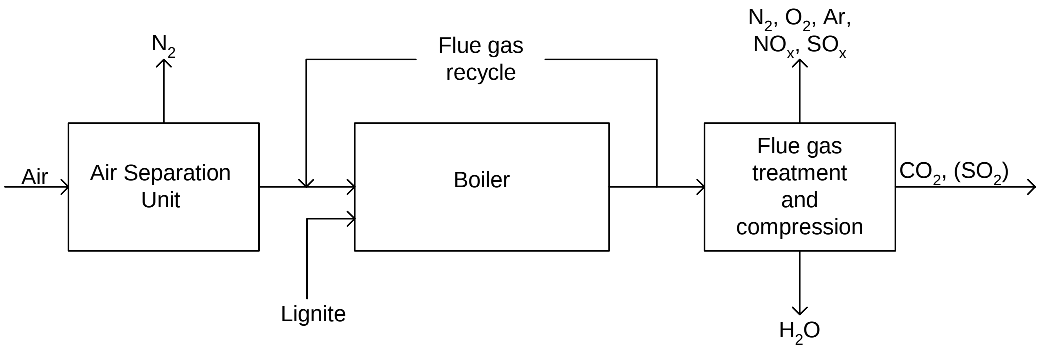


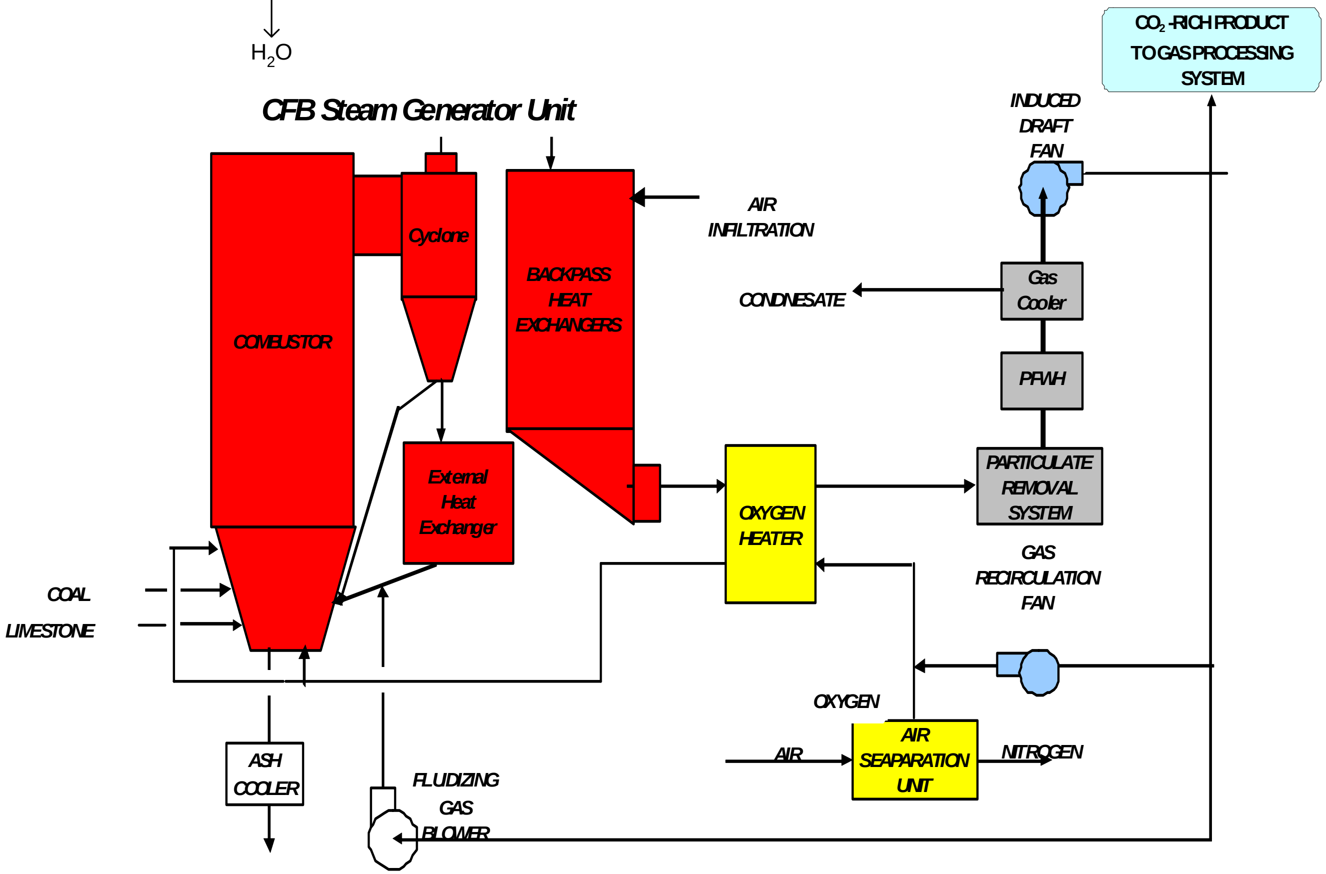
1. Air compressor
2. Compressor cooling
3. Direct contact air cooler
4. Evaporative cooler
5. Molecular sieves
6. Heat exchanger
7. Expansion turbine
8. Destillation column
9. Boiler
10. Super heater
11. Economizer
12. TEG heat exchanger
13. Flue gas condensation unit
14. Flue gas cooler
15. Compressor unit 1, 30 bar
16. TEG
17. Compressor unit 2, 58 bar
18. CO_2 condenser
19. Heat exchanger (CO_2/CO_2)
20. Gas/Liquid separator
21. Subcooler
22. High pressure pump
23. HP Steam turbine
24. IP Steam turbine
25. LP Steam turbine
26. Condenser
27. Cooling tower
28. District heating
29. Feed water preheater
30. Feed water preheater
31. Nitrogen heater

Study yields CO2 capture cost of approx 20 €/t CO2

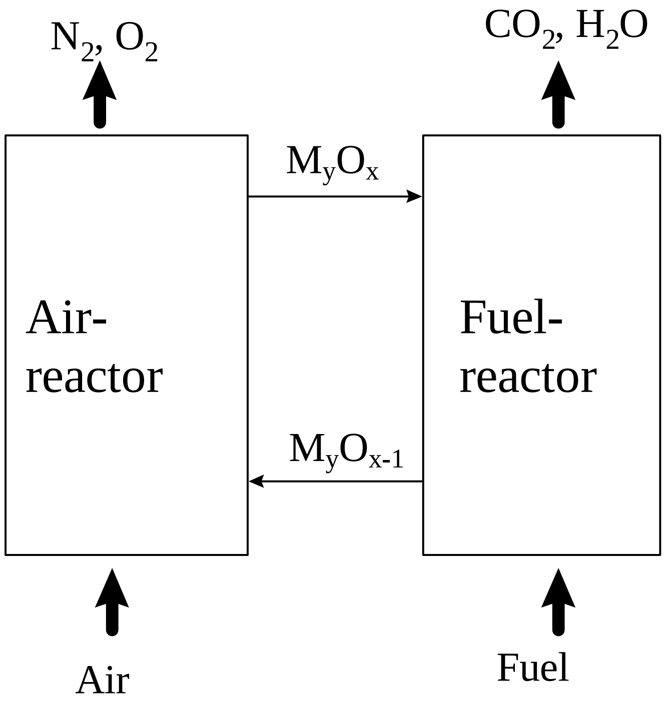
Andersson et al.(2003) VGB Power Tech Journal No 10

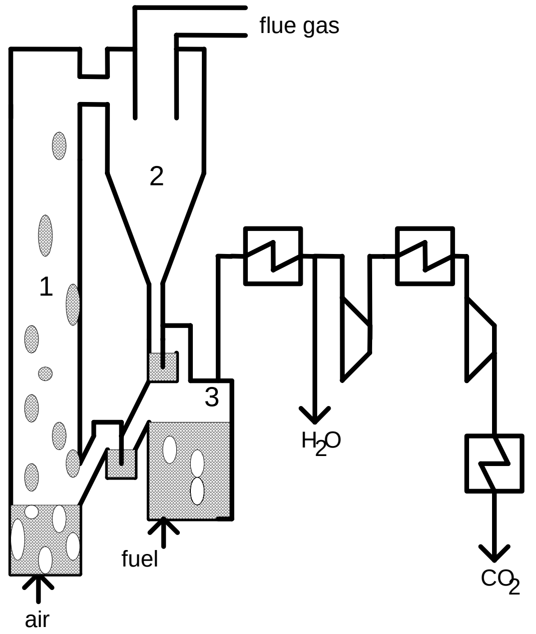
Oxyfuel (O_2/CO_2 recycle) FBC combustion (Alstom)





Chemical looping combustion

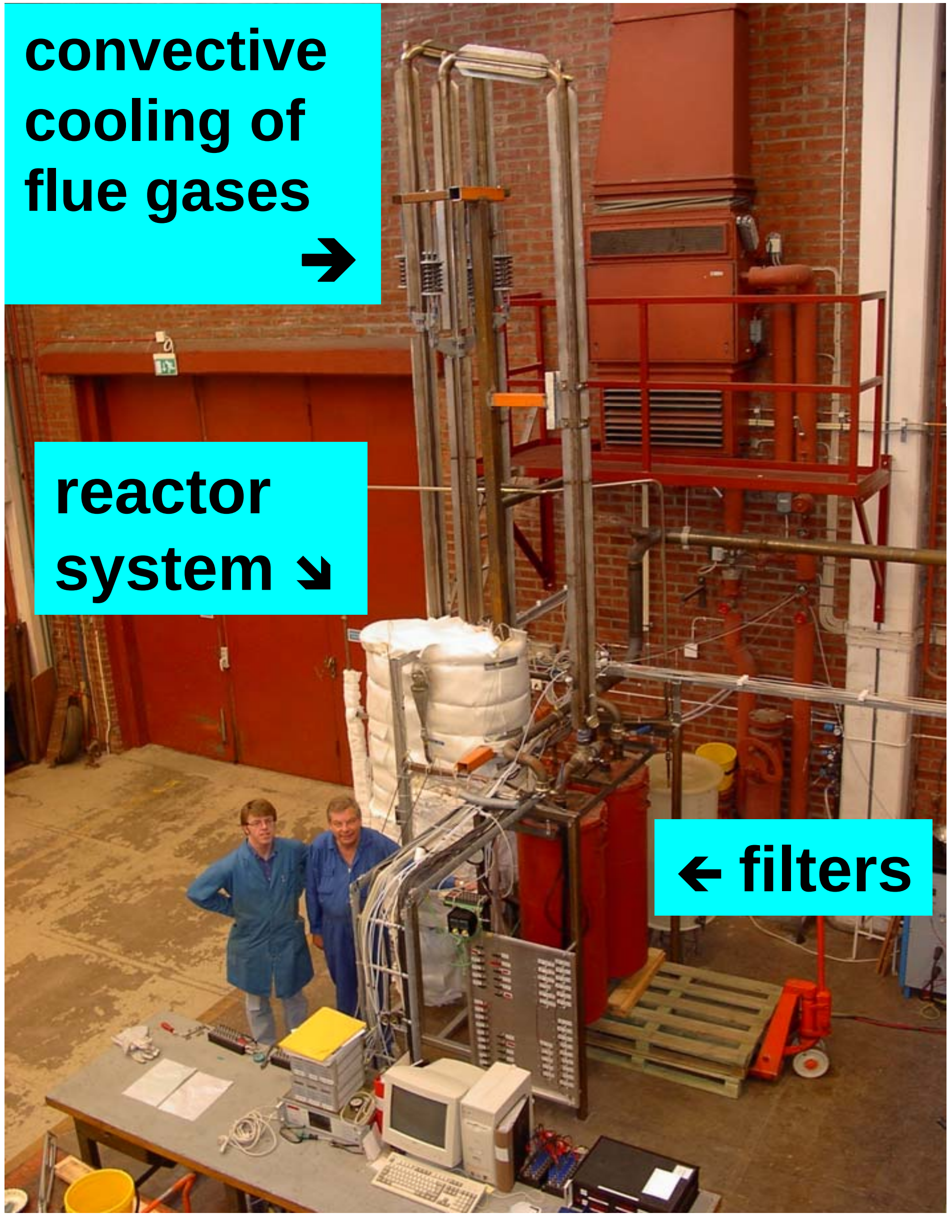


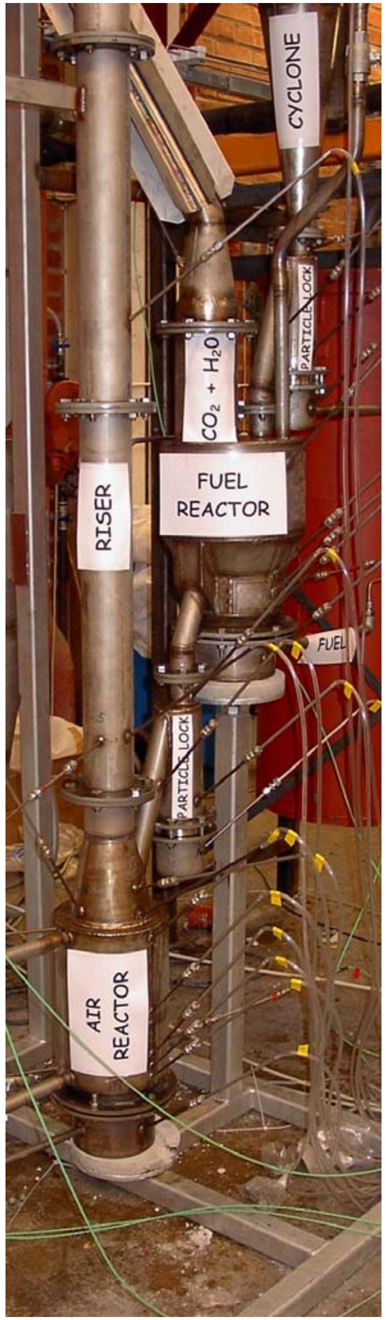


$$(2n+m)Me_xO_y + C_nH2_m \rightarrow (2n+m)Me_xO_{y-1} + mH_2O + nCO_2$$

$$Me_xO_{y-1} + \tfrac{1}{2}O_2 \rightarrow Me_xO_y$$

Chalmers' 10 kW chemical-looping combustor 2003





Chemical-Looping Combustion

Reactor system (fluidized beds):
- well established
- commercially available
- simple
- moderate costs

Oxygen-carrier particles:
- very encouraging results
- scale-up of particle manufacture
- raw materials
- long-term testing needed

Applications of chemical-looping combustion for CO_2 capture:

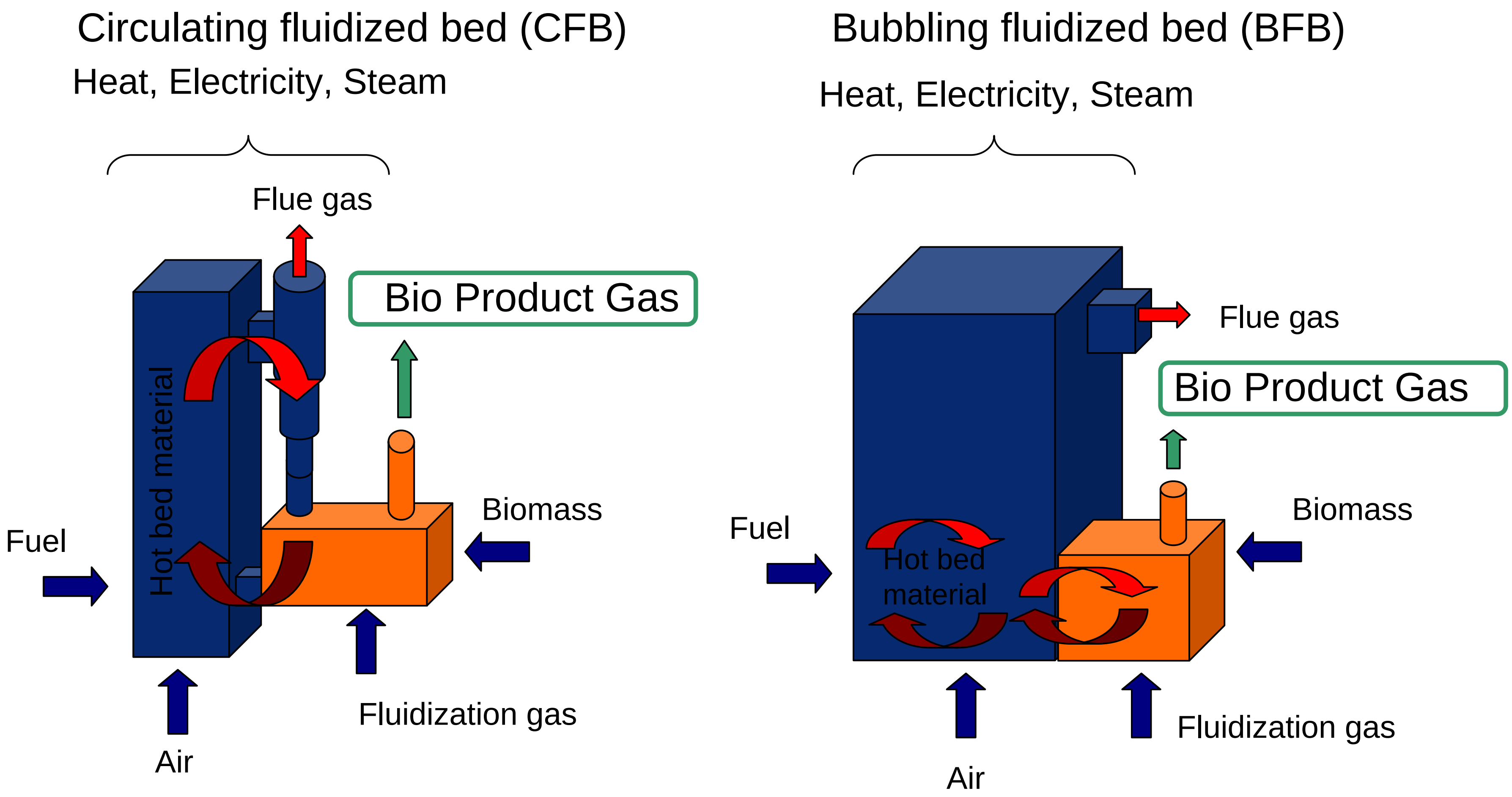
Combustion of gaseous fuel, natural gas, refinery gas, syngas

Chemical-looping reforming, i.e. hydrogen production

Combustion of solid fuels

CHALMERS Chalmers University of Technology

Integration of biomass gasification in existing boiler infrastructure – a new low cost gasification concept

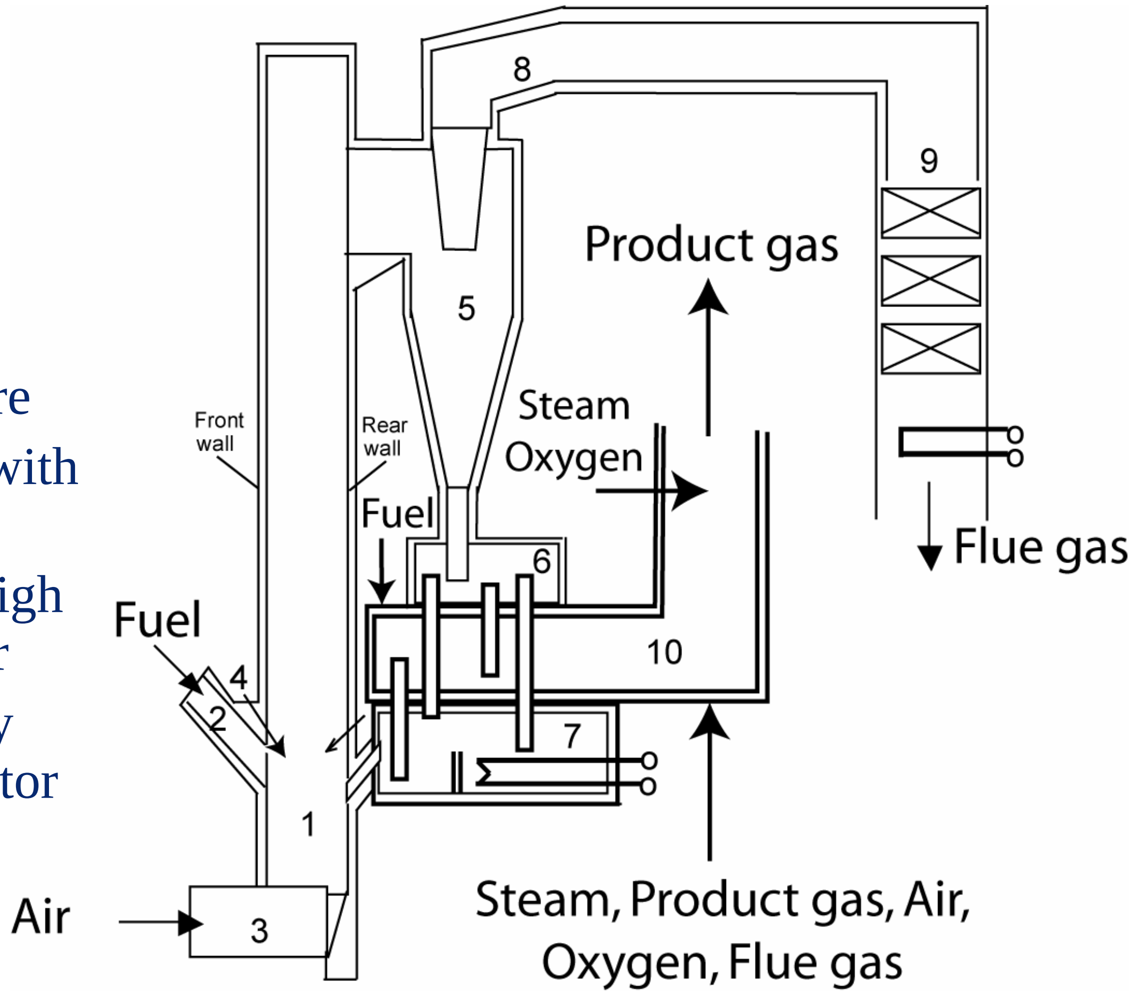


CHALMERS Chalmers University of Technology

Chalmers gasifier for demonstration och research

Advantages

- Heat balance always fulfilled
- Minimization of char losses
- Optional fluidization medium
- Operation at "any" temperature
- Possibility to gasify wet fuel with a high efficiency
- Possibility to burn fuel with high moisture content in combustor
- The gasifier does not have any negative effect on the combustor
- Can be integrated in existing energy system infrastructure



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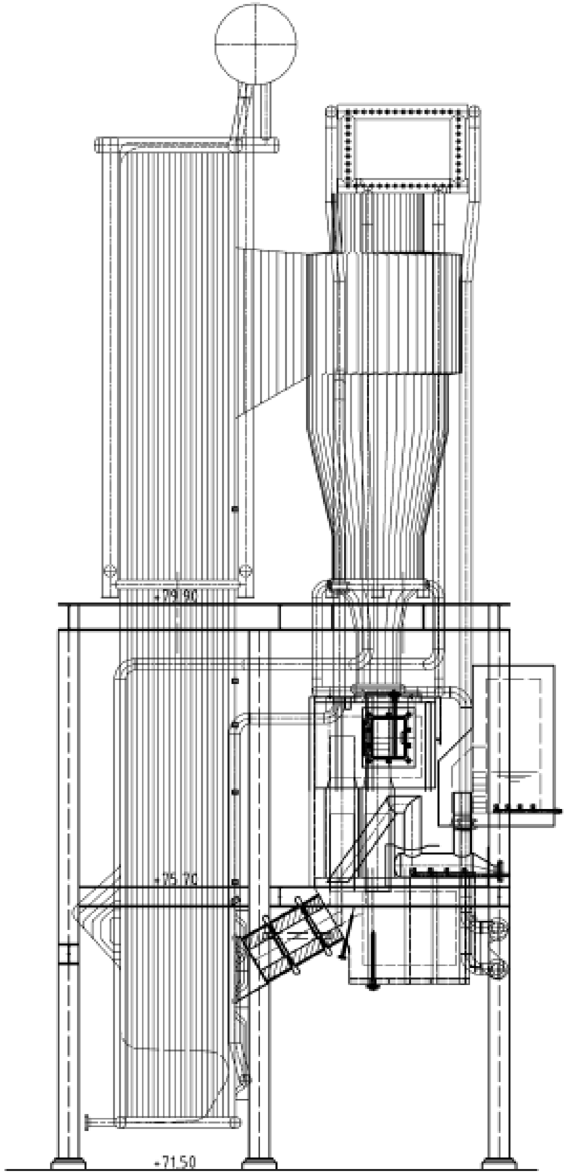

Conclusions

- Large investments in the energy system are required over the coming decades, both as a result of an increased demand for heat and power, as well as due to replacement of old plants
- The prospects for the FBC technology for clean energy is high, but there are competing technologies
- Research and development is required in order to improve the FBC technology
  - establish models for reliable design and scale up of the technology (fuel mixing, solids segregation)
- Rather than competing with the PC technology, the FBC technology (CFBC) will take important niche markets, where fuel flexibility is or can be foreseen to be of future importance
- New concepts (oxyfuel, CLC, indirect gasifiers)

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