A future ”CO_2 Free” Power Plant for Coal
Technology and Economics

The annual fall meeting of the German Physical Society

Bad Honnef, October 21-22, 2004

Lars Strömberg
Vattenfall AB
Group Function Strategy
Berlin/Stockhom

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The Vattenfall Group

- Vattenfall is one of the major Energy companies in Europe
- Vattenfall sells about 180 TWh electricity
  - The main part is produced by hydropower, nuclear power, coal and natural gas.
  - A smaller part is produced by biofuels and wind power
  - About 17 TWh is produced in combined heat and power plants
- Vattenfall also sell about 37 TWh heat
  - The main part is produced by biofuels, coal and gas in cogeneration plants
- Vattenfall emits almost 80 million tons of CO_2 per annum

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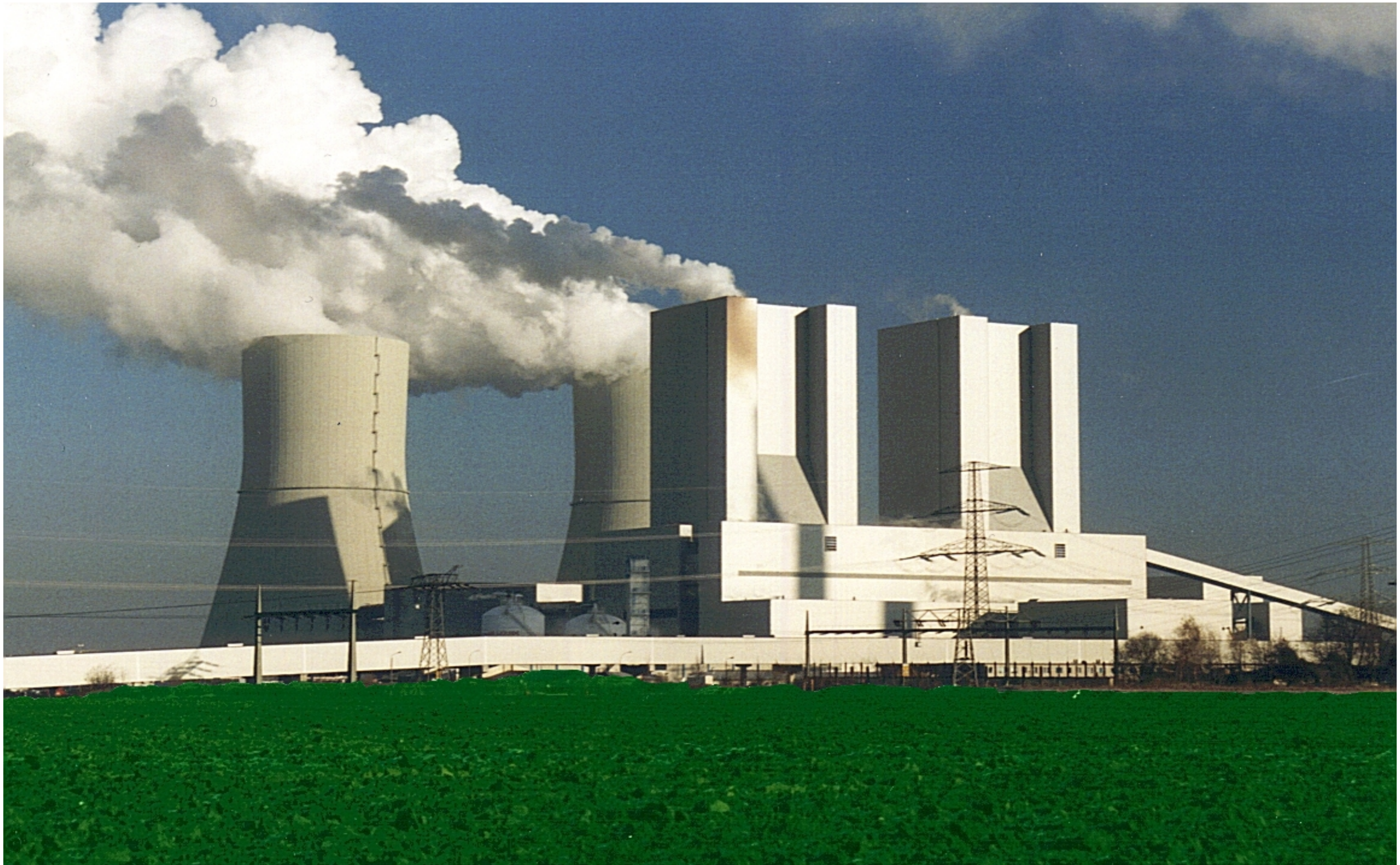
Power Plant Lippendorf



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CO_2 free power plant

Fossil fuels are needed

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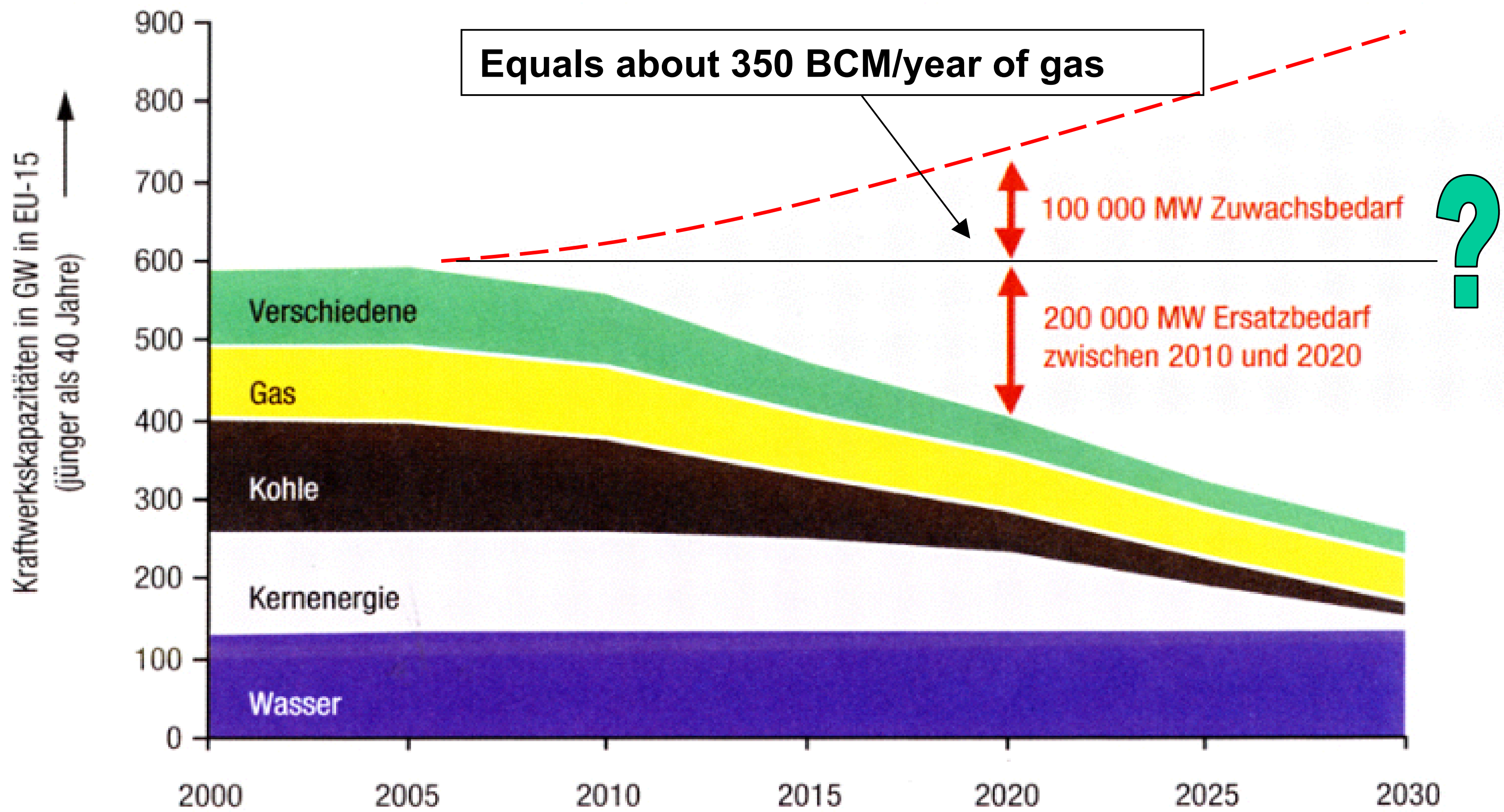
Need for new capacity in Europe (EU 15)



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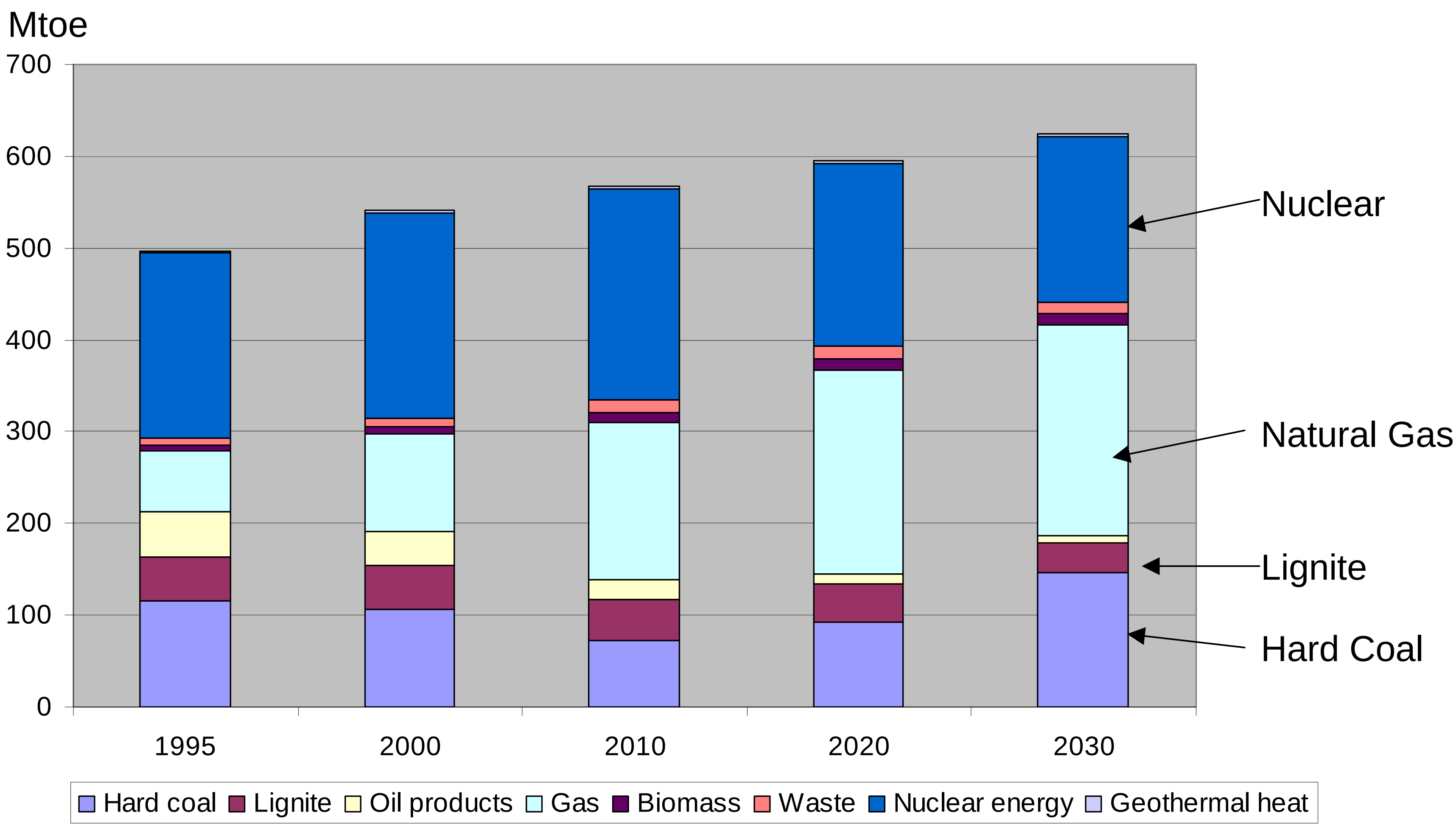
Source: VGB PowerTech Annual Report 2002 / 2003 + EU and Eurelectric

Fuel use for electricity generation EU-15



Source EU Commission Energy and Transport Outlook 2030 (2003)

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Fossil fuels – an essential part of our society

Today, fossil fuels are completely dominant in world wide energy supply. World Energy Outlook 2002:

“*Global primary energy demand is projected to increase by 1.7% per year from 2000 to 2030. Fossil fuels will remain the primary sources of energy, meeting more than 90% of the increase in demand”*

According to the Green Paper on Energy Supply, 80% of the energy consumption in EU-30 derives from fossil fuels:

EU 30	Today	2030
Fossil fuels	80%	85%
Nuclear	15%	6%
Renewables	6%	8%

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CO_2 free power plant

The big challenge for Coal is the CO2 issue

© Vattenfall AB

Kraftwerk Boxberg

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The challenge for Coal

Coal is a very good fuel …..

- It is very easy to burn and it is safe to store and transport
- The cost is low and stable. It costs less than half compared with gas and it is available all over the world.

Modern technology allow us to….

- Eliminate almost all emissions of "conventional" pollutants as sulfur and nitrogen oxides, hydrocarbons and particulates, it is only a matter of cost.
- Get a very high efficiency (over 45 %)If the trading system prevails

The big challenge for Coal is the carbon dioxide emission. If this can be eliminated we can utilize coal with confidence without endangering the Climate

Emission Trading

Emission Trading sets the commercial framework for new technology

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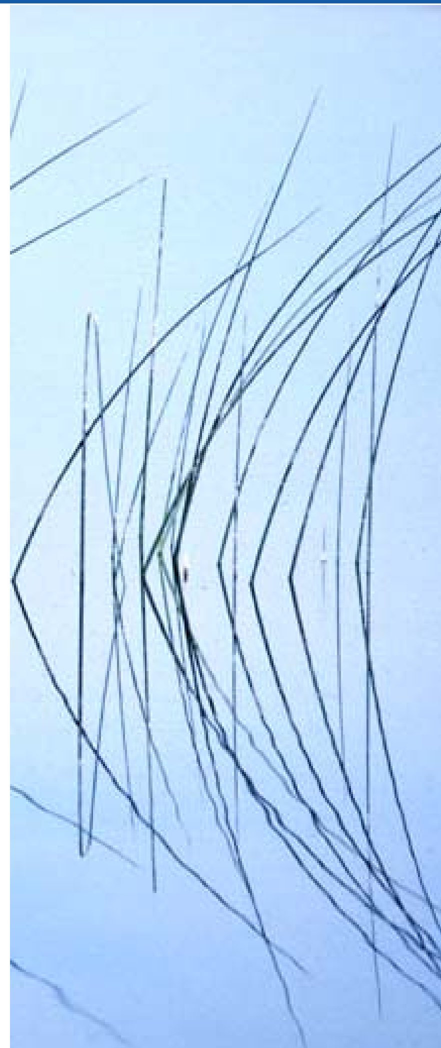
The EU scheme for GHG emission trading

"The Directive establishes a scheme for greenhouse gas emission allowance trading within the European Community to promote reductions of greenhouse gas emissions in an economically efficient manner".

Adopted by European Parliament 2 July 2003

Sept 2003: Adopted by European Council
March 2004: National Allocation Plans
Sept 2004: Allocations fixed
January 2005: Effective
First period: 2005-2007
Second period: 2008-2012



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The EU emission trading system

The long term price of the allowances will be set by reduction requirements and the costs of physical reduction

As emission allowances become scarce they will have an increasing value

The cost for allowances will be added as a direct marginal production cost and therefore increase the spot price of electricity

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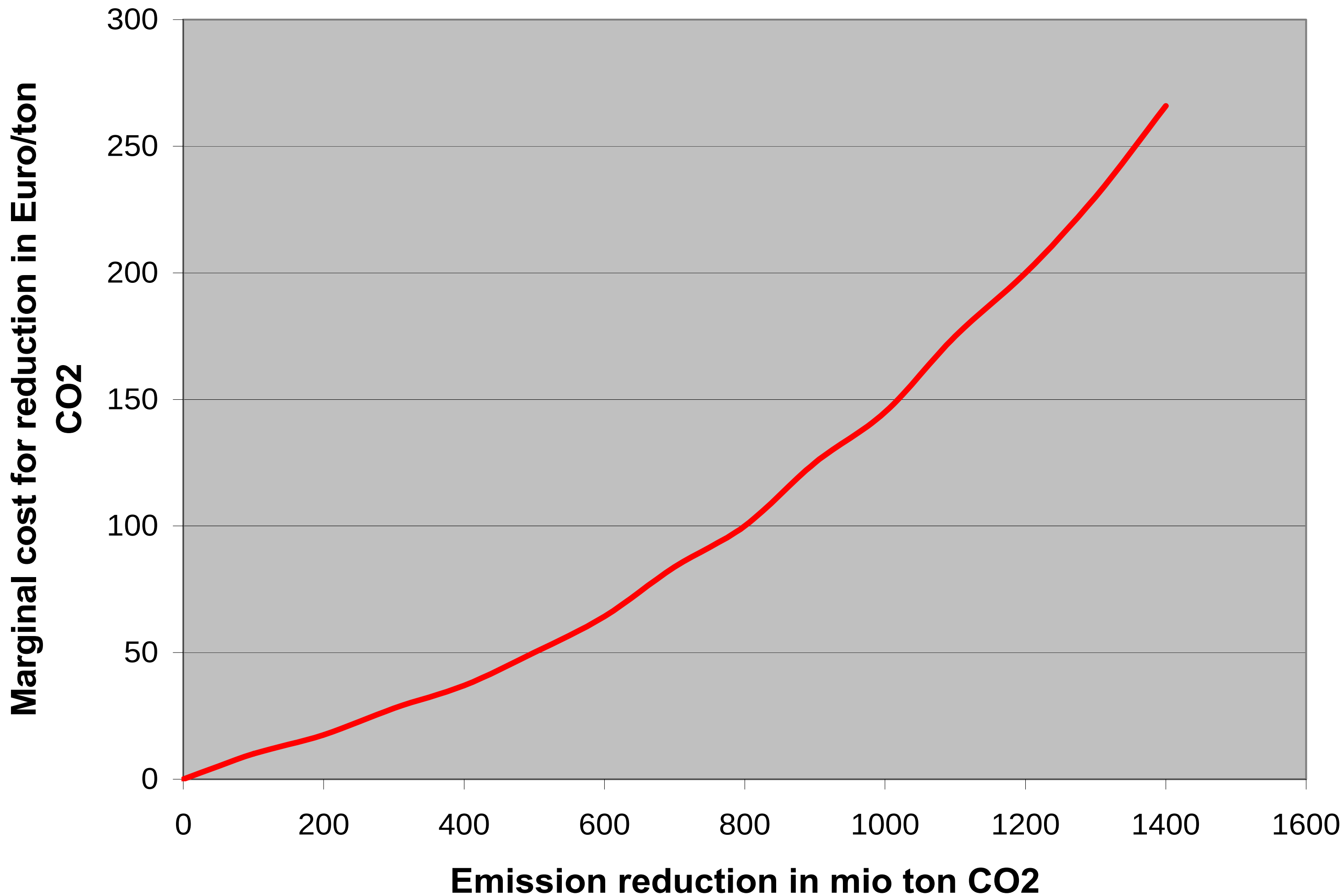
Marginal cost vs. Reduction of CO_2 emissions in EUR/ton CO_2

Source: ECOFYS Economic evaluation of sectorial reduction objectives for climate change



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Analyses show that…

by 2010 …..

- Costs for emission allowances might be around 10 EUR/ton of CO2

but in 2015….

- If the trading system prevails
- When new technology for fossil fuels with near zero emissions, can play a significant role
- The cost for emission allowances will increase to 20 EUR/ton of CO_2 or higher depending on reduction demand.

This is the target to be met by new ”zero emission” technology

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Capture and storage

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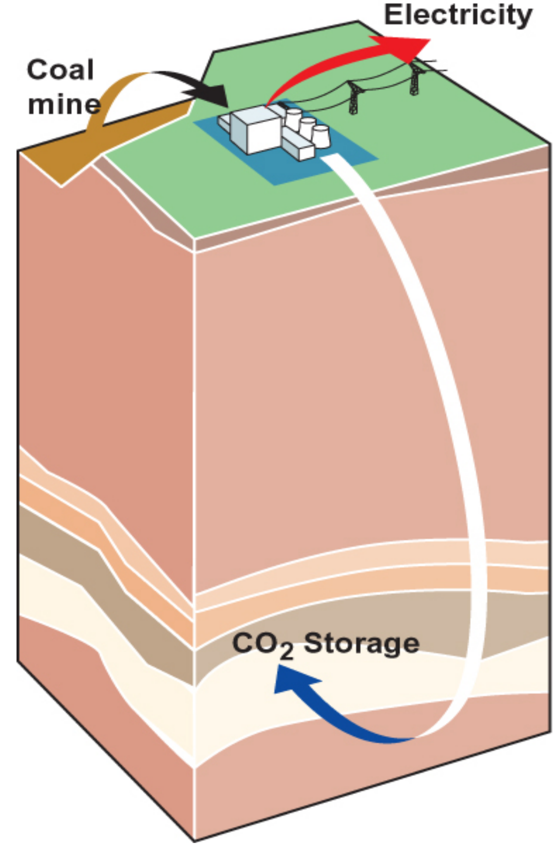
The CO_2-free Power Plant principle

The principle of capture and storage of the CO_2 under ground

The CO_2 can be captured either from the flue gases, or is the carbon captured from the fuel before the combustion process.

The CO2 is cleaned and compressed. Then it is pumped as a liquid down into a porous rock formation for permanent storage.



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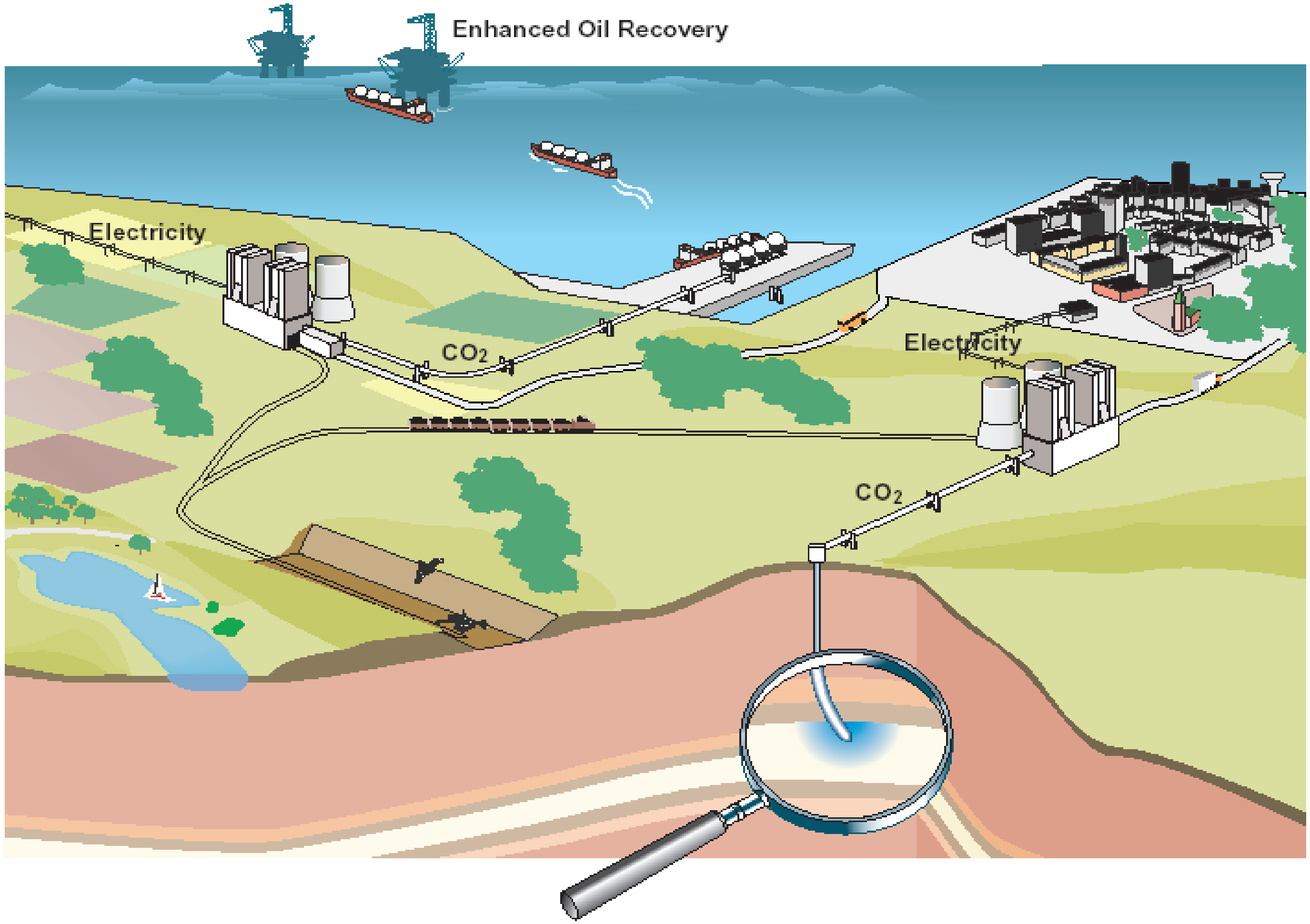
CO_2 Capture and storage



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CO_2 free power plant

Storage

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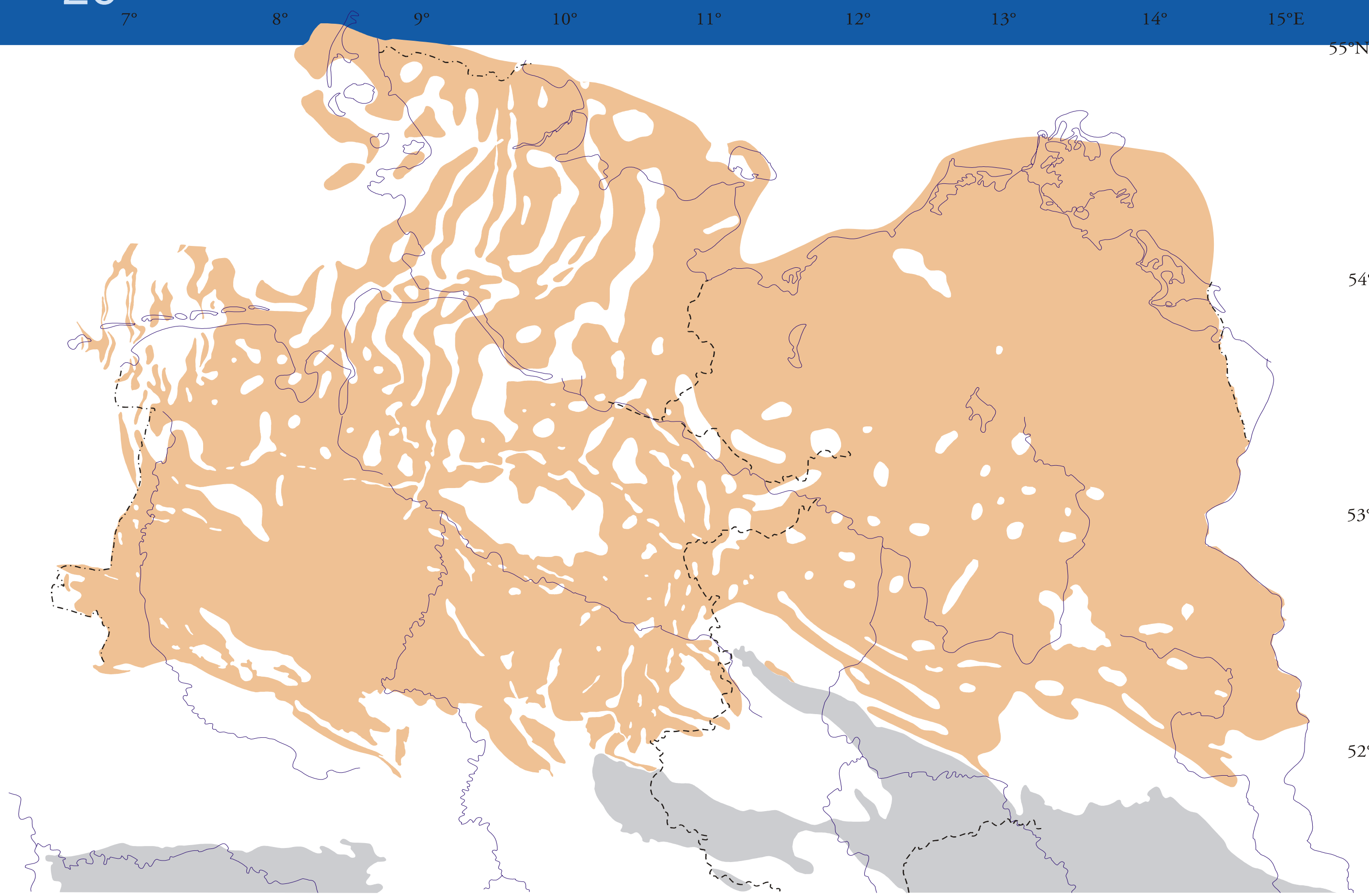
Storage Capacity, saline aquifers



Specific problems:

- structurally complex
- thickness variation
- porosity variation
- residual saturation

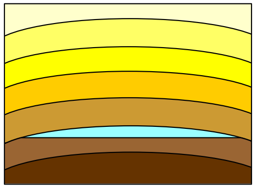
Source:

Franz May,

Peter Gerling,

Paul Krull

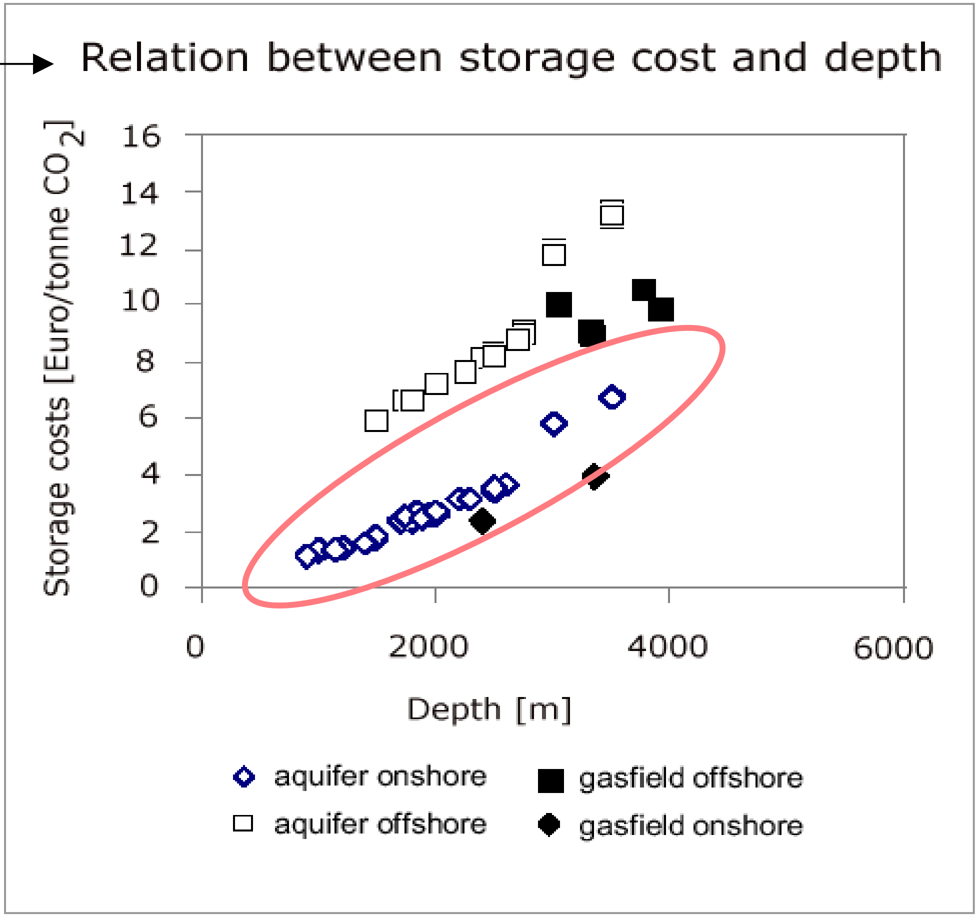
Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover



Storage cost estimates

Storage in aquifer traps (GESTCO Figures)

- **Costs depend strongly on the depth of subsurface layers used for storage**
- **The strongest subsurface uncertainty in storage costs lies in the time it takes to fill the trap**
- **The second important uncertainty parameter is the exploration success ratio of finding a suitable trap**
- **Dutch case: CO2 source of 5.7 Mton/year stored in one megatrap or a conglomerate of traps. Total sequestration cost: 17-20 Euro/ton CO2 av.**



Källa: Christian Bernestone Vattenfall Utveckling

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CO_2 free power plant

Transport

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CO_2 pipelines in operation in the USA

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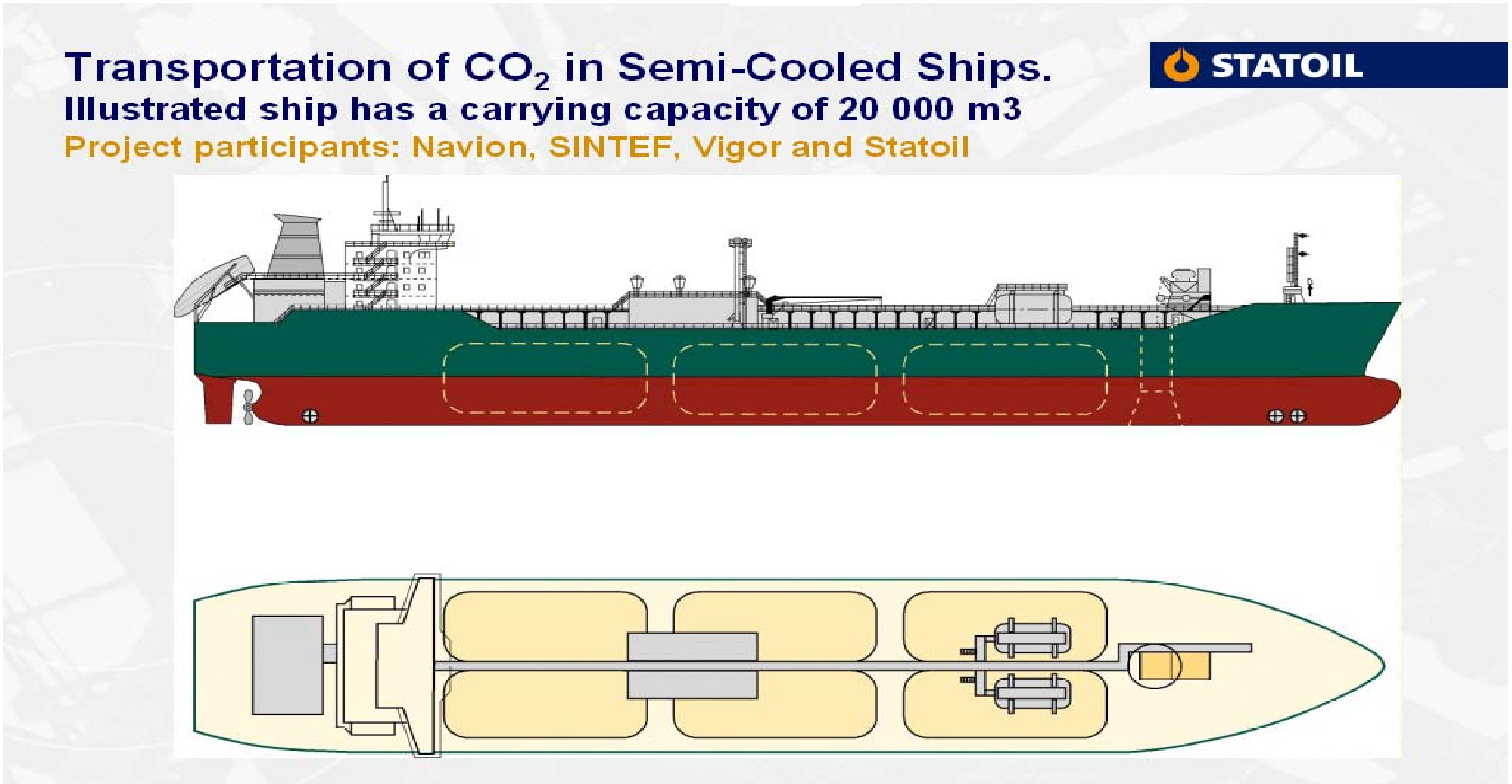
Transportation with water carriers



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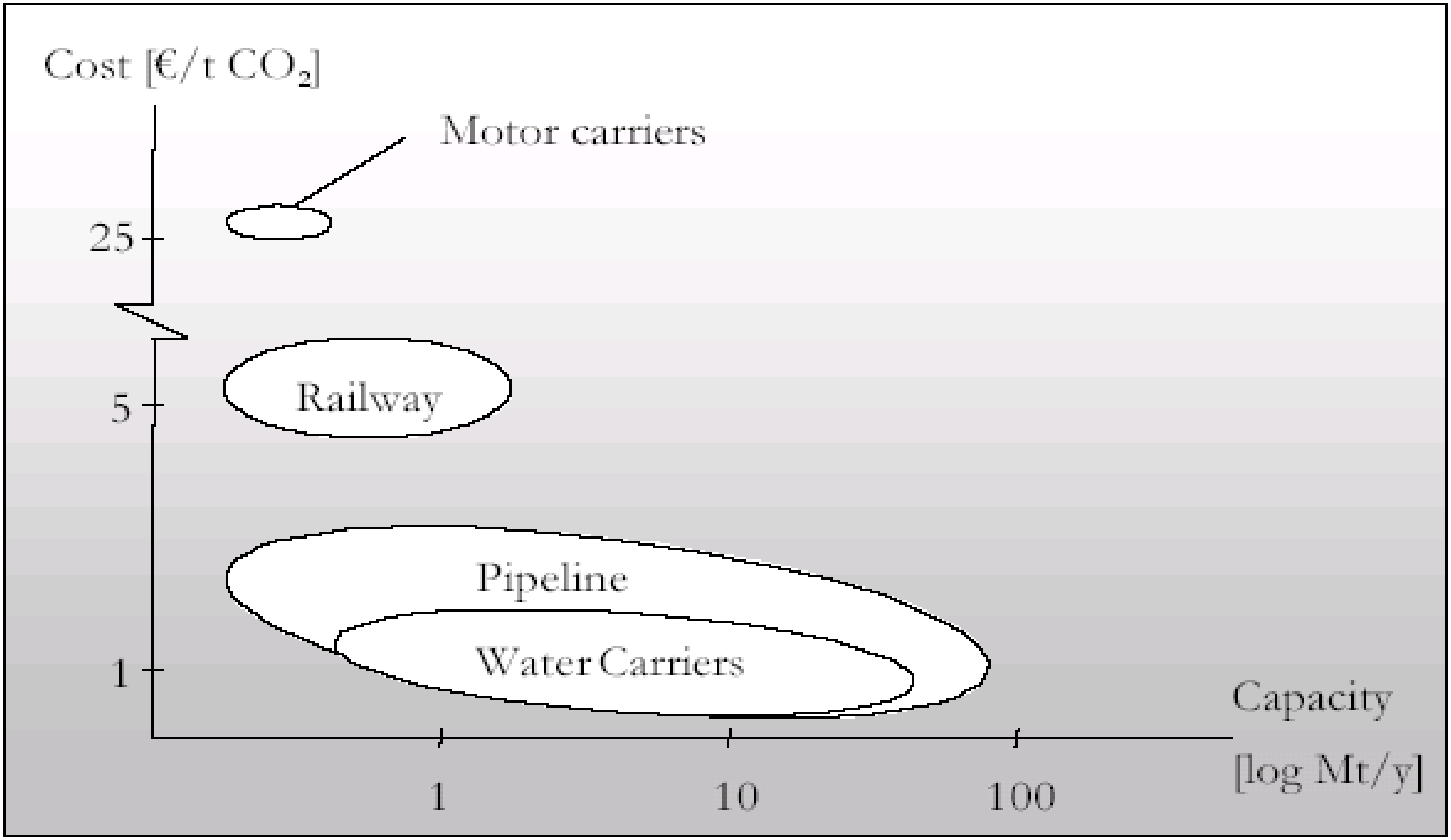
Transport costs for CO_2

Cost and capacity ranges



Source: Odenberger M, Svensson R, Analysis of Transportation Systems for CO2, Chalmers, 2003

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CO_2 free power plant

Capture

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CO_2 free power plant

Different ways to capture the CO2 – minimize costs

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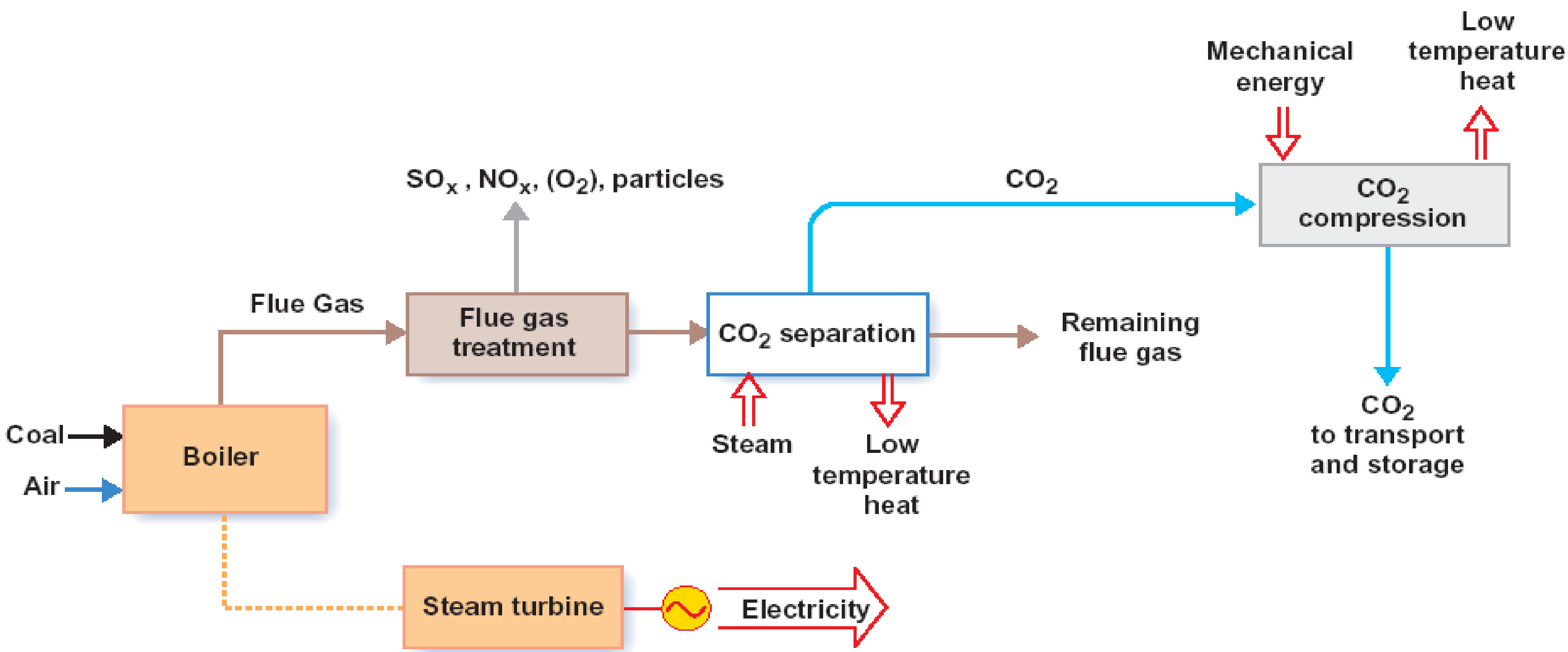
CO_2 free power plant - Capture

- Reasonably matured technologies for capture of CO_2 are usually divided in three categories
  - Post-combustion capture, where the flue gas from the combustion is cleaned from CO_2.
  - Pre combustion capture, where the carbon is removed from the fuel before the combustion.
  - Utilization of oxygen for the combustion, but without the nitrogen in air, in form of either air separation or a solid oxygen carrier

Vattenfall works with all three options, but we have made an agreement with our collegues to share the workload and share results

Post-combustion capture – absorption process



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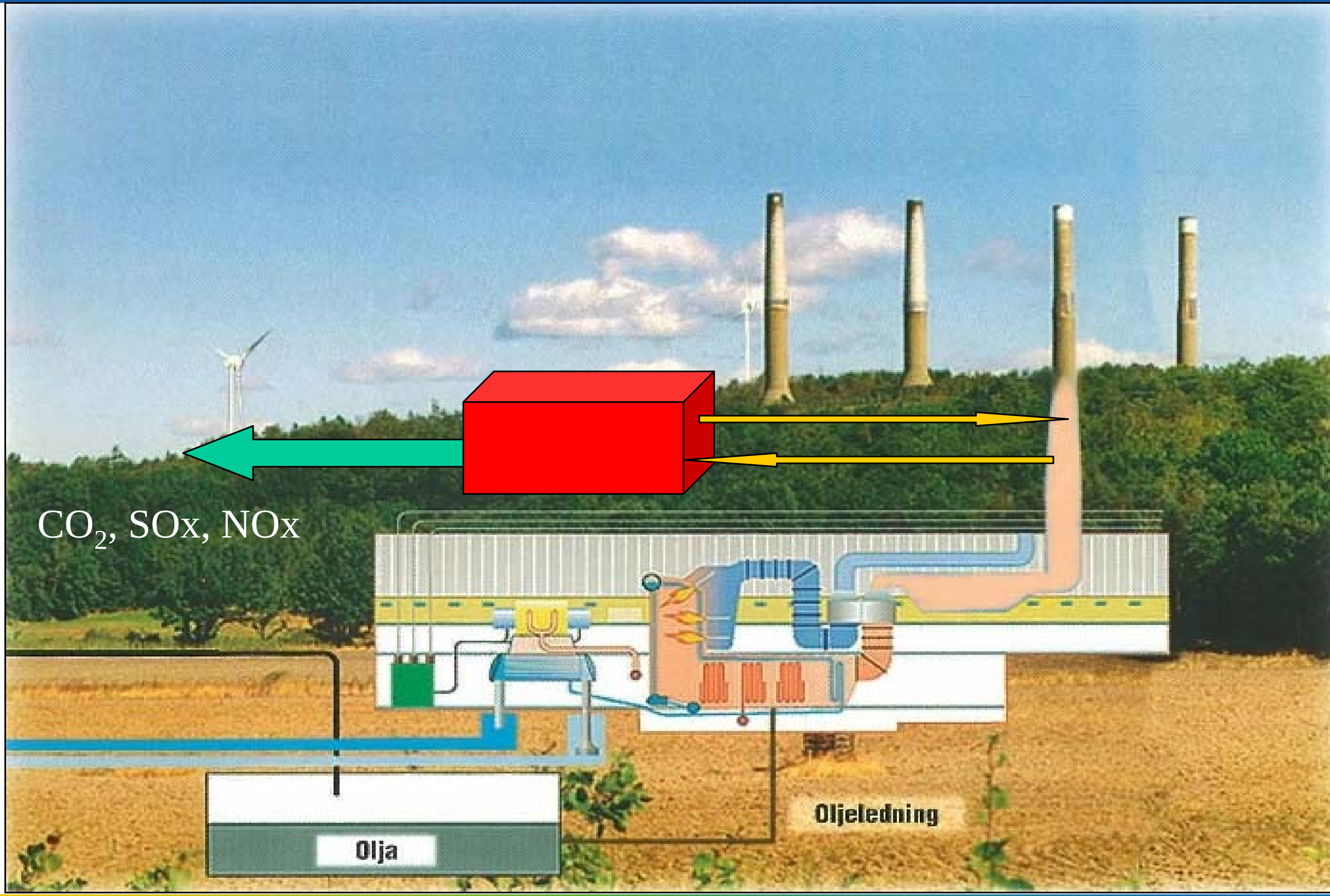
Stenungsund - The Power plant inside the mountain



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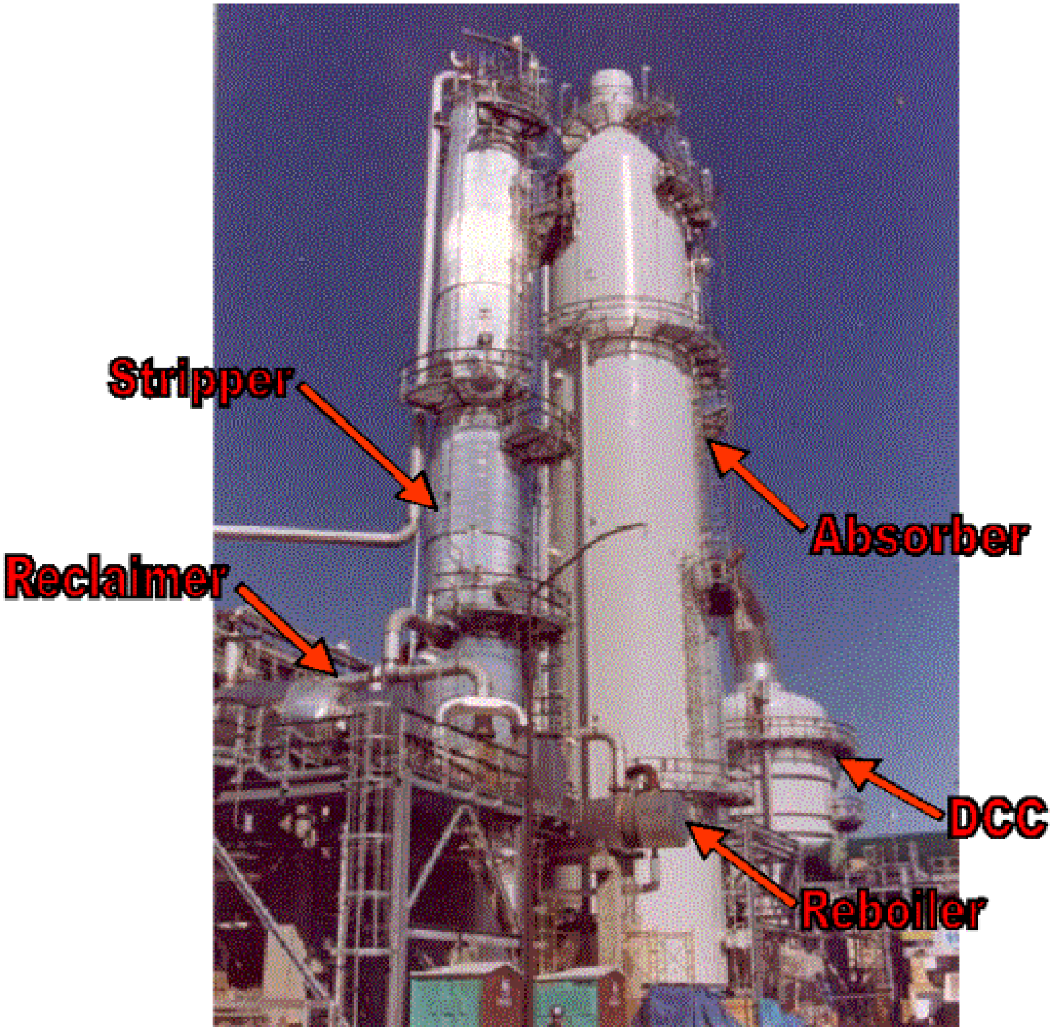
Bellingham Plant, CO_2 absorption



"Largest economic single train plant is approximately 4600 t/day for coal, based on absorber column diameter of 13 m" acc. to Fluor

Stenungsund 3+4 needs two trains, one for each block with a common Stripper

Note! At Bellingham CO2 is captured from a gasturbine's exhaust

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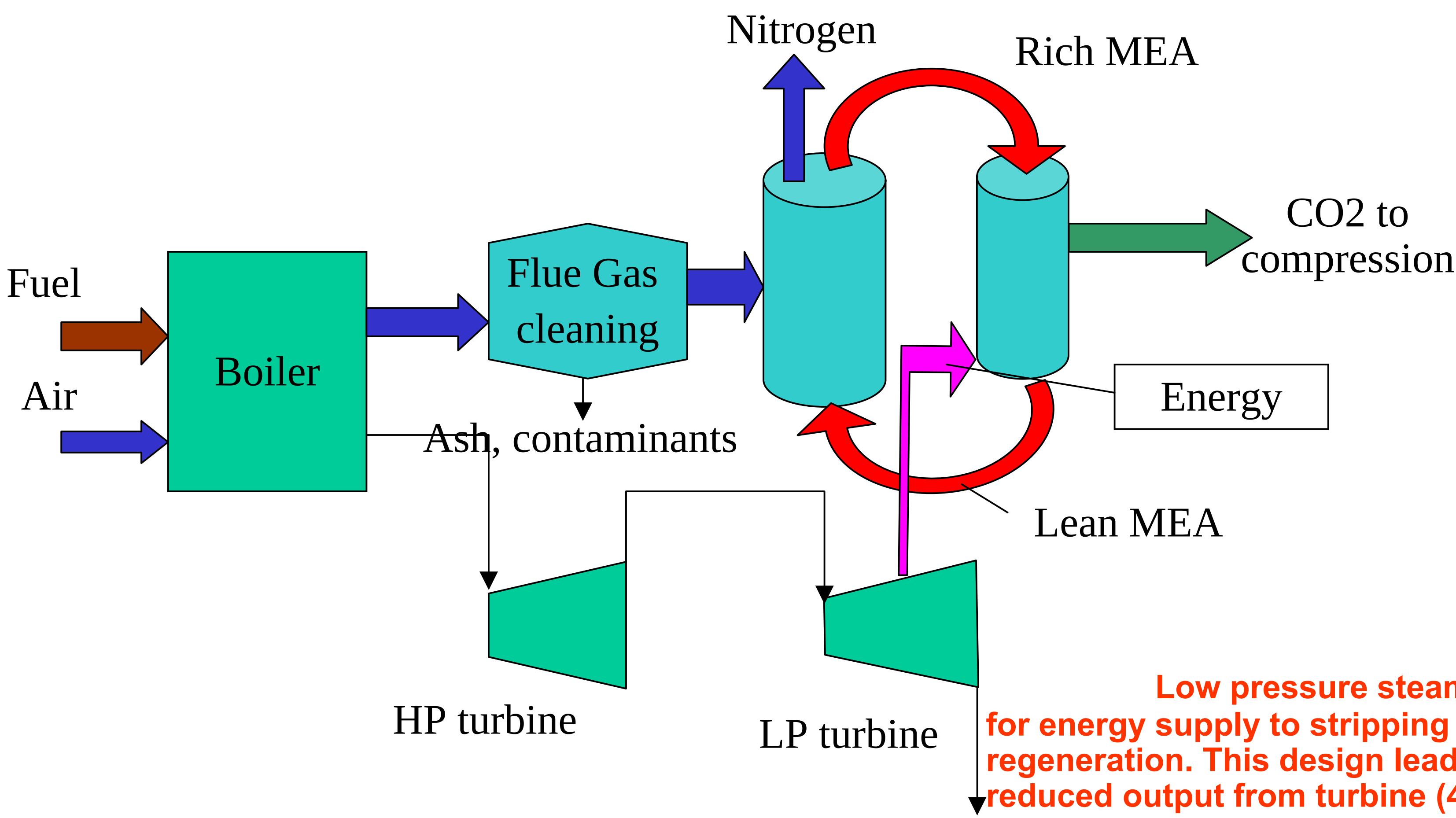
Amine Absorption process principle



Low pressure steam is used for energy supply to stripping and regeneration. This design leads to reduced output from turbine (400 MW instead of 500)

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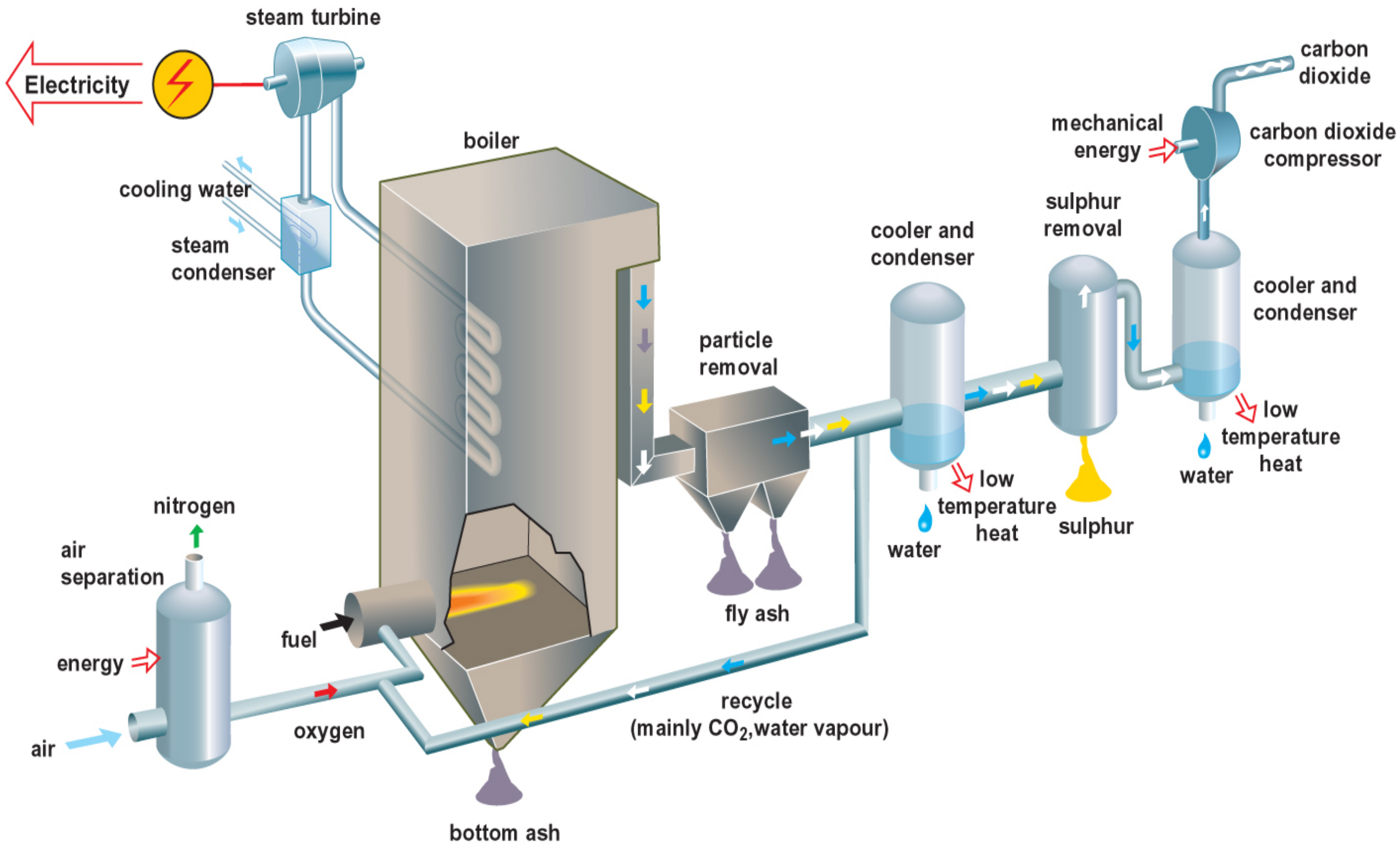
O_2/CO_2 combustion is the preferred option at present



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The reference power plant Lippendorf

Lignite fired plant of 2x933MW_{el}

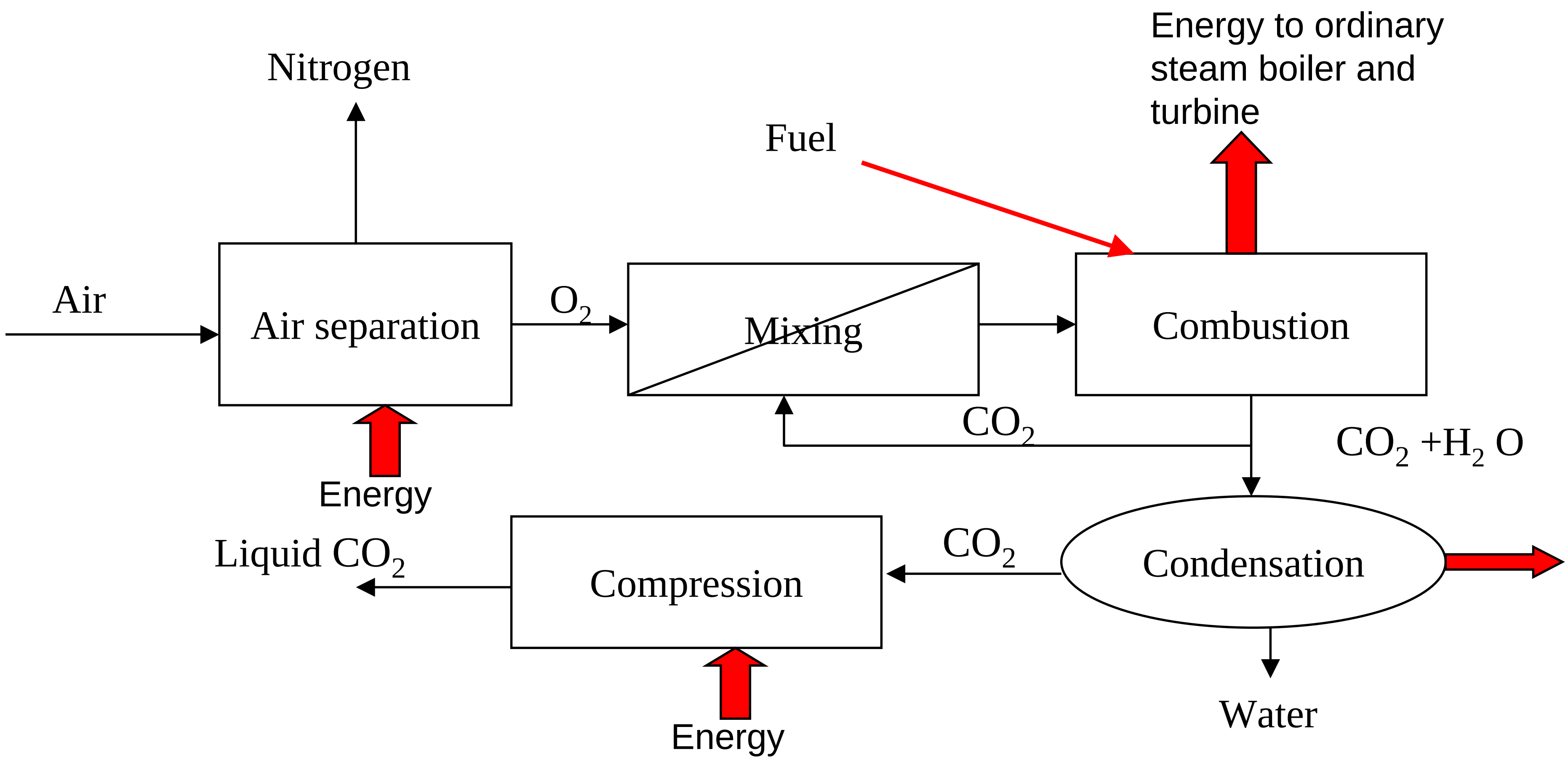
Efficiency 42.7 % (LHV)

Commissioned in year 2000

10 million tons of CO_2/year

© Vattenfall AB

CO_2 free power plant : O_2 /CO_2 combustion

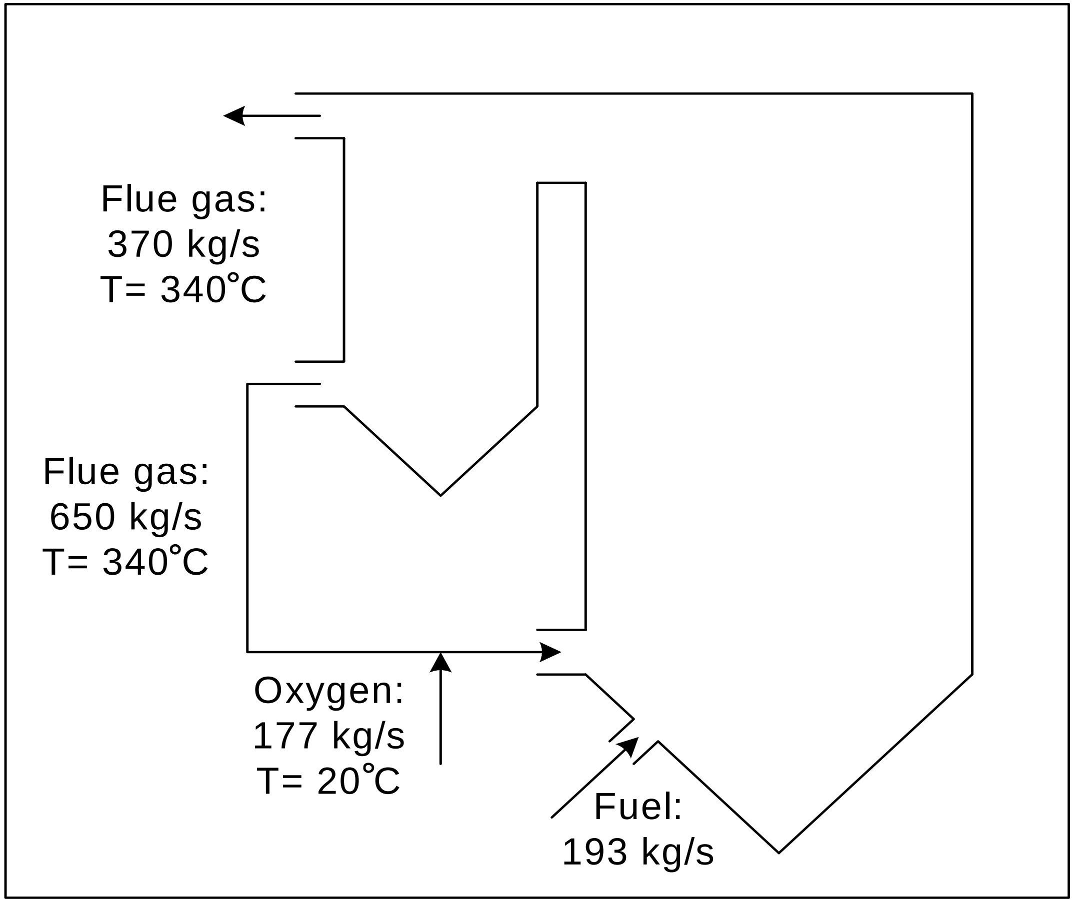


The gas flows in the boiler if fed with an oxidizer with 21% O2

To flue gas treatment

300 m^3_n/s

180 m^3_n/s H_2O
105 m^3_n/s CO_2
7 m^3_n/s Ar
4 m^3_n/s O_2
2 m^3_n/s SO_x
1 m^3_n/s NO_x



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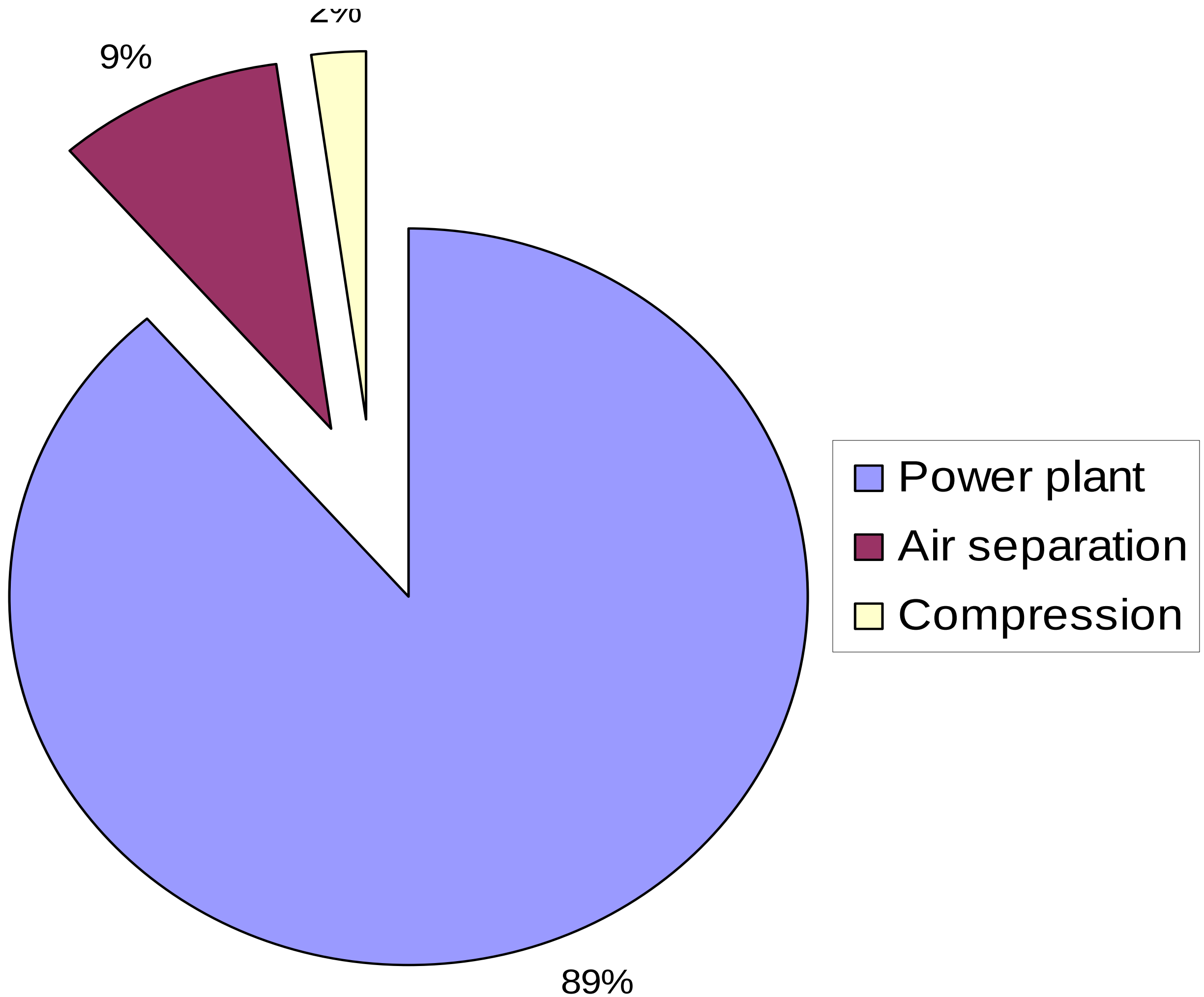
Investment cost for a large lignite fired power plant with O_2/CO_2 combustion



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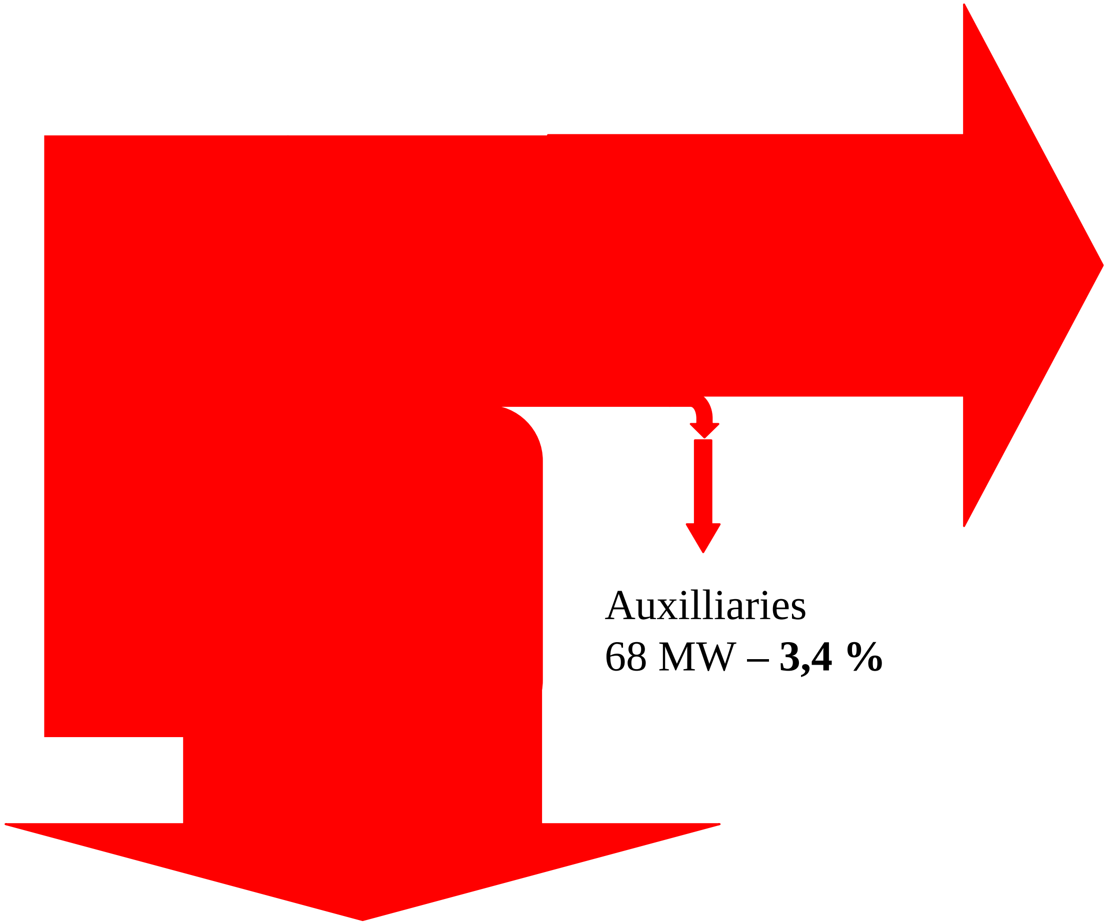
Energy flow diagram for a lignite fired Power Plant



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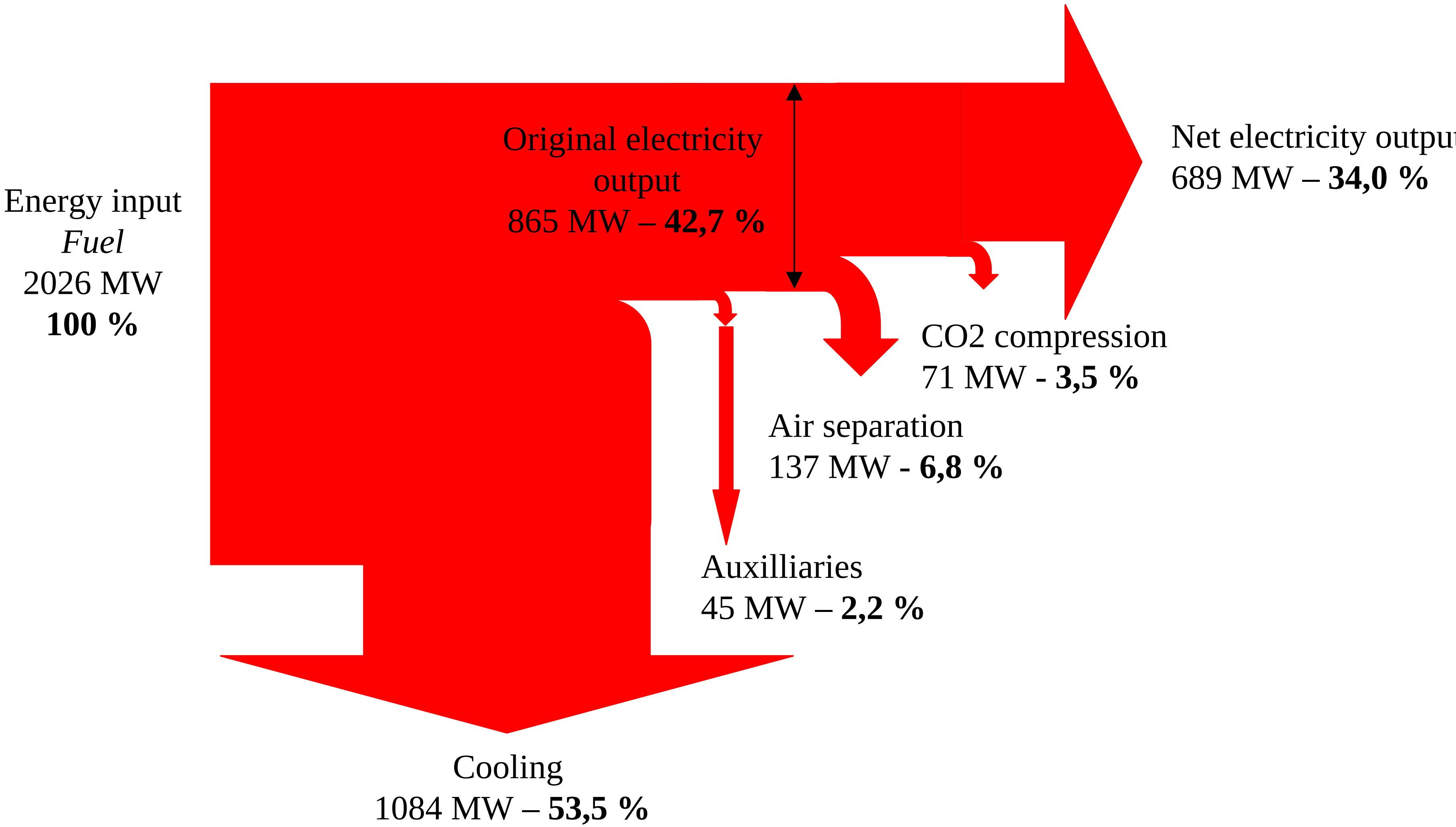
Energy flow diagram for lignite fired plant with O_2/CO_2 combustion



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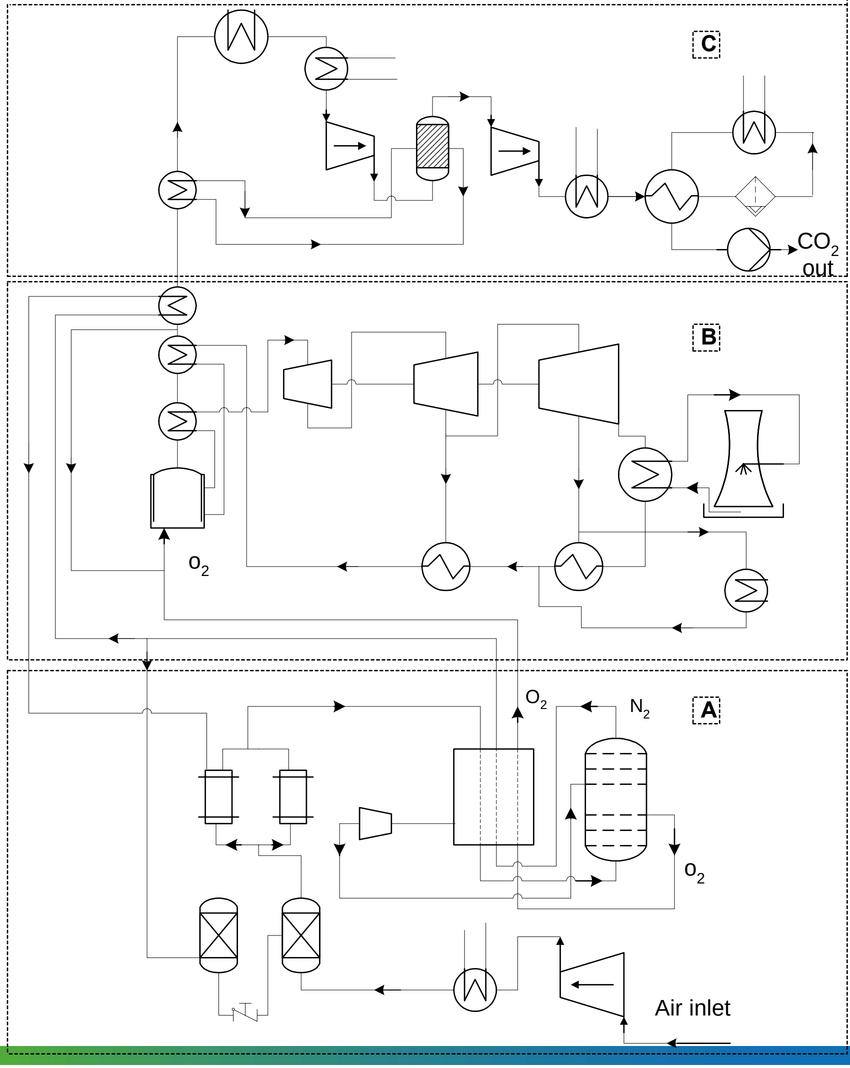
The process design of the O2/CO2 power plant

Flue gas treatment and liquifaction of the CO2. Power consumption –71 MW

The power plant process. Original gross output 933 MW

Air separation Power Consumption -141 MW



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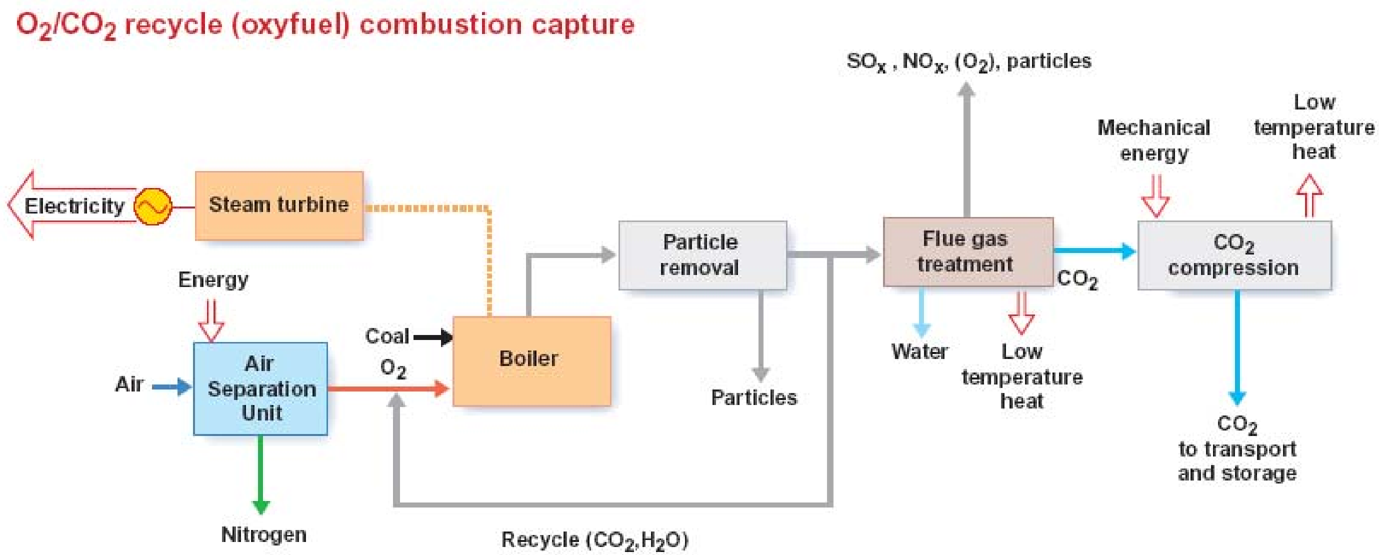
The CO_2/O_2 combustion principle



Large energy penalty for O_2 production

Large amount of waste heat, not only from steam condenser but also from flue gas condenser and CO_2 compression

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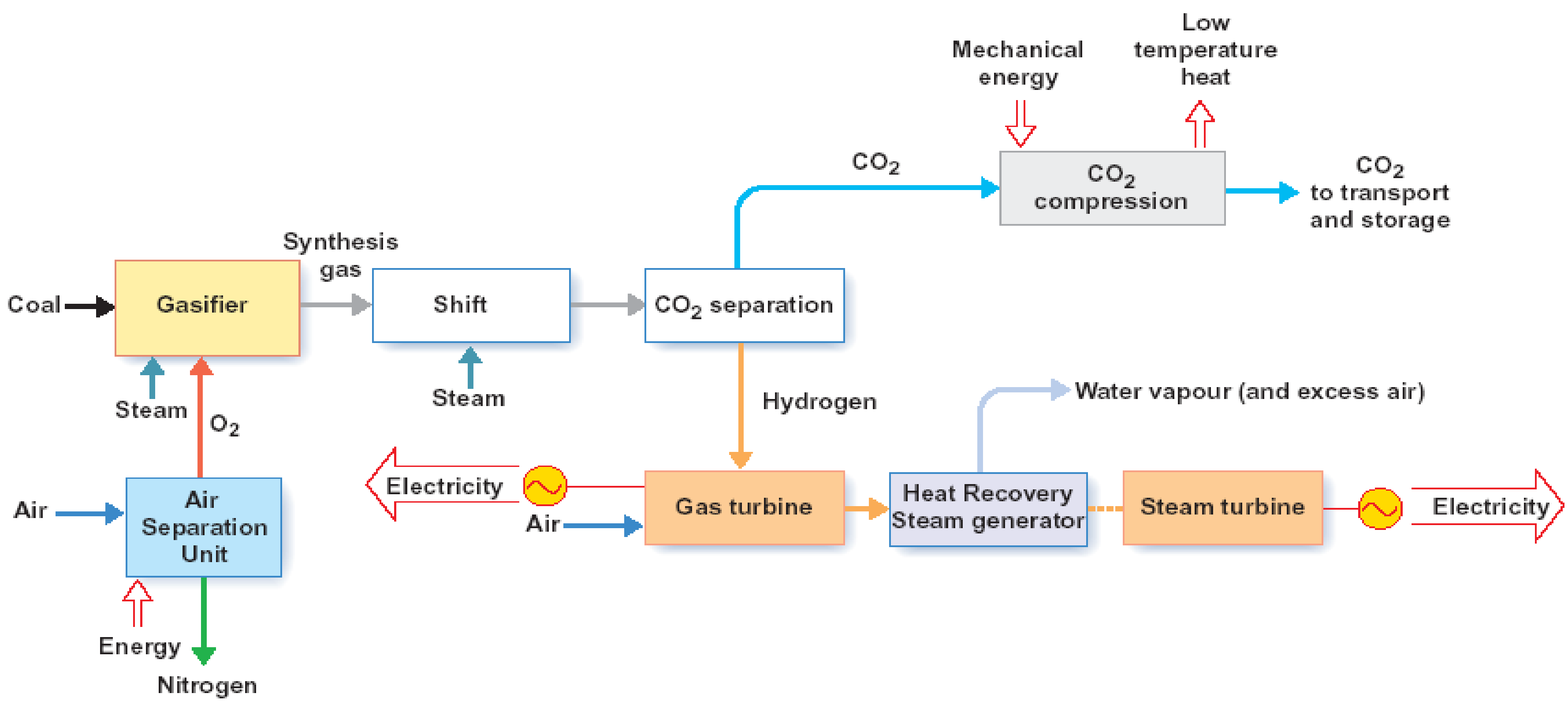
Pre-combustion - decarbonisation capture



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Lars Stromberg 2004

Evaluation of the options

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CO_2 Capture
Evaluation of options

	Gas CC	Gas CC CO2 free Precomb	Lignite Lippendorf	CO2 free CO2/O2 Lignite	Lignite SA	CO2 free CO2/O2 Lignite	IGCC	IGCC CO2 free	IGCC	IGCC CO2 free
Reference	Sintef	Sintef	VAB	VAB	VAB	VAB	IEA	IEA	IEA	IEA
Fuel	Gas	Gas	Lignite	Lignite	Lignite	Lignite	Coal	Coal	Coal	Coal
Power output MW	400	392	865	700	500	500	776	676	750	700
Specific Investment cost EUR/kW	625	1430	1272	1570	1005	1366	1371	1860	900	1250
Efficiency %	60	49	42,7	34,3	47	39,8	43,1	34,5	48	43,2
Fuel cost EUR/MWh fuel	12,5	12,5	4	4	4	4	5,8	5,8	5,8	5,8
O&M cost EUR/MWh	2,7	5,8	4,0	5,0	3,4	3,9	6,7	9,5	6,0	7,8
CO2 emitted kg/MWh	335	53	836	7	760	4	786	142	706	102

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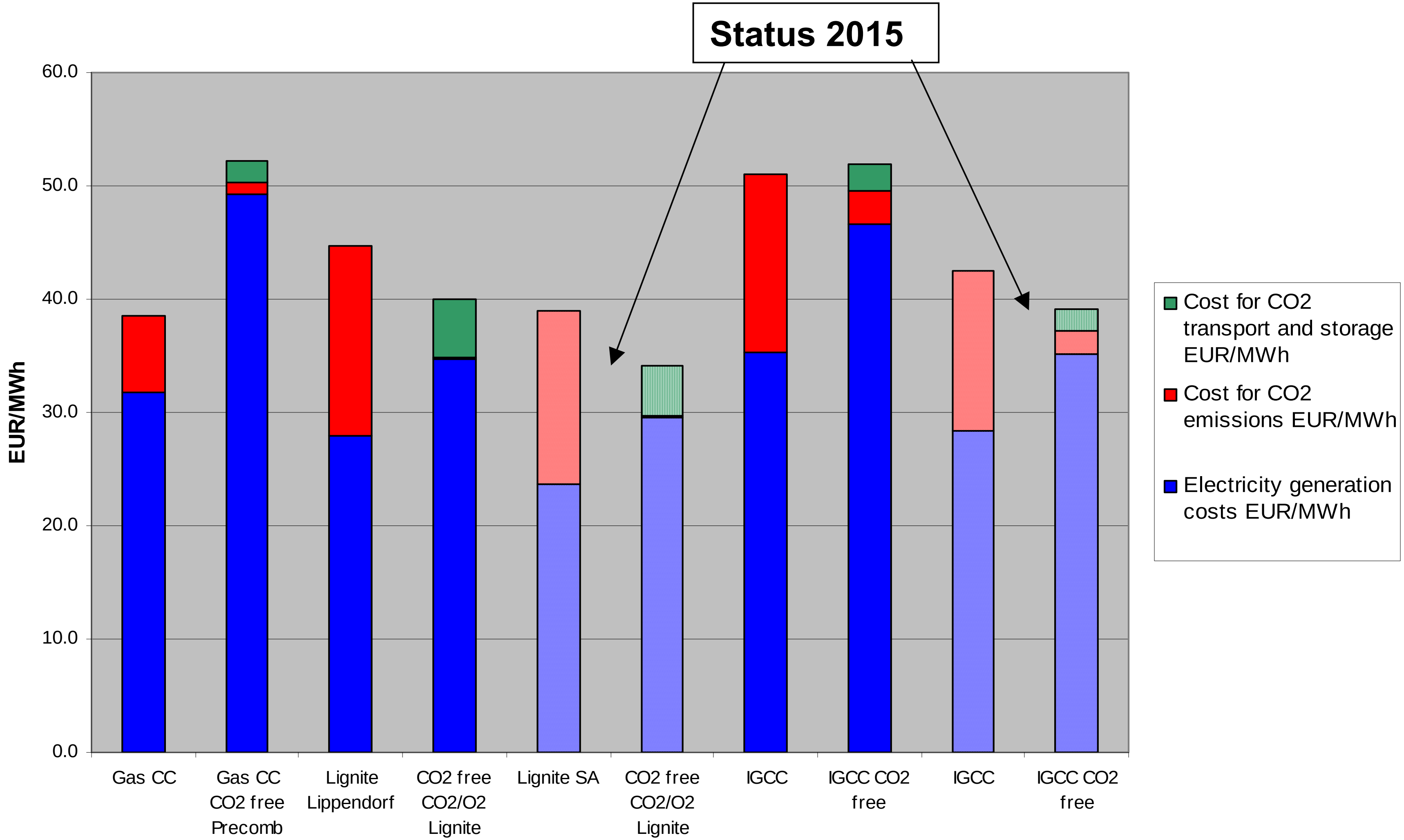
CO_2 Capture

Evaluation of options



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Opportunities with oxyfuel combustion

- Based on existing boiler and steam cycle technology
  - Can take advantage of ongoing development to increase efficiency of conventional power plants, e.g. AD700
- Co-capture of CO_2 and other pollutants gives a near zero emission power plant
  - Reduction in cost of flue gas treatment
- Next generation novel boiler designs
  - Compact PF boiler design through low recycle rate (higher oxygen concentration)
  - CFB gives opportunity to even lower recycle rate through use of solids for heat transfer

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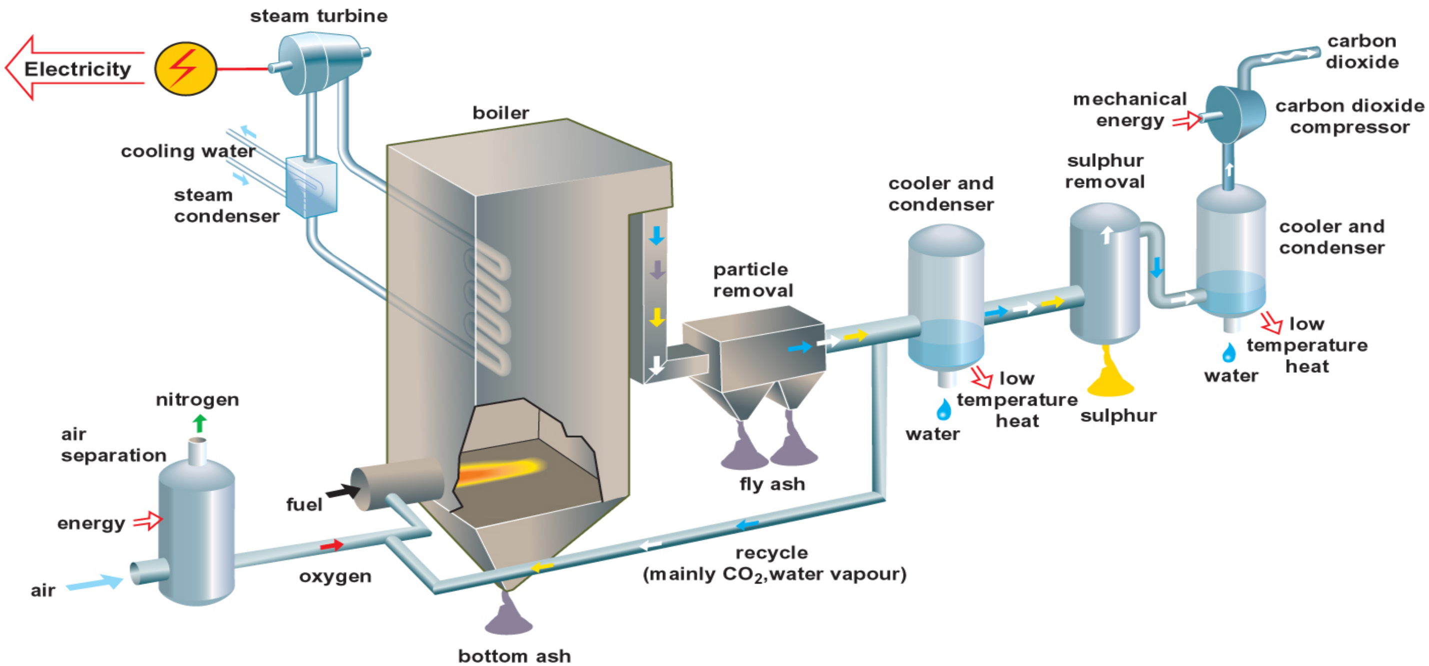
Challenge 1: Boiler design

- Design of next generation oxyfuel boiler, combustion considerations
- Reduced recycle rate or complete removal of recycle
- Optimisation of combustion for reduced formation of NO_x, to eliminate catalytic reactors



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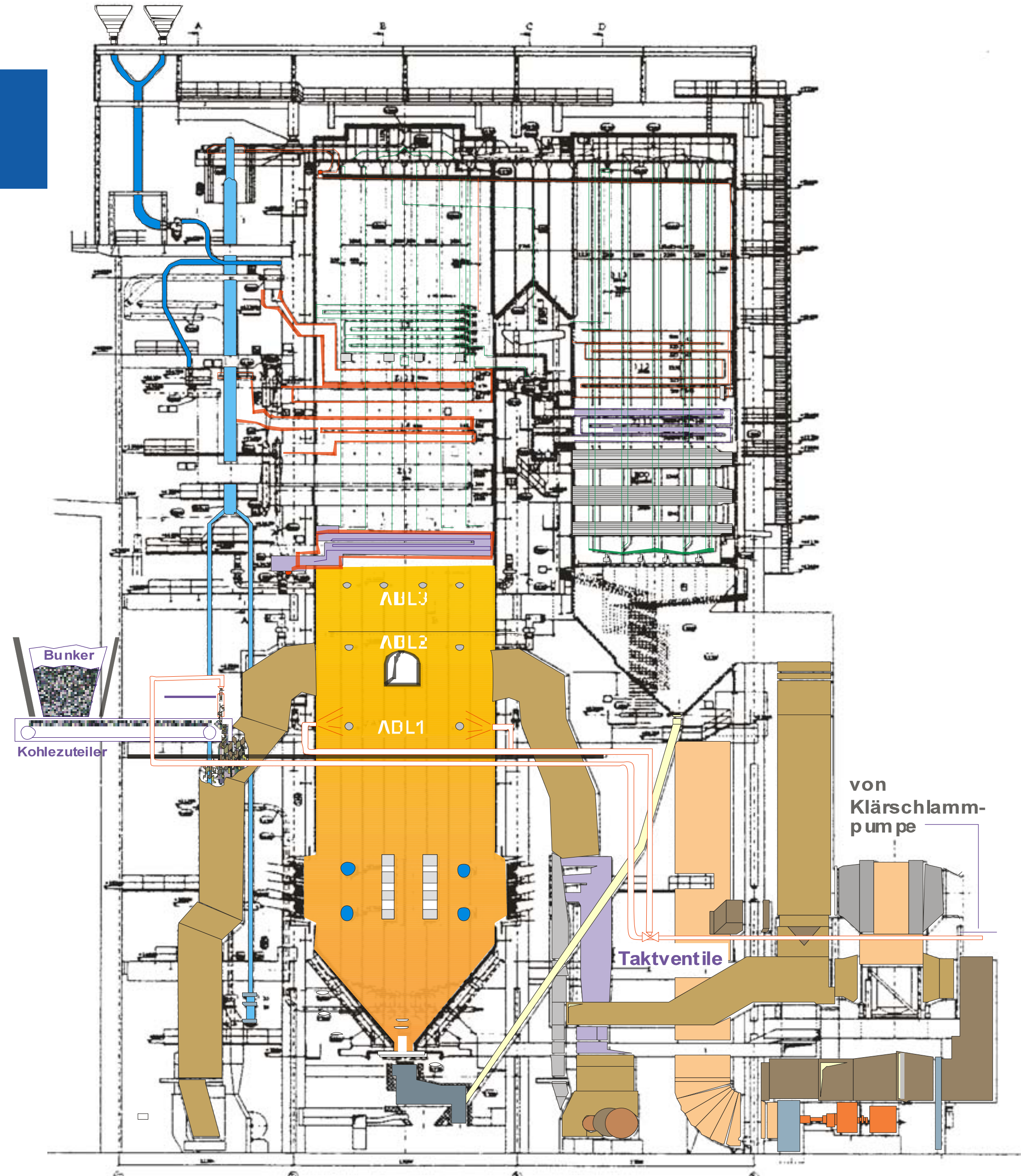
Boxberg IV



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O_2 /CO_2 combustion – experiments and modeling

Modeling of an experimental CO2/O2 flame

23 % oxygen + CO2+H2O

1300 Celcius

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Combustion in a CO_2/H_2O rich atmosphere

A number of parameters vary when combustion takes place with CO2/O2 instead of air as oxidizer

- Transport properties
- Thermal & radiative properties
- Volumetric flow rates
- Combustion kinetics
- Ash character

- ➔Heat release rate
- ➔Flame temperature
- ➔Heat fluxes
- ➔Thermal performance

Some figures honestly stolen from: Raj Gupta

The University of Newcastle

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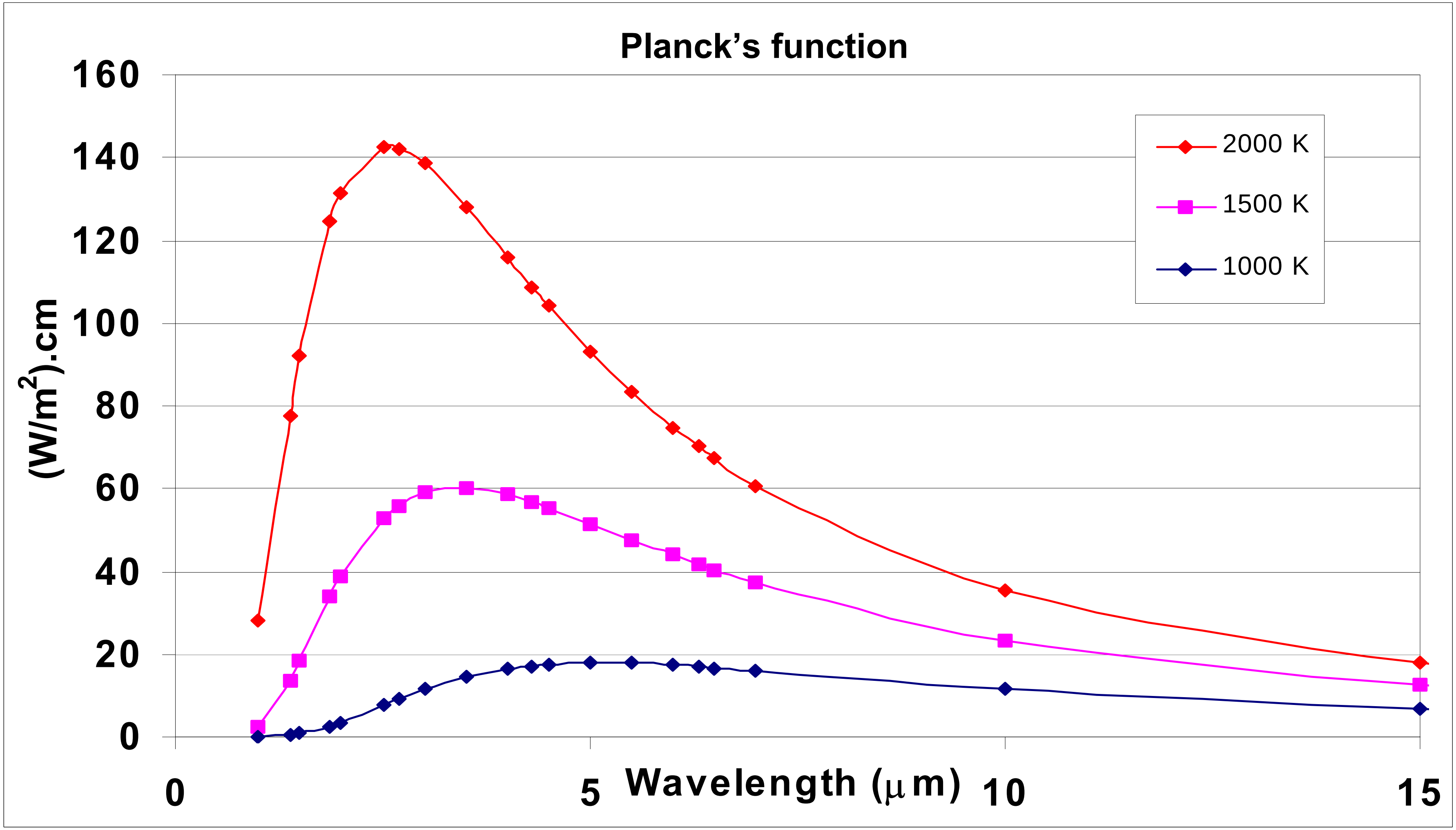
Planck's Distribution Function – H_2O & CO_2 Bands



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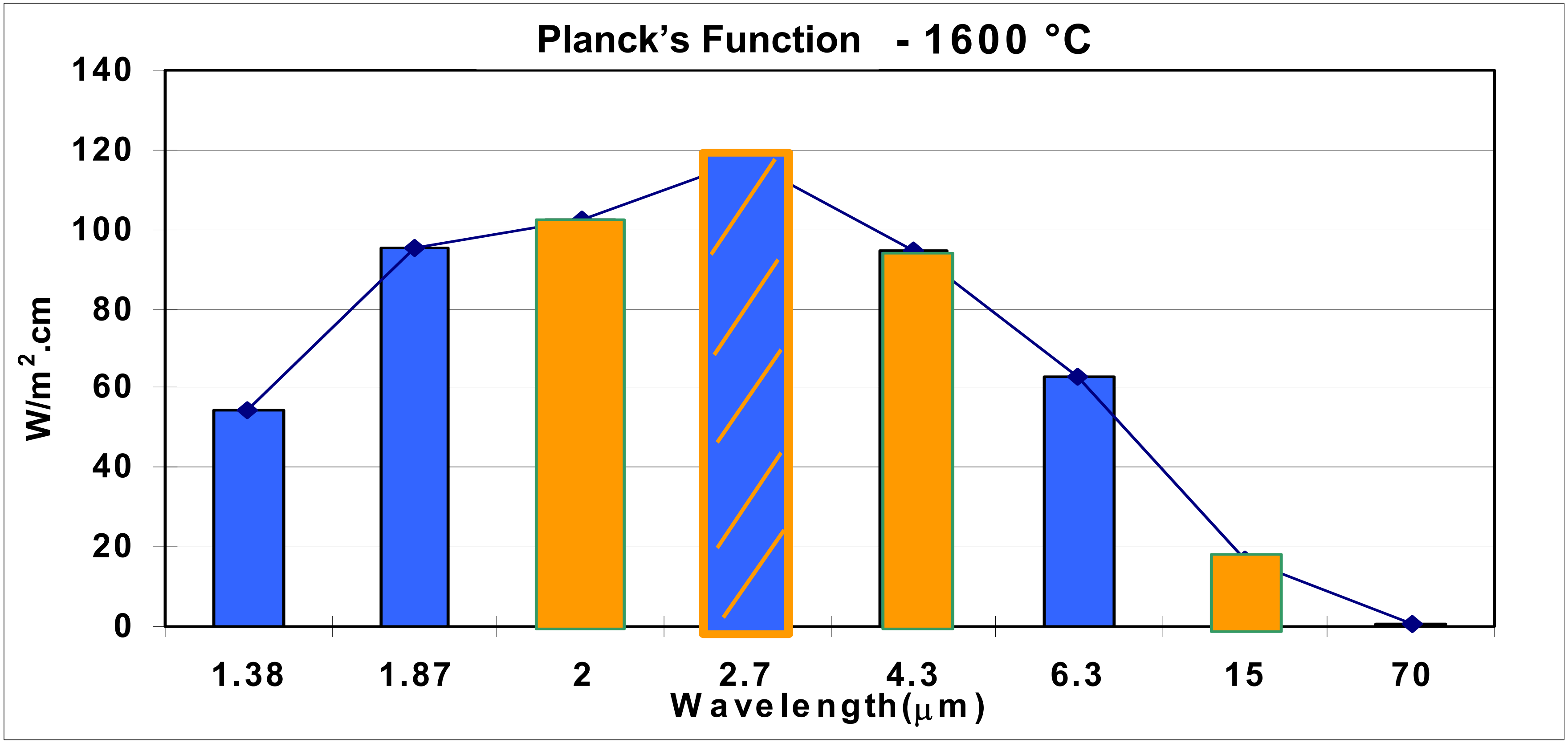
Principle Emission Bands: H_2O & CO_2

H_2O Bands (λ) (µm)

1.38 ; 1.87 ; 2.7 ; 6.3 ; 71

CO_2 Bands (λ) (µm)

2.0 ; 2.7 ; 4.3 ; 15.0



2.7 µm Common Band

Source Raj Gupta, U of Newcastle, Australia

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3-gray gas model

Total emissivity of gray gases:

Source Raj Gupta, U of Newcastle, Australia

I i $\left[\quad k \quad PS \right]$ i

$$a_{\varepsilon,i} = \sum_{j=1}^{J} b_{\varepsilon,i,j} \; T^{\,j-1}$$

Optimized values for:

***i* = 3** *(no. of gray gases)*

***j* = 4** *(polynomial order)*

Where,

$a_{\varepsilon,i} = i^{th}$ *gray gas emissivity weighting factors*

$\left[\quad k \quad PS \right]$ th i

S *(Partial pressure * Path Length) of absorbing gas*

$b_{\varepsilon,i,j} =$ *emissivity gas temperature polynomial coefficients*

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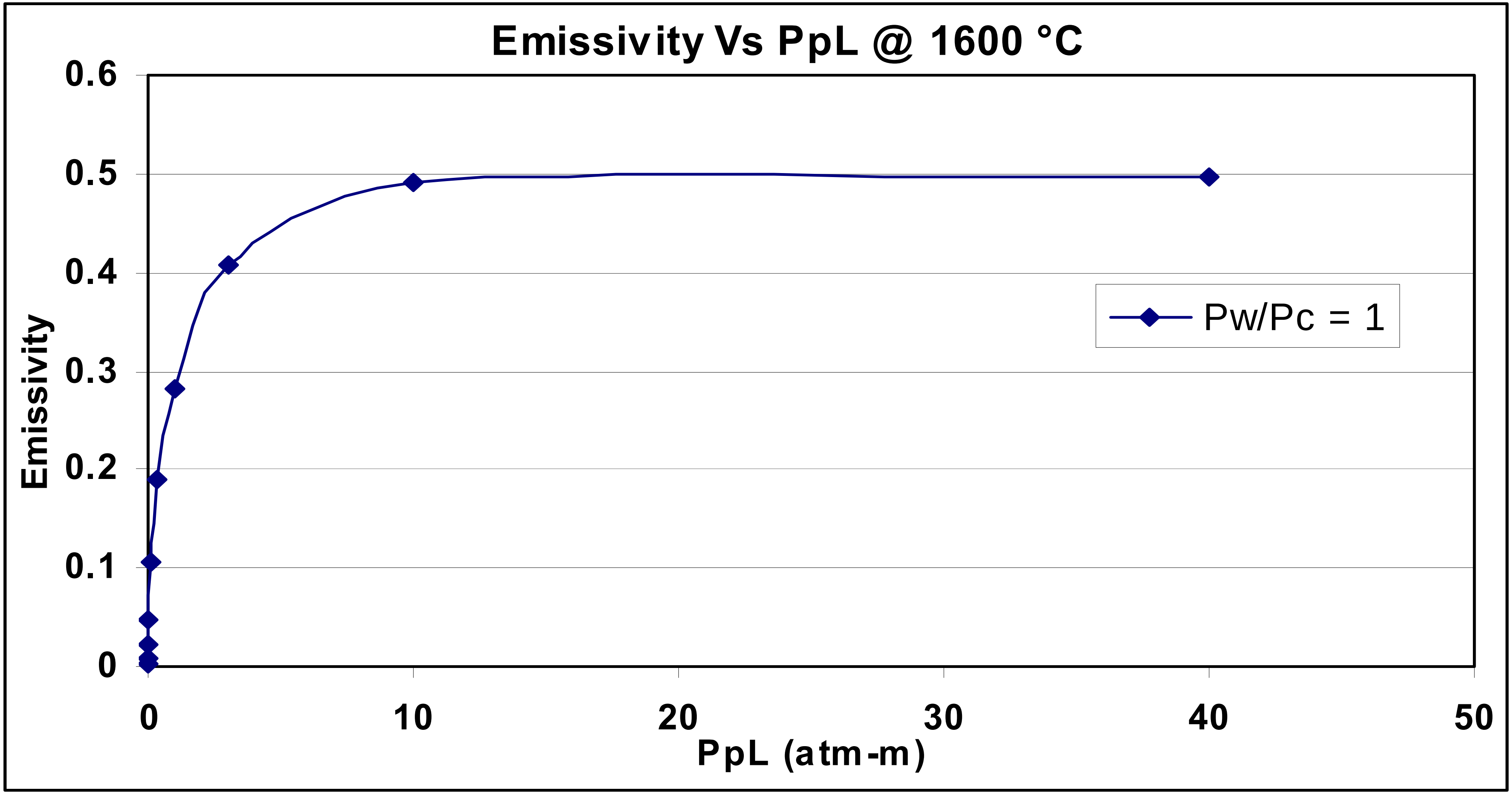
Article: T.F.Smith et al (1982)

WSGGM – Emissivity Vs PpL – 1600 °C



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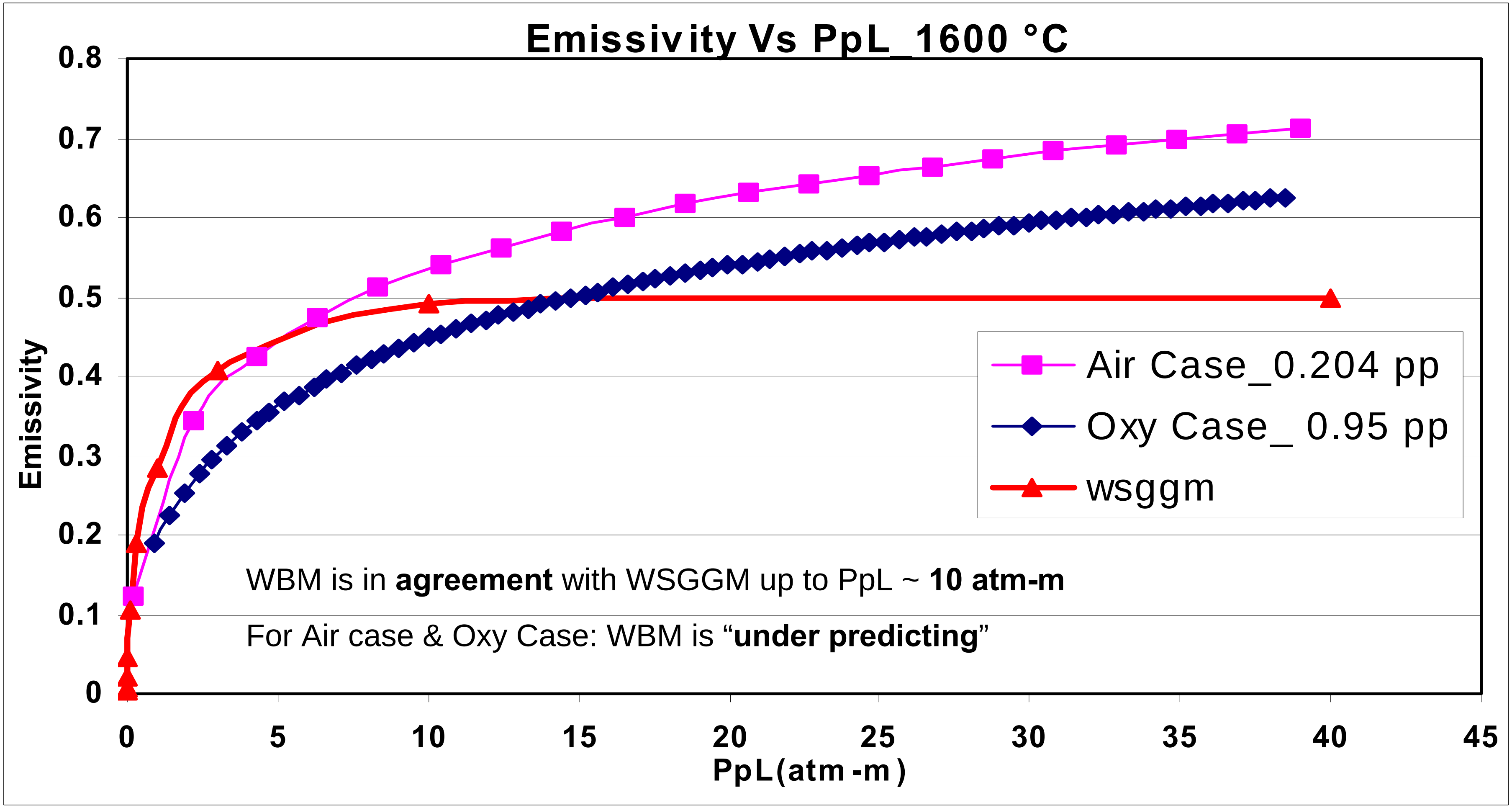
Source Raj Gupta, U of Newcastle, Australia

WBM vs WSGGM Model for PpL @ 1600 °C



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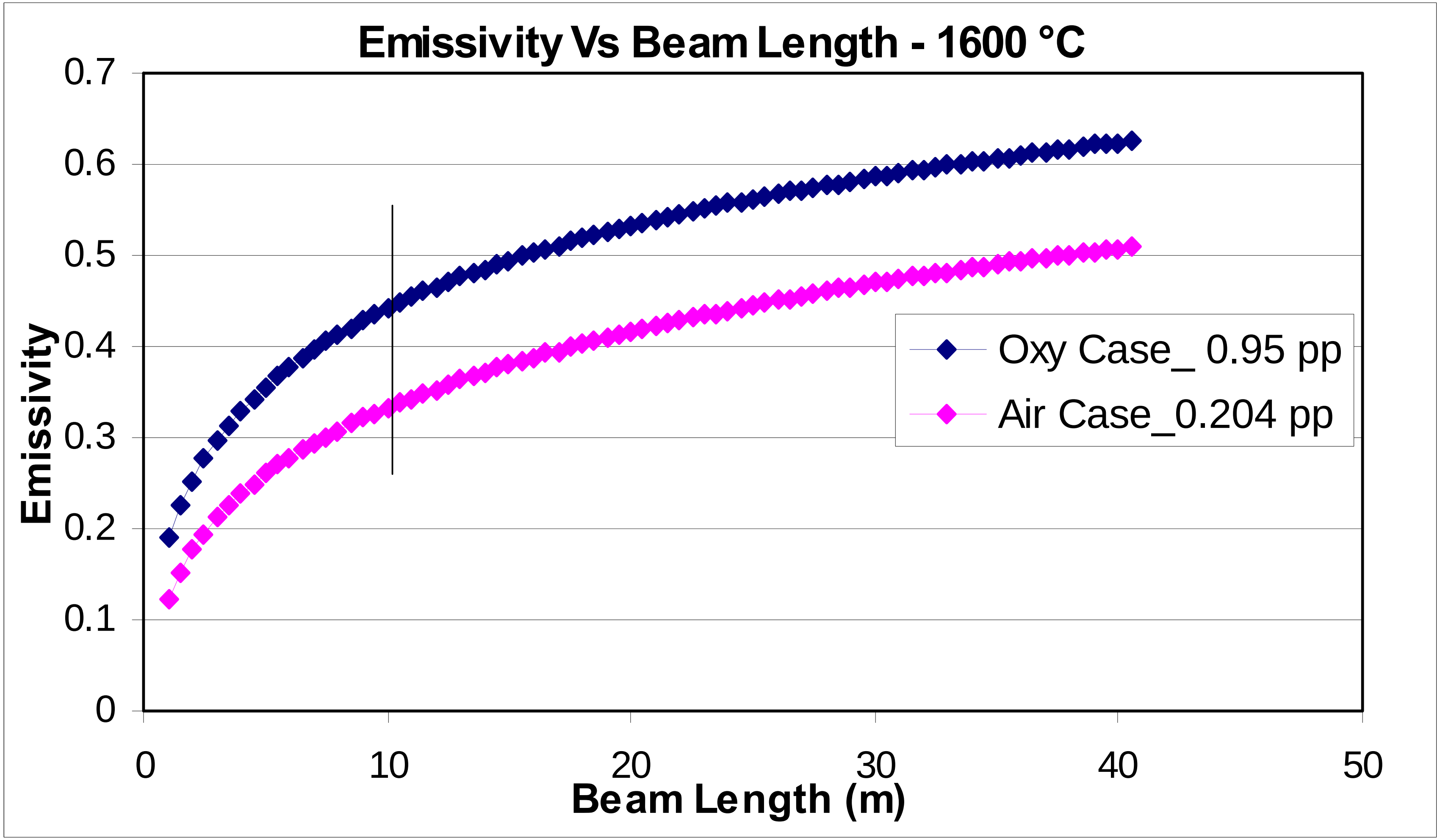
Source Raj Gupta, U of Newcastle, Australia

WBM – Air vs. Oxy Case for BL – 1600 °C



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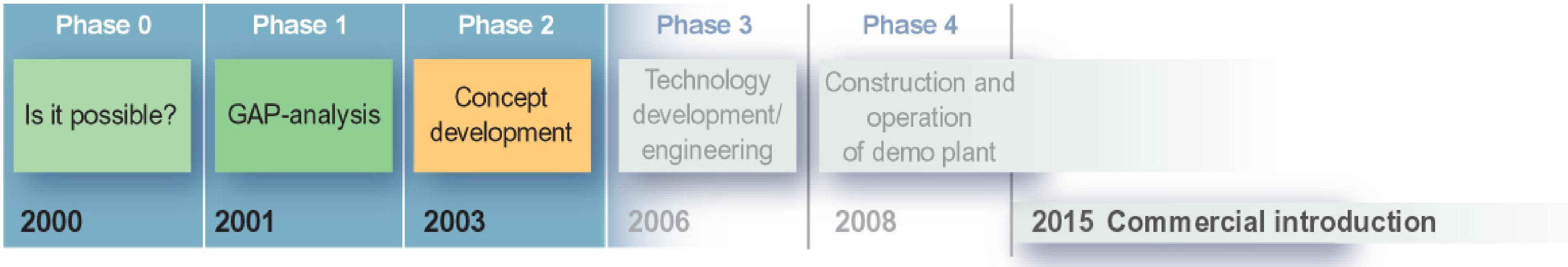
Source Raj Gupta, U of Newcastle, Australia

CO_2 free Power Plant
15 years of research and development



– Development target 20 €/ton stored CO_2

– Initial feasibility studies in 2001

– GAP analyses in 2002

– Concept development in 2003-2006

– A 250 MW electric demo-plant by latest 2010

– Commercial concept after 2015

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Focus of the work to reduce CO_2

Focus is different for each part of the chain

Capture

- Develop and evaluate the concepts
- Cost reduction
- Validation and verification

Transport

- Apply known concepts to scale
- How to develop an infrastructure

Storage

- Verification of technology
- Potential, actual availability
- Risk, Security and Environmental consequences
- Building confidence and acceptance

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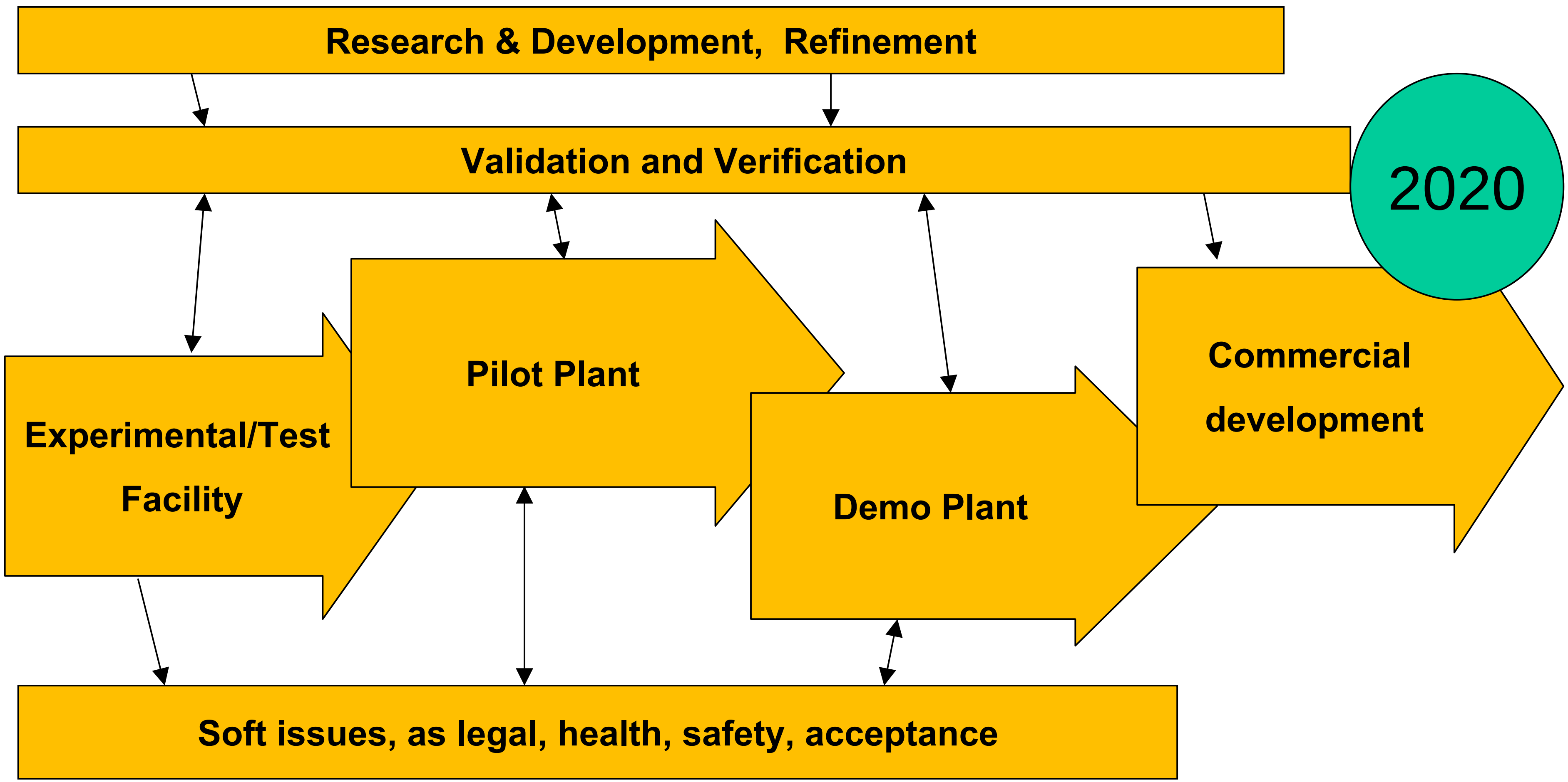
CO_2 Free Power Plant – Work Scheme



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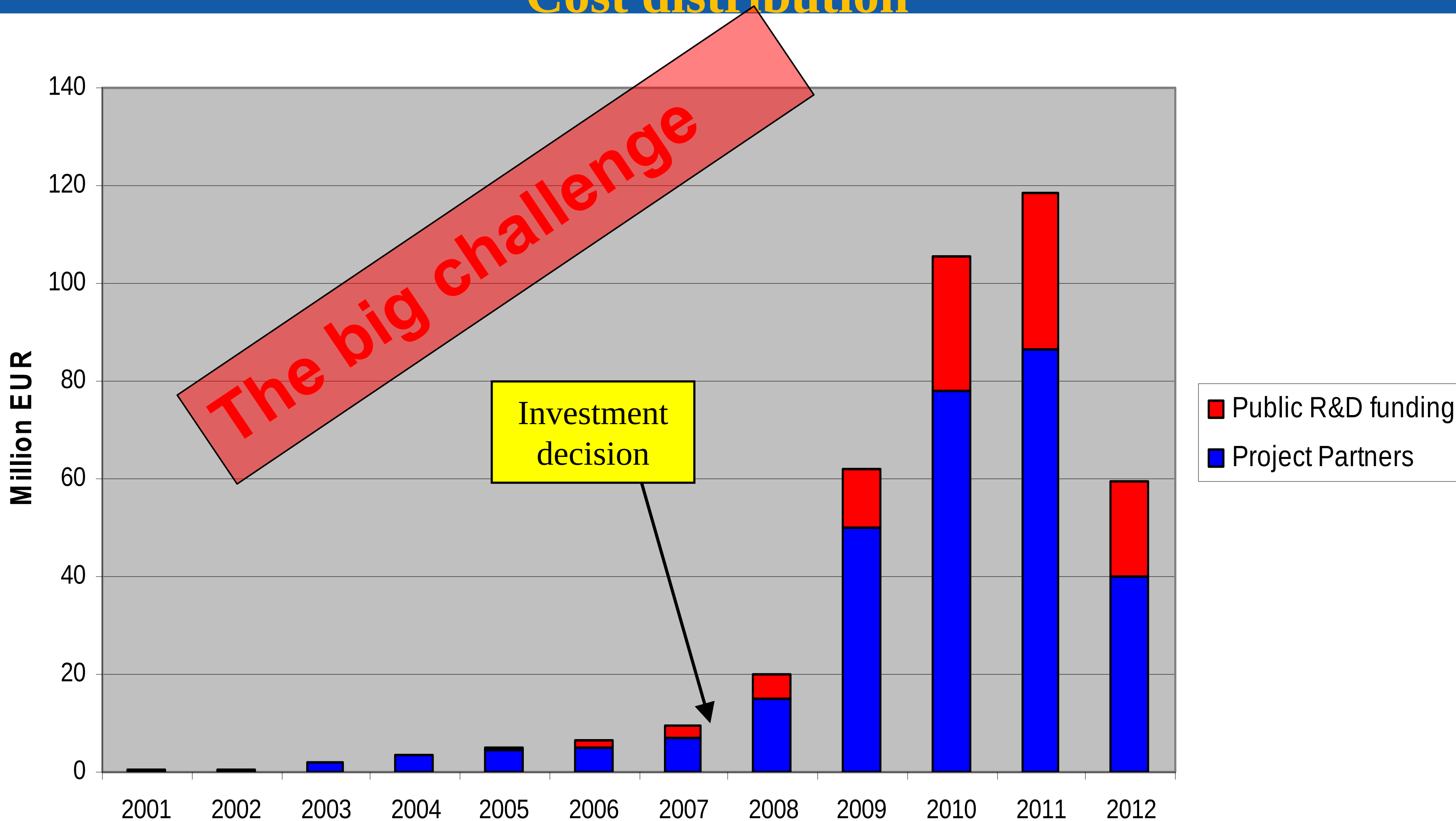
CO_2 free Power Plant Demo
Cost distribution



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Conclusions

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Conclusions

- Fossil fuels are needed many decades yet. There is no other option available large enough
- CO_2 capture and storage can enable energy generation without CO_2 emissions at a lower cost than most renewable alternatives.
- The CO_2 emission trading scheme sets the commercial framework for new technology
- If CO_2 capture and storage is developed to a viable option with avoidance costs down to 20 €/ton of CO_2, the technology can be commercially introduced.
- ”Carbon dioxide free” energy production from fossil fuels can not be introduced at a larger scale before 2015.
- Coal is competitive with gas. The commercial alternatives will be coal with CO2 capture and storage and gas without capture, taking the punishment from the trading system.

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Schwarze Pumpe power plant

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