CO_2 capture and sequestration (CCS)

Overview of technology options for CO_2 separation and permanent geological storage

Sustainable Power Generation course (SPG)
MJ2405

Miro Petrov

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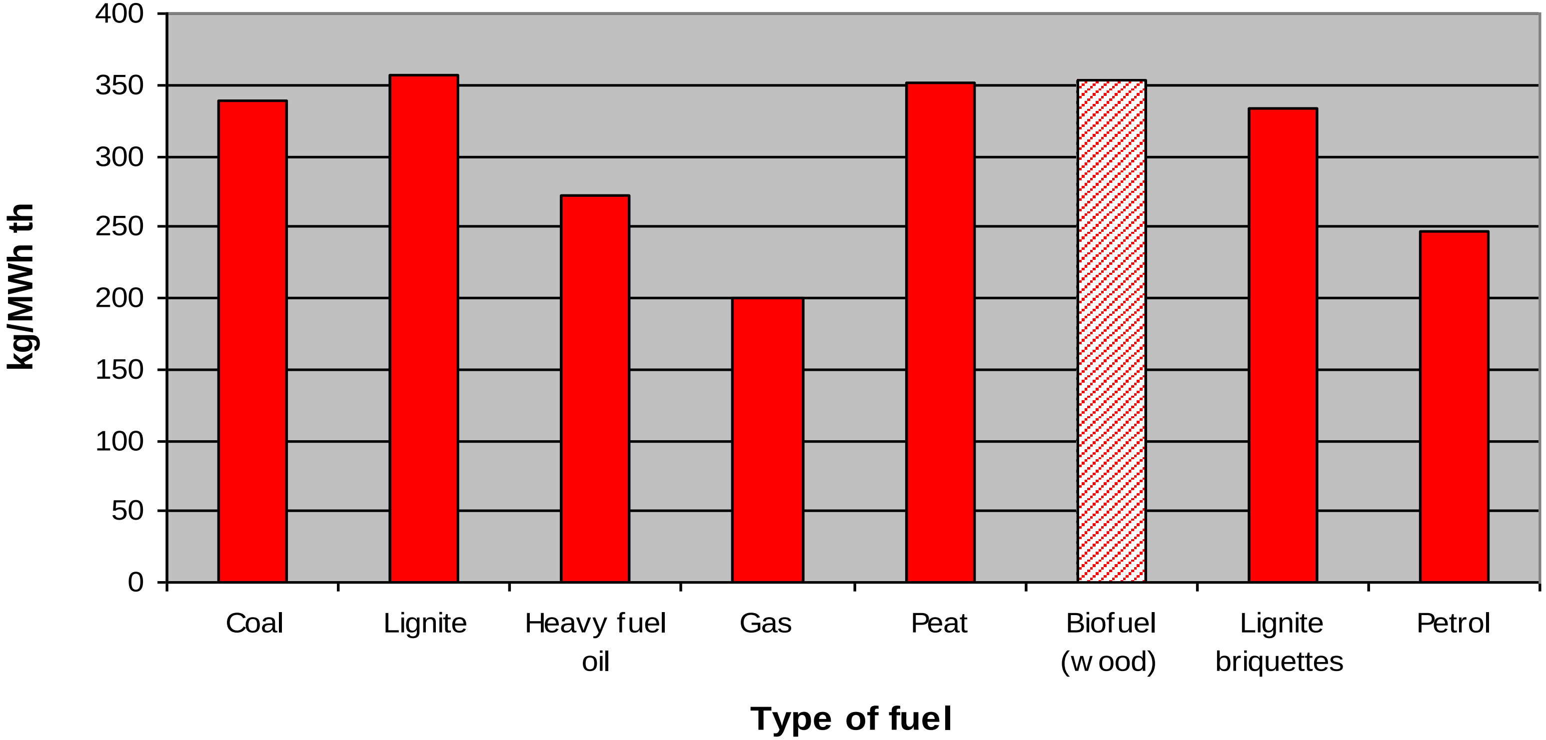
CO_2 release from combustion of different carbon-based fuels

Rough average values for some typical fuels, in kg CO2 per unit heat output:



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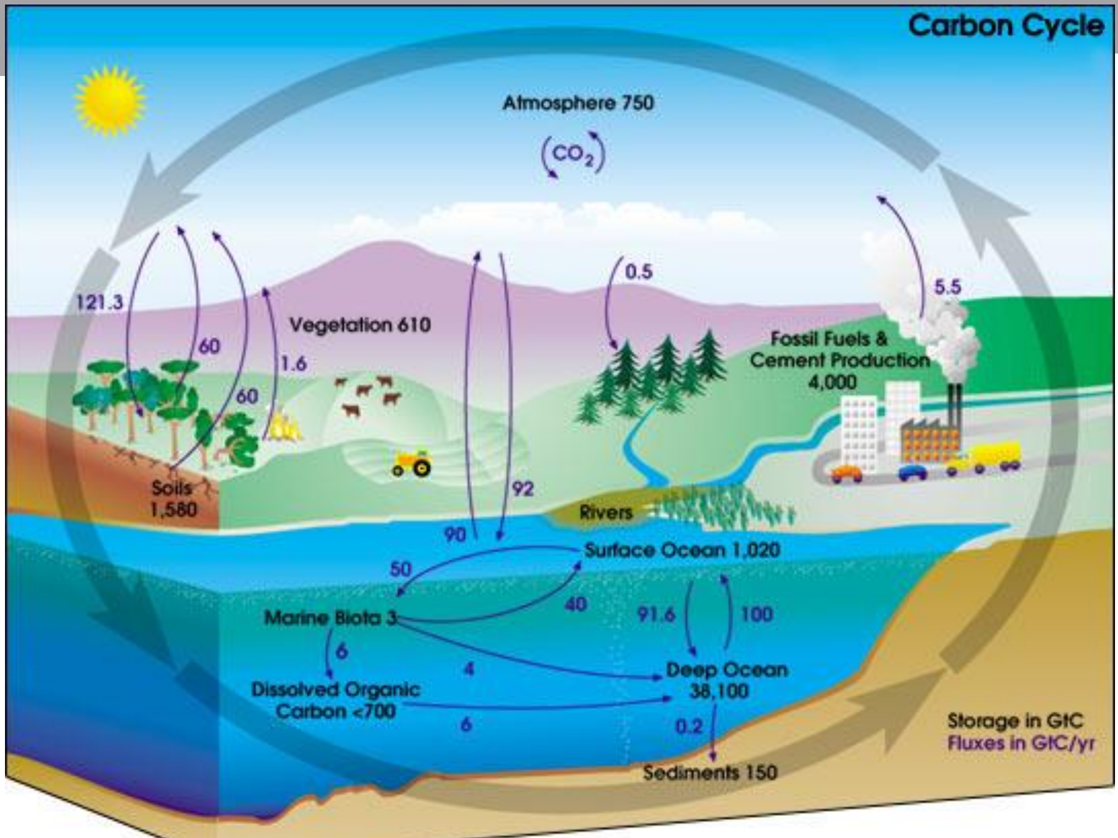
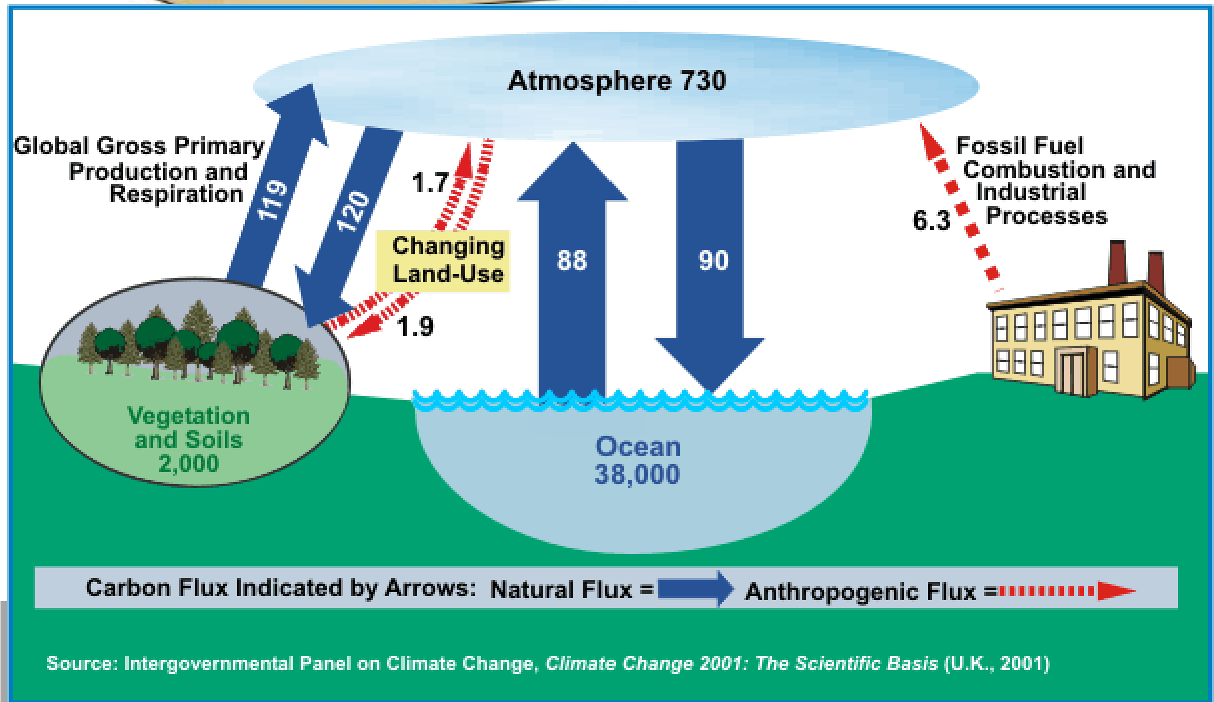
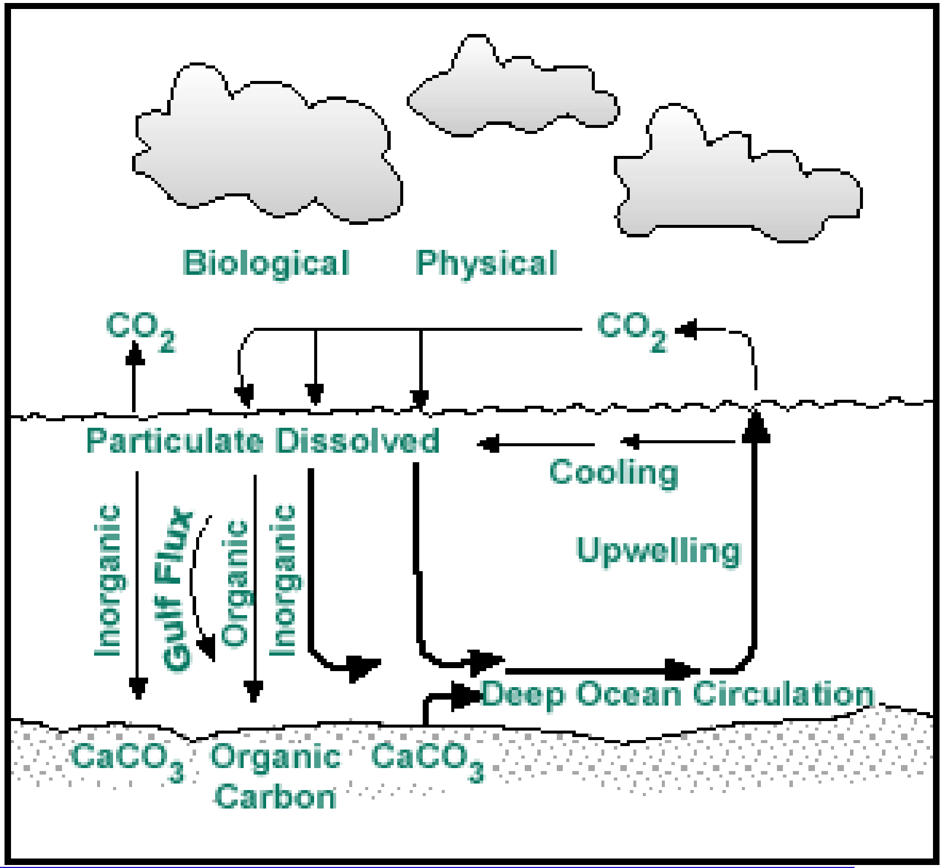


Carbon recirculation on our Planet

Most stable form of carbon – in carbonates!

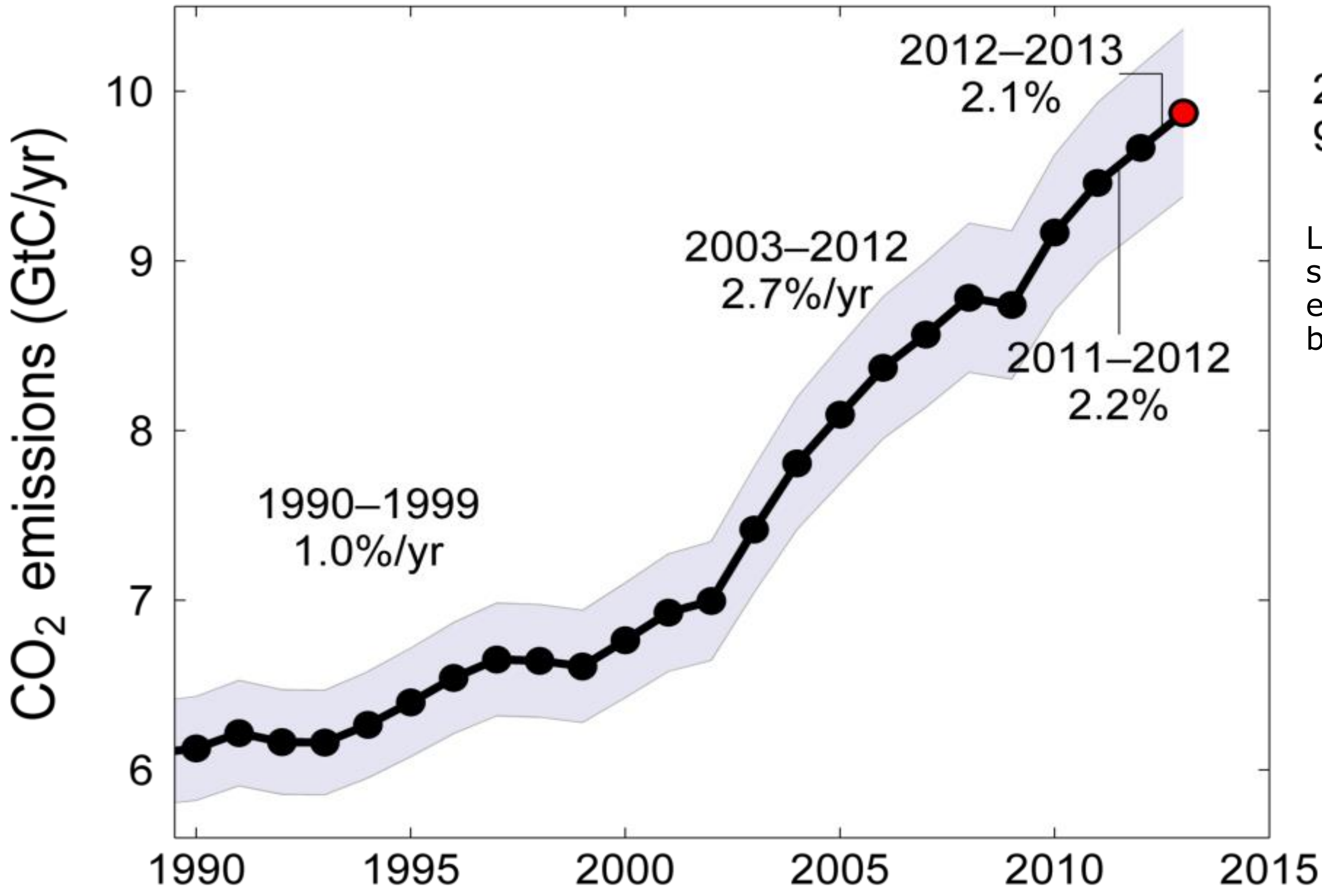




Growing CO_2 emissions

(GigaTon of Carbon per year, %-growth rate worldwide)

Not only from fossil fuels, but also from various industrial activity; natural sources like volcanoes and bogs; other man-made factors like deforestation, etc..



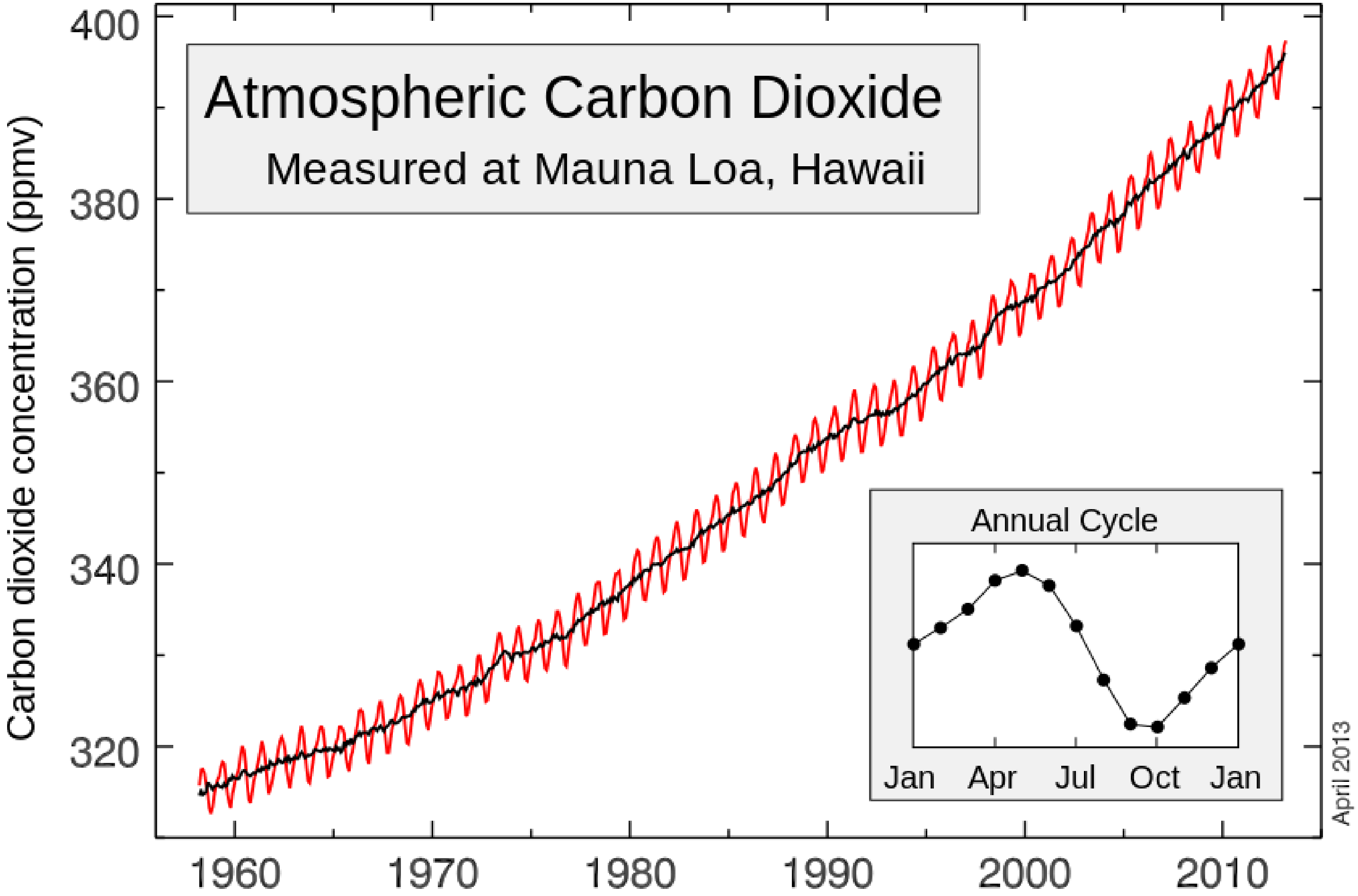
2013
9.9 GtC

Latest stats again show 2% expected emission increase by 2017-2018

Annual CO_2 concentration cycle

Vegetation growth in the summer season for the large land mass in the Northern hemisphere acts as a carbon trap.

This underlines the importance of using & preserving biomass as the best & fastest option for carbon capture and storage.



Three main alternatives for CO_2 capture
from power generation sources

- All possible technologies for CO2 separation are difficult and expensive
- Could be applied not only to power generation but also for CO2 capture from industrial processes or from other CO2 sources
- ***Three main capture methods exist, and all of them have a chance to reach commercial status:***

  1) Post-combustion capture;

  2) Pre-combustion capture;

  3) Oxyfuel combustion options:

  a) with air distillation unit and combustion in pure oxygen,

  b) with a metal oxide as oxygen carrier (chemical looping).

- There is no quick solution. Refurbishment of old plants is difficult and sometimes impossible. New developments are costly. Always some efficiency losses and ancillary power consumption are involved.

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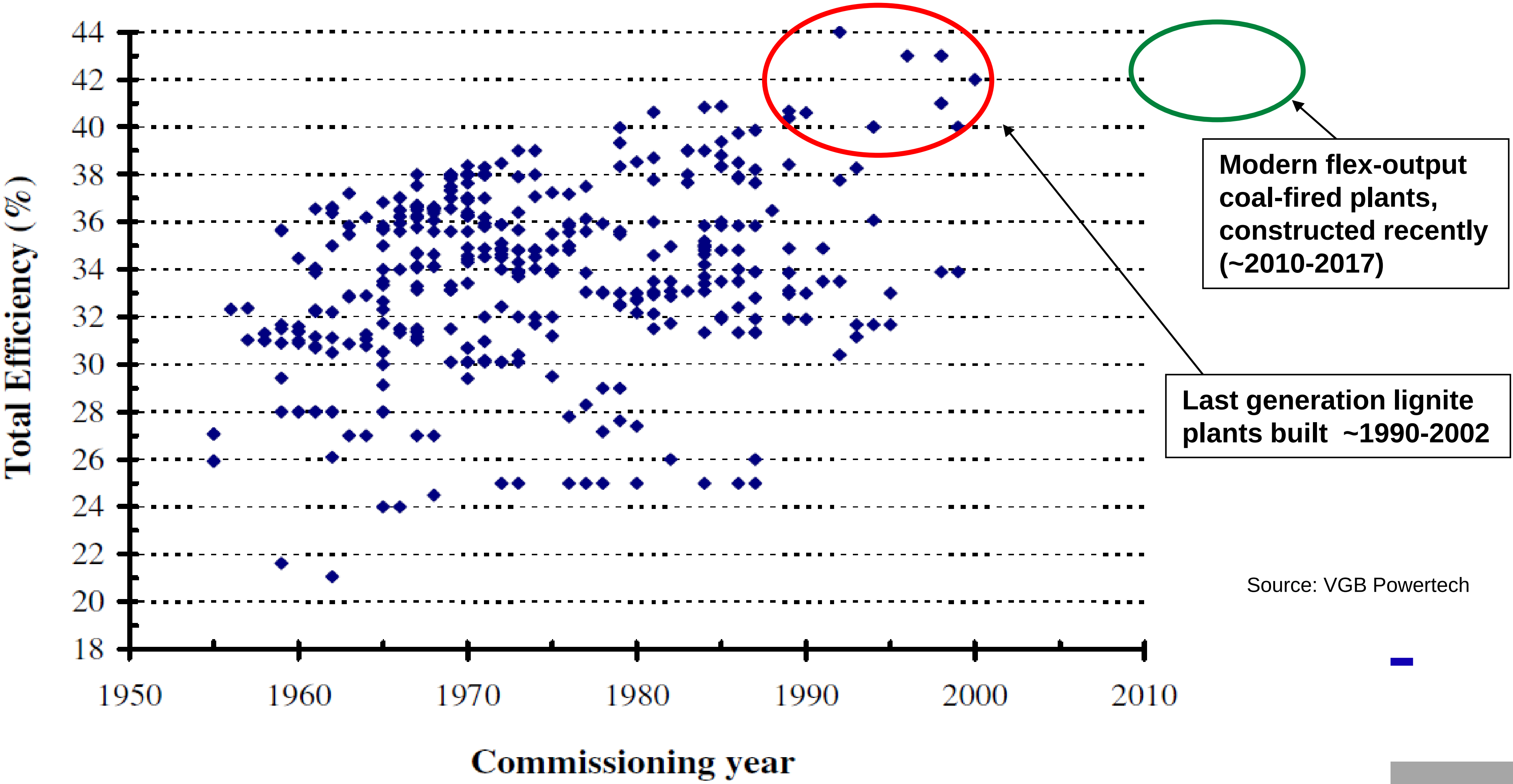
The better way forward:
Higher efficiency instead of CO_2 separation

Coal-fired power plant efficiency: Historical development in Germany:



Source: VGB Powertech

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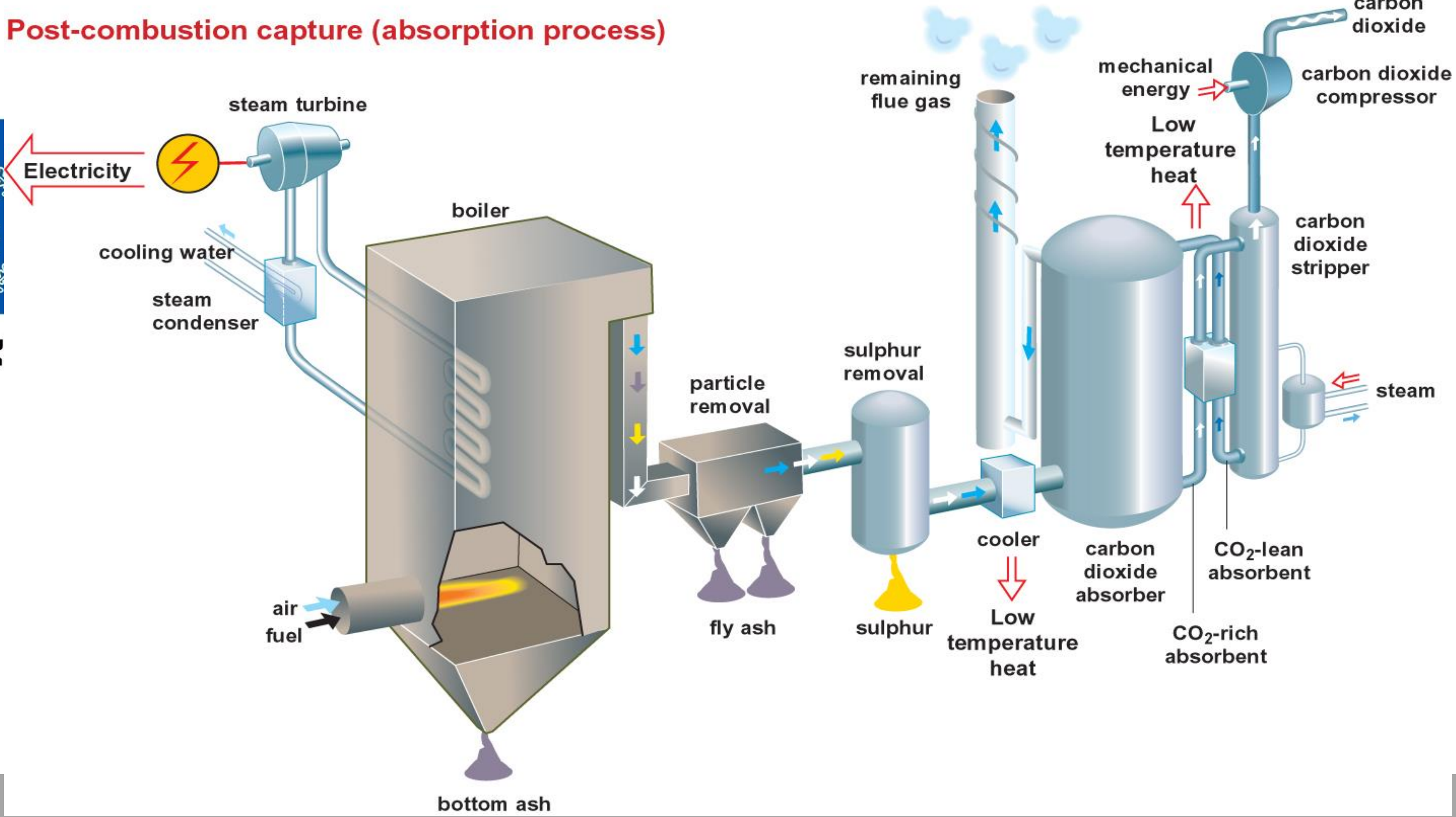
Post-combustion CO_2 capture

Keeping the combustion process intact and scrubbing away CO_2 from the exhaust gases. Commercially available in small or medium scale industrial applications. Expensive and energy-consuming for power plant applications.
Will be a winner if energy consumption can be reduced!



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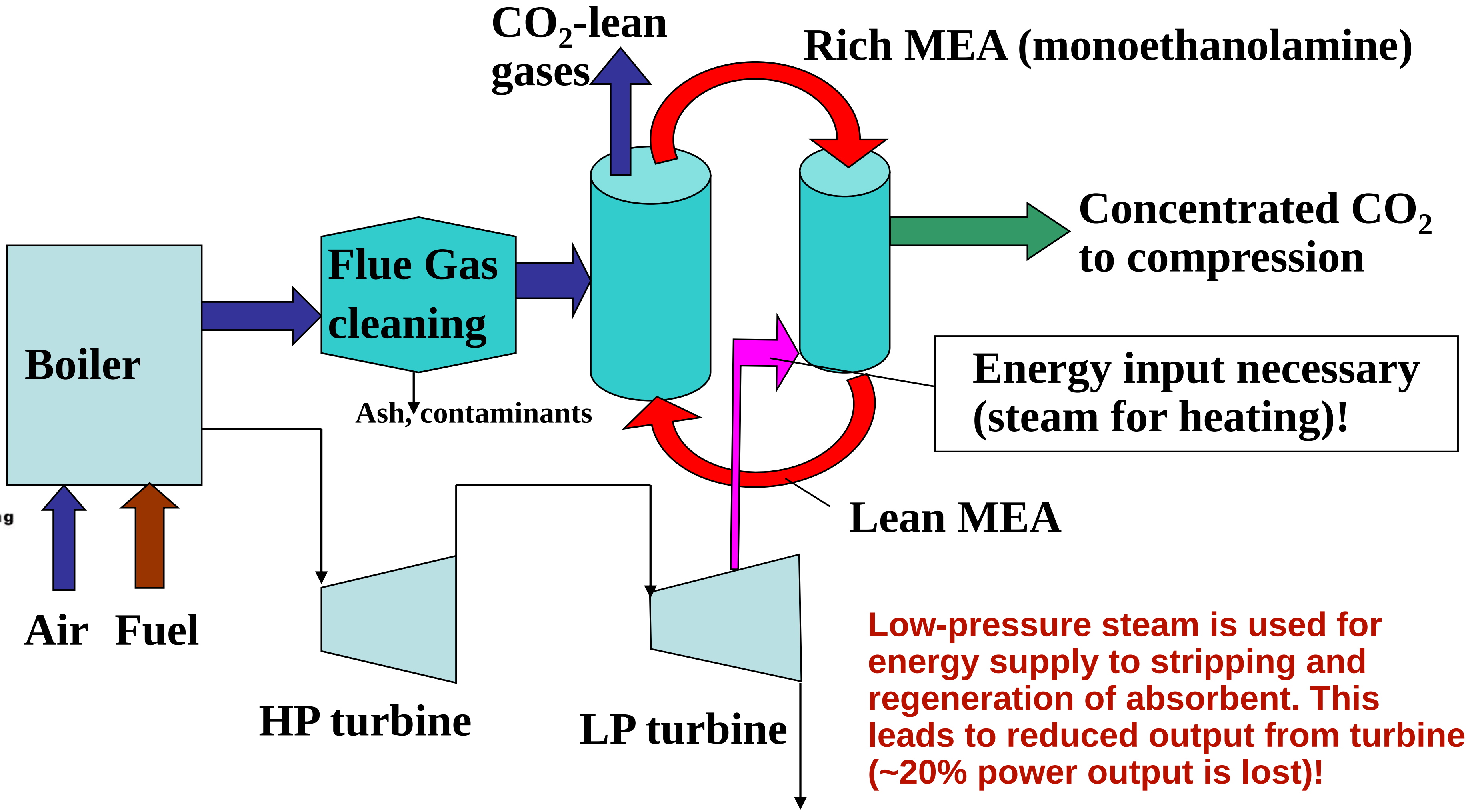
Amine Absorption process scheme



Low-pressure steam is used for energy supply to stripping and regeneration of absorbent. This leads to reduced output from turbine (~20% power output is lost)!

Main difficulty:
Low CO_2 concentration in typical exhaust gases

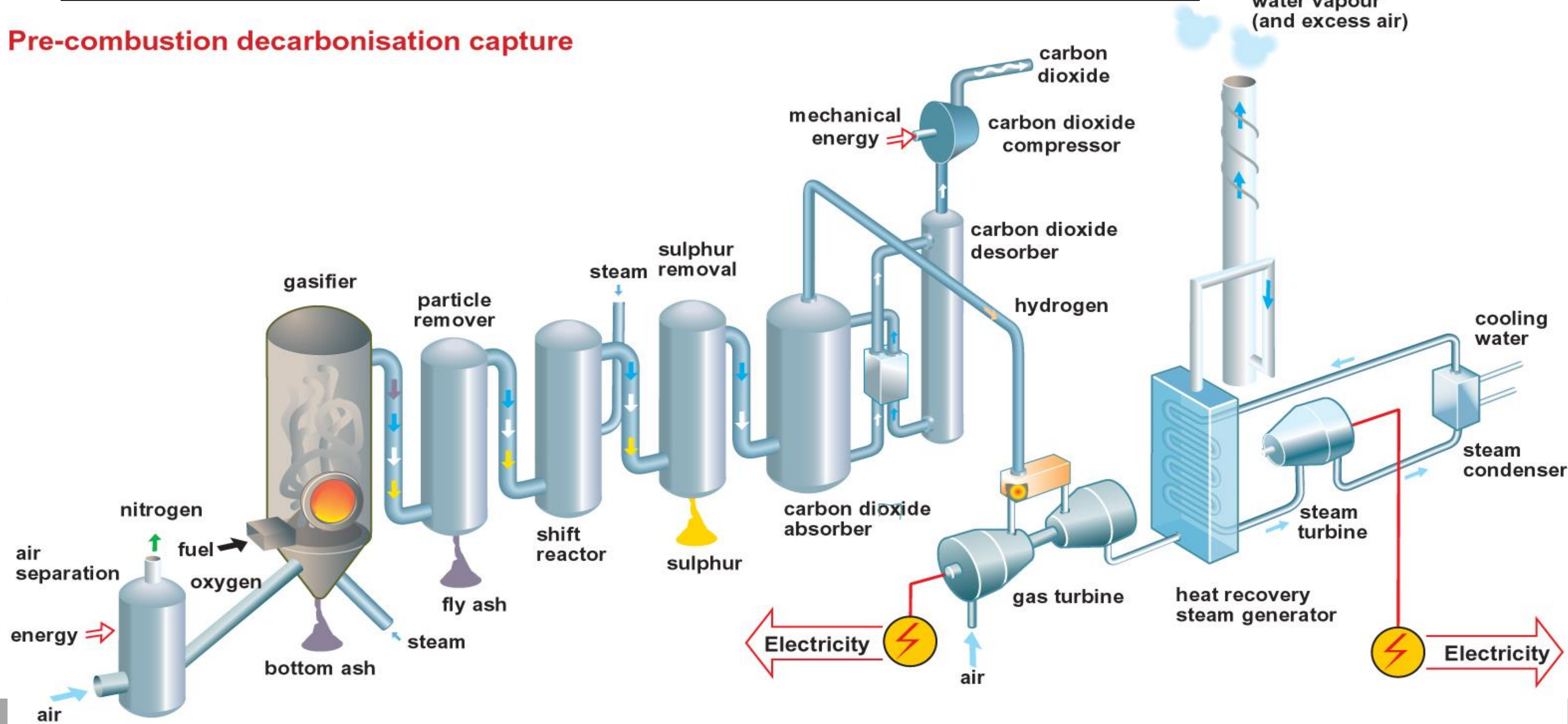
Together with impurities and acid species, typical combustion gases are not easy for CO2 absorption processes because they are very diluted

	CO_2	Impurities	Pressure
Natural Gas Turbine Exhaust	3-4%	low SO_x and NOx levels, 12-15% O_2	1 atm
Coal/Oil Fired Boilers	11-14%	high SO_x and NOx levels, 2-5% O_2	1 atm
IGCC Syngas Turbine Exhaust	4.5-6%	Low SO_x and NOx	1 atm
Blast Furnace Gas (after combustion)	25-30%	SO_x and NOx present	1 atm
Cement Kiln off-gas	15-35%	Could have many impurities	1 atm

Pre-combustion CO_2 capture

Altering the fuel before the combustion process (extracting carbon from the fuel), for example via gasification and production of hydrogen as an intermediary energy carrier.

Internal Gasification Combined Cycle (IGCC) can do the job if carbon capture is integrated with it. Several demo plants around the world.



Pre-combustion CCS project example

The RWE project of a 450 MW power plant with CO_2 storage (IGCC-CCS)

RWE

- Basic technology: IGCC
- El. capacity: 450 MW_{gross}, 330 MW_{net}
- Net efficiency: up to 40 %
- CO_2 storage: 2.6 mill. t/a in depleted gas reservoir or saline aquifer
- Commissioning: 2014

In RWE Power, RWE has inhouse power plant and gasification know-how and, in RWE Dea as an upstream company, it has basic inhouse know how for CO_2 storage.

RWE Power, Werner Renzenbrink 05.10.2007

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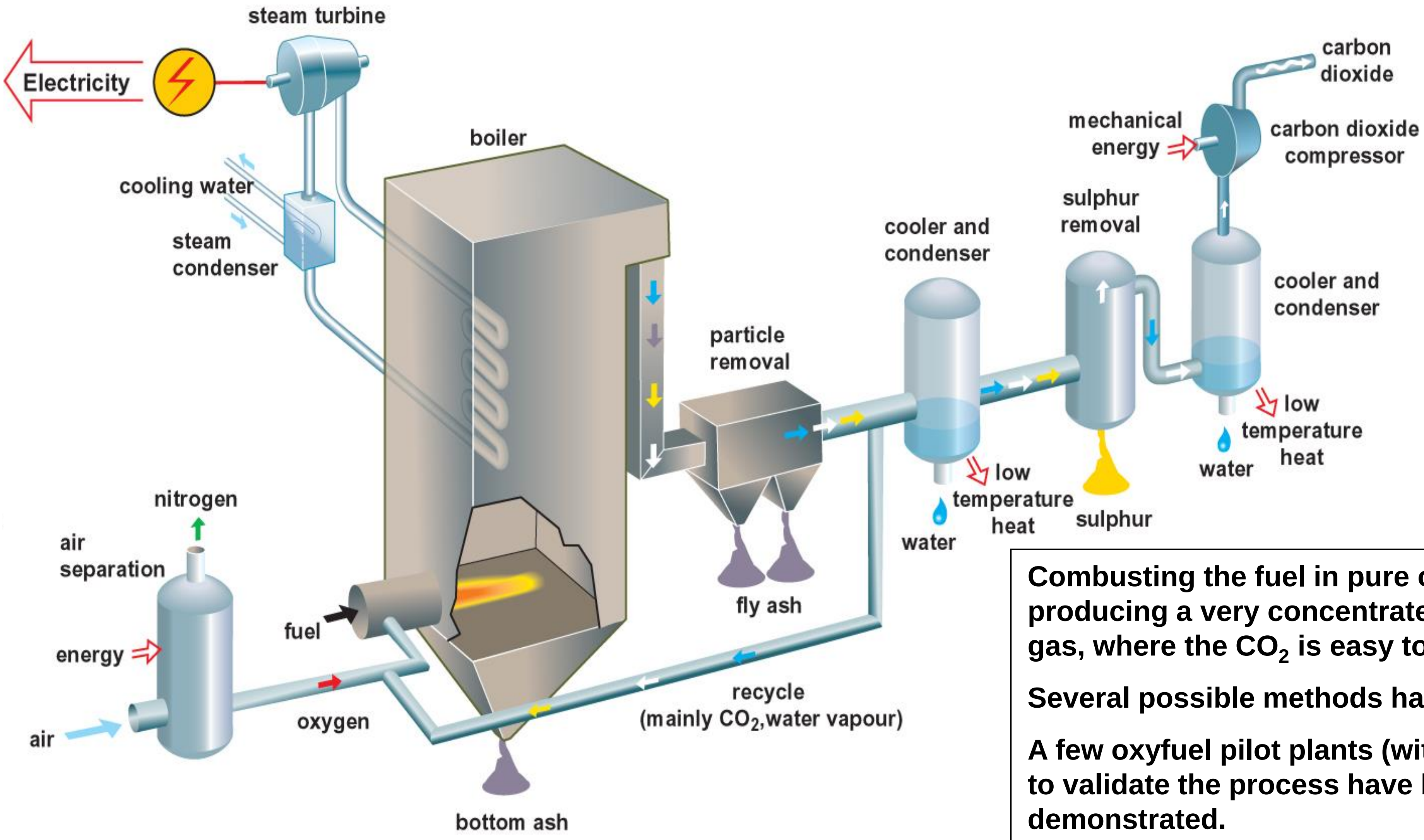
"Oxyfuel" technology with air distillation



Combusting the fuel in pure oxygen and thus producing a very concentrated CO_2-rich flue gas, where the CO_2 is easy to extract.

Several possible methods have been tested.

A few oxyfuel pilot plants (with air distillation) to validate the process have been designed and demonstrated.

Schwarze Pumpe oxyfuel pilot plant construction phase (2008)

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Schwarze Pumpe pilot plant
- successful operation in 2011

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Coal flame in the oxyfuel boiler

Results from Schwarze Pumpe, by June 2012

Operating hours	17 000
Captured amount of CO2	110 500 t
CO_2 - removal rate	> 93 %
CO_2 - purity	> 99.7 %

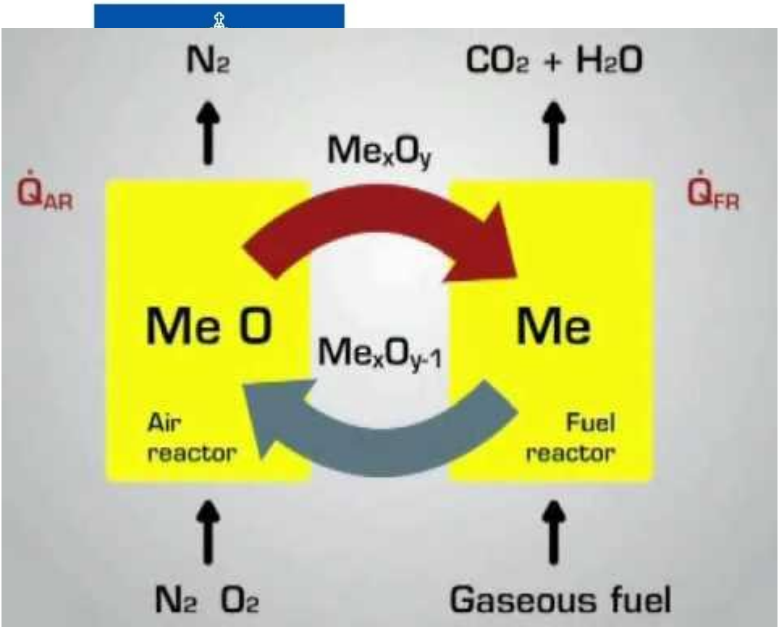
- Stable oxyfuel operation
- All emission and safety values contained
- Interaction between all plant components and subsystems validated
- Over 50 different tests with the Boiler, ASU, CO2 plant and all other components
- Plant availability & reliability: very high
- Integration of a "cold DeNOx" successful

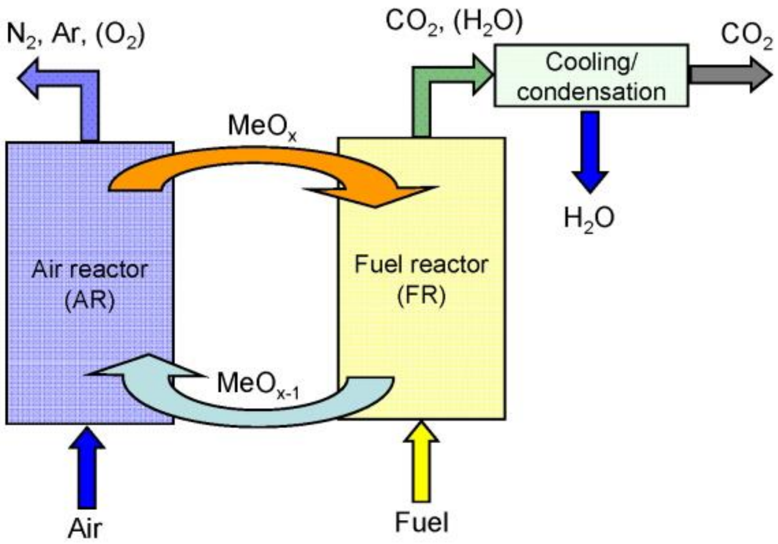
Four different coal burners were tested.
New tail-end concepts commissioned with good results.

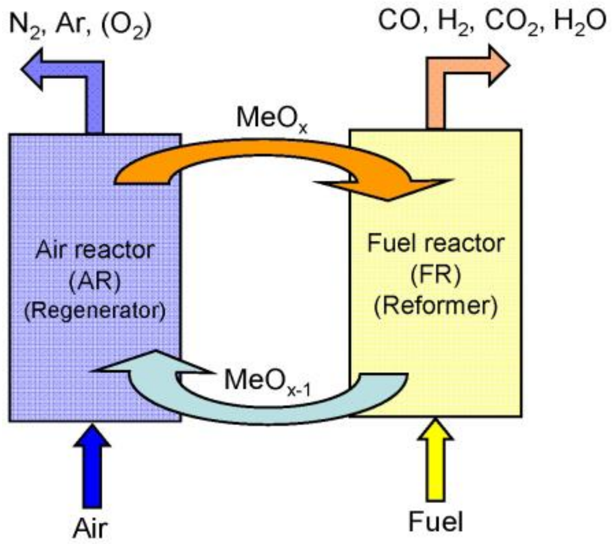
(Data from Lars Strömberg, Vattenfall/Chalmers)

Chemical Looping Combustion - oxyfuel technology with a metal oxide as oxygen carrier

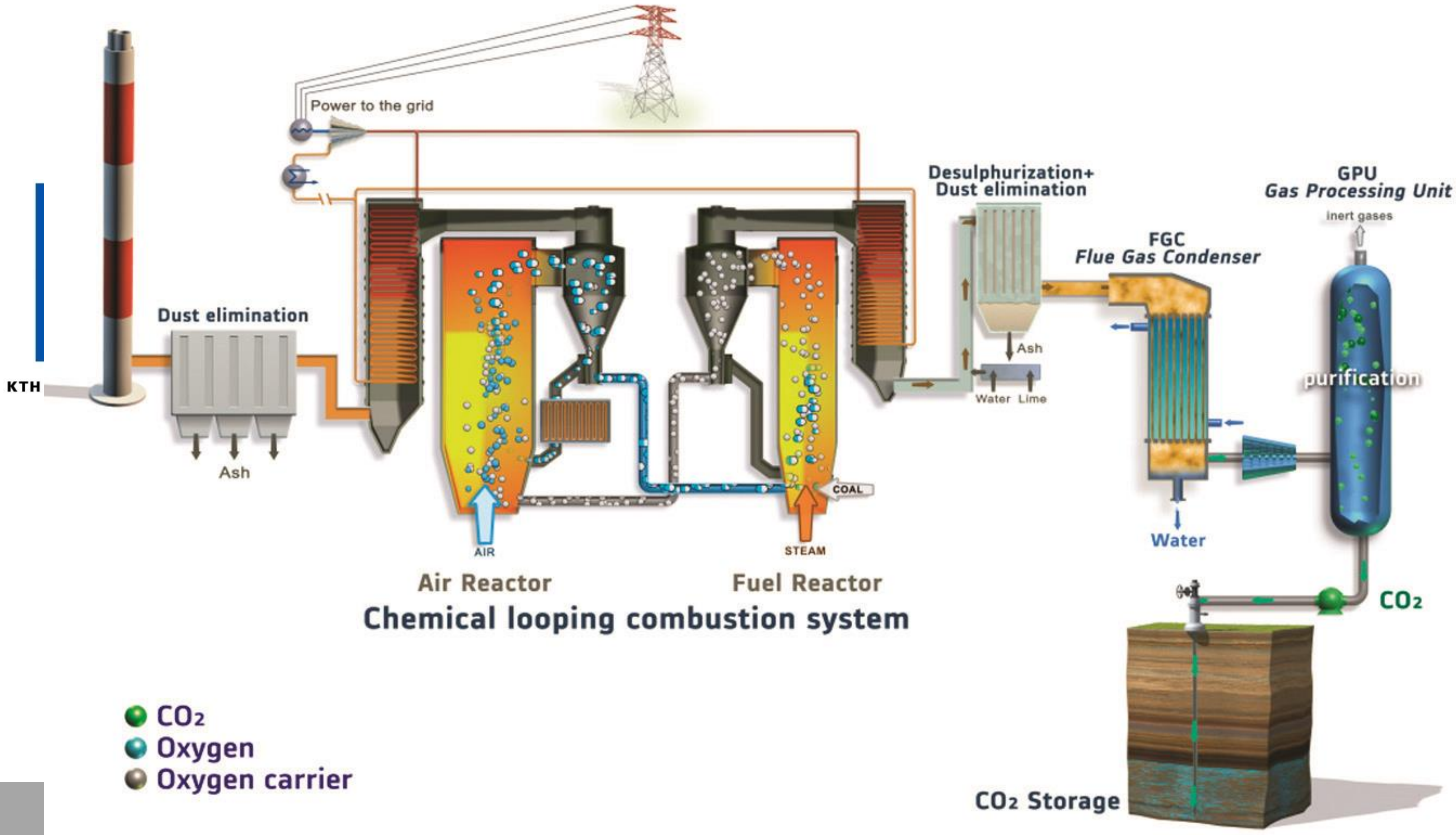
Believed to be very promising and received lots of research funding in the past. Seems to be forgotten now. Different reactants can be used, most suitable are the oxides of some transition metals. Practically difficult to achieve and challenging to maintain efficient continuous process. The metal particles are oxidized in the air reactor, extracting oxygen from air. The "combustion" is the exchange of oxygen between the metal oxide and the fuel in the fuel reactor.







Chemical Looping Combustion process scheme



KEPCO/KOSEP - Yongdong (PC - 100MWe) - ???
Endesa/CIUDEN - El Bierzo (CFB - 300MWe) - ???

Finish Line

Target : "Commercialised by 2020"

China: 2 Oxyfuel Projects – in progress
UK: White Rose Project (PC – 426MWe)
FutureGen2 - Illinois (PC - 168MWe)

By 2016-2018

Demonstration of 100– 300MWe full scale power plant.

Alstom	Schwarze Pumpe	2008	30MWth	Lignite
Hitachi Babcock	Schwarze Pumpe	2010	30MWth	Lignite
Doosan Babcock	Schwarze Pumpe	2012	30MWth	Lignite
IHI	Callide	2011	90MWth	Coal
Alstom / AL	Lacq	2009	30MWth	Gas/Oil?
CIUDEN	El Bierzo CFB Facility	2012	30MWth	Coal
CIUDEN	El Bierzo PC Facility	2012	20MWth	Coal

2012 – Callide: World's first 30MWe retrofitted Oxy-coal power plant

2015 – HUST Industrial Project for 35 MWt Oxyfuel Pilot Plant

2009 – Lacq: World's first 30MW$_t$ retrofitted Oxy-NG boiler w/storage

2012 – CIUDEN – World's first 30MWt Oxy-CFB Pilot Plant

2008

World's FIRST 30 MW$_{th}$ whole-chain demonstration pilot at Schwarze Pumpe

2007

B&W CEDF (30MWt)
large scale burner testing started

2003 - 2005

Vattenfall (ENCAP ++)
CS Energy / IHI Callide Project

1998 – 2001

CANMET
US DOE Project / B&W / Air Liquide

1990 - 1995

EC Joule Thermie Project
- IFRF / Doosan Babcock / Int'l Combustion
NEDO / IHI / Jcoal Project

1980's

ANL/Battelle/EERC completed the first industrial scale pilot plant

B&W	CEDF	2008	30MWth	Coal
Alstom	Alstom CE	2010	15MWth	Coal
Doosan Babcock	DBEL - MBTF	2009	40MWth	Coal

First large-scale 35MW$_{th}$ Oxy-Coal Burner Retrofit Test done by "International Combustion"

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Existing commercial CO_2 recovery for industrial purposes

CO_2 separation has been used since long time, mostly for the chemical or food industries

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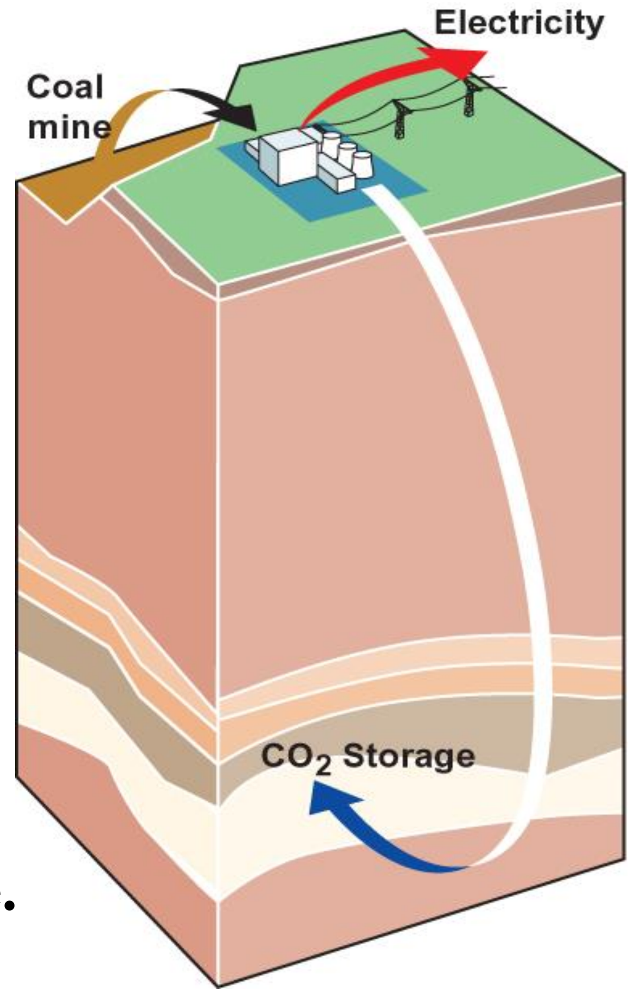
Operator	Location	Capacity (tons/day CO_2)	Fuel Source	CO_2 Use	Technology	Status
Carbon Dioxide Technology	Lubbock, TX	1200	gas boiler	EOR	Dow MEA	Shut
North American Chemical Co.	Trona, CA	800	coal boiler	Carbonation of brine (soda ash)	Kerr-McGee MEA	Operational since 1978
Mitchell Energy	Bridgeport, TX	493	gas heaters, engines, turbine	EOR	Inhibited MEA	Shut
Northeast Energy Associates	Bellingham, MA	320	gas turbines	PURPA (food-grade)	Fluor Daniel	Operational since 1991
Soda Ash Botswana	Sua Pan,	300	coal boiler	Carbonation of brine (soda ash)	Kerr-McGee MEA	Operational since 1991
Applied Energy Systems	Poteau, OK	200	coil boiler (fluidized bed)	PURPA (food-grade)	Kerr-McGee MEA	Operational since 1991
Sumitomo Chemicals	Chiba, Japan	165	gas boilers plus oil/coal boiler	food-grade	Fluor Daniel	Operational since 1994
Luzhou Natural Gas	China	160	NH_3 plant reformer exhaust	Urea	Dow MEA	No Information
Indo Gulf Fertilizer Co.	India	150	NH_3 plant reformer exhaust	Urea	Dow MEA	Operational since ~1988
N-ReN Southwest	Carlsbad, NM	104	gas boiler plus NH_3 reformer exhaust	EOR	Retrofit to Dow MEA	Shut
Prosint	Rio de Janeiro, Brazil	90	gas boiler	food-grade	Fluor Daniel	Operational since 1997
Liquid Air Australia	Australia	2 x 60	gas boiler	food-grade	Dow MEA	Operational since ~1985

Notes:
1. ABB Lummus Crest licensed the Kerr-McGee MEA technology in 1990.
2. Fluor Daniel licensed the Dow MEA technology (ECONAMINE FG) in 1989.
3. A number of small plants (~6 tons/day CO_2) producing food-grade CO_2 exist in the Philippines and other places using Fluor Daniel/ Dow MEA technology.

Source: Howard J. Herzog, MIT Energy Laboratory

The CO_2 sequestration principle

After CO2 is captured (whatever the process), it needs to be purified and compressed to a high-pressure liquid state.



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The CO2 can be pumped as a liquid down into a porous rock layer or in water-layer (aquifer) formations for permanent underground storage.

CO_2 permanent storage

- Stored in porous rocks deeper than 1000 m.
  - The rock has 5 – 20 % porosity. It is the same type of formation as the one where oil and gas deposits are usually found.
  - CO2 remains liquid due to its own hydrostatic pressure.
  - There is no pressure difference between the liquid CO2 and the surrounding rock, but a non-porous impermeable cap rock is needed to safely seal the permeable layer.
  - CO2 could also chemically bind with some types of sedimentary rocks to produce carbonates (CO_3 or HCO_3) - the most stable forms of carbon.

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- Or, stored in dissolved state in deep aquifers, usually of saline water.
  - CO2 is the gas that most readily dissolves in water and remains stably dissolved under the high pressure at high depths.
  - Actually, the world's oceans naturally act as effective CO2 sink when the CO2 concentration rises in the atmosphere.

CO_2 injection in underground storage (Ketzin field in Germany)

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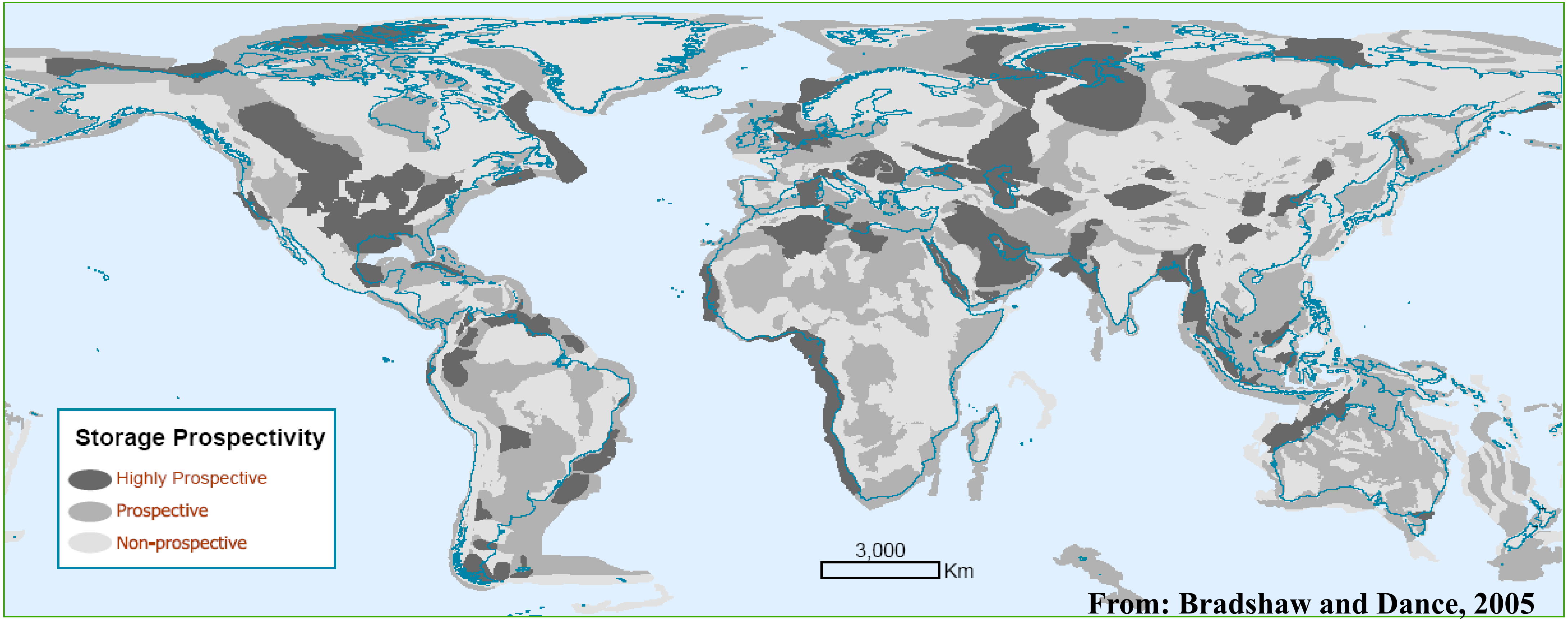
Prospects for CO_2 Storage Around the World

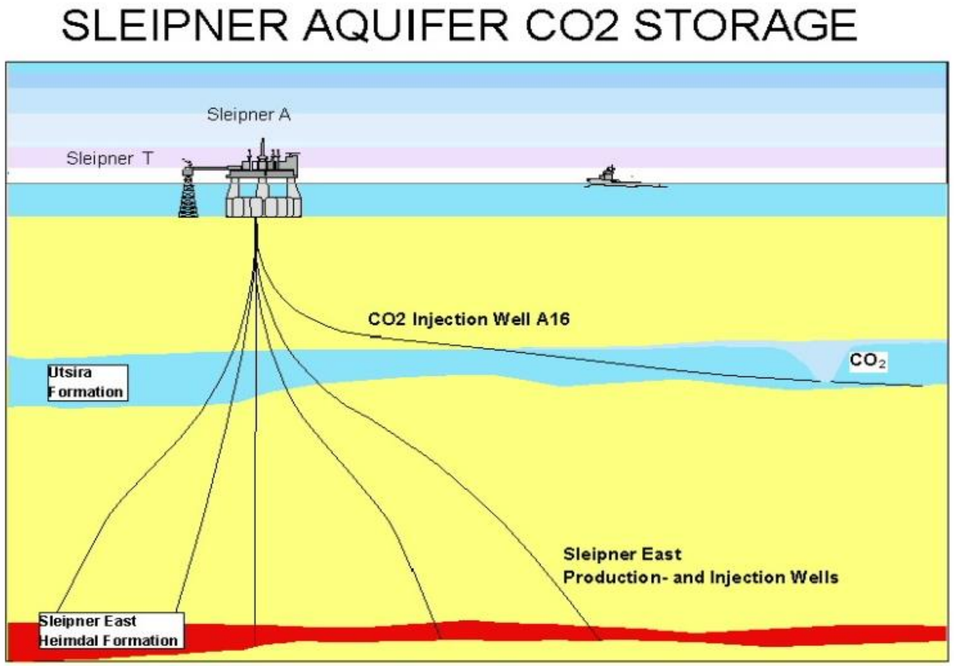


From: Bradshaw and Dance, 2005

"It is likely that the technical potential for geological storage is sufficient to cover the high end of the economic potential range (2200 GtCO2), but for specific regions, this may not be true."

Storage of CO_2 in a saline aquifer under the North Sea – since 1996

The Sleipner field – STATOIL's offshore natural gas production facility. The produced gas is rich in CO2. The CO2 is separated from the raw gas and immediately pumped back in an underground water table.



CO2-injection into the saline aquifer Utsira – operational since 1996!

(Source: STATOIL)

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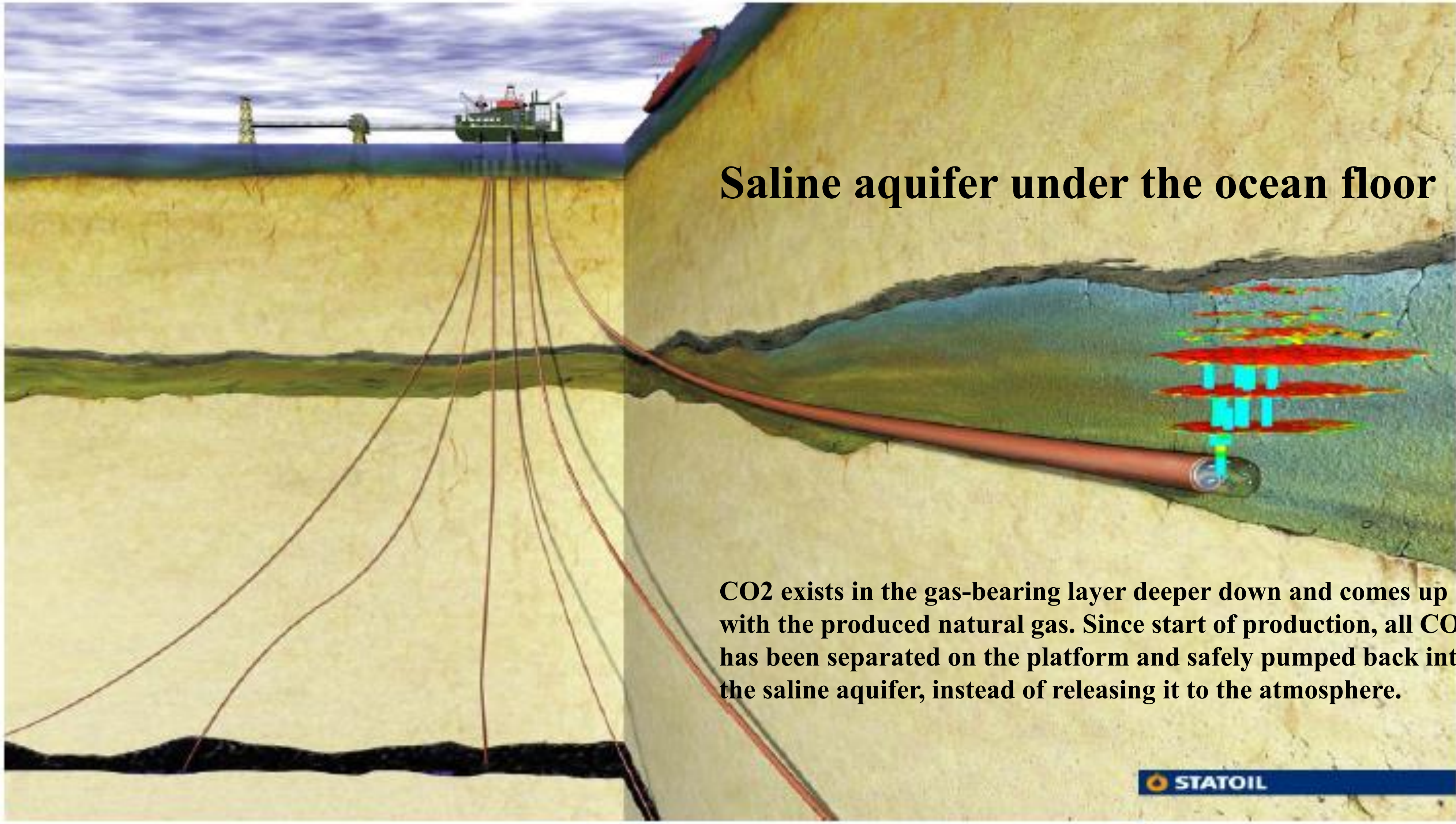
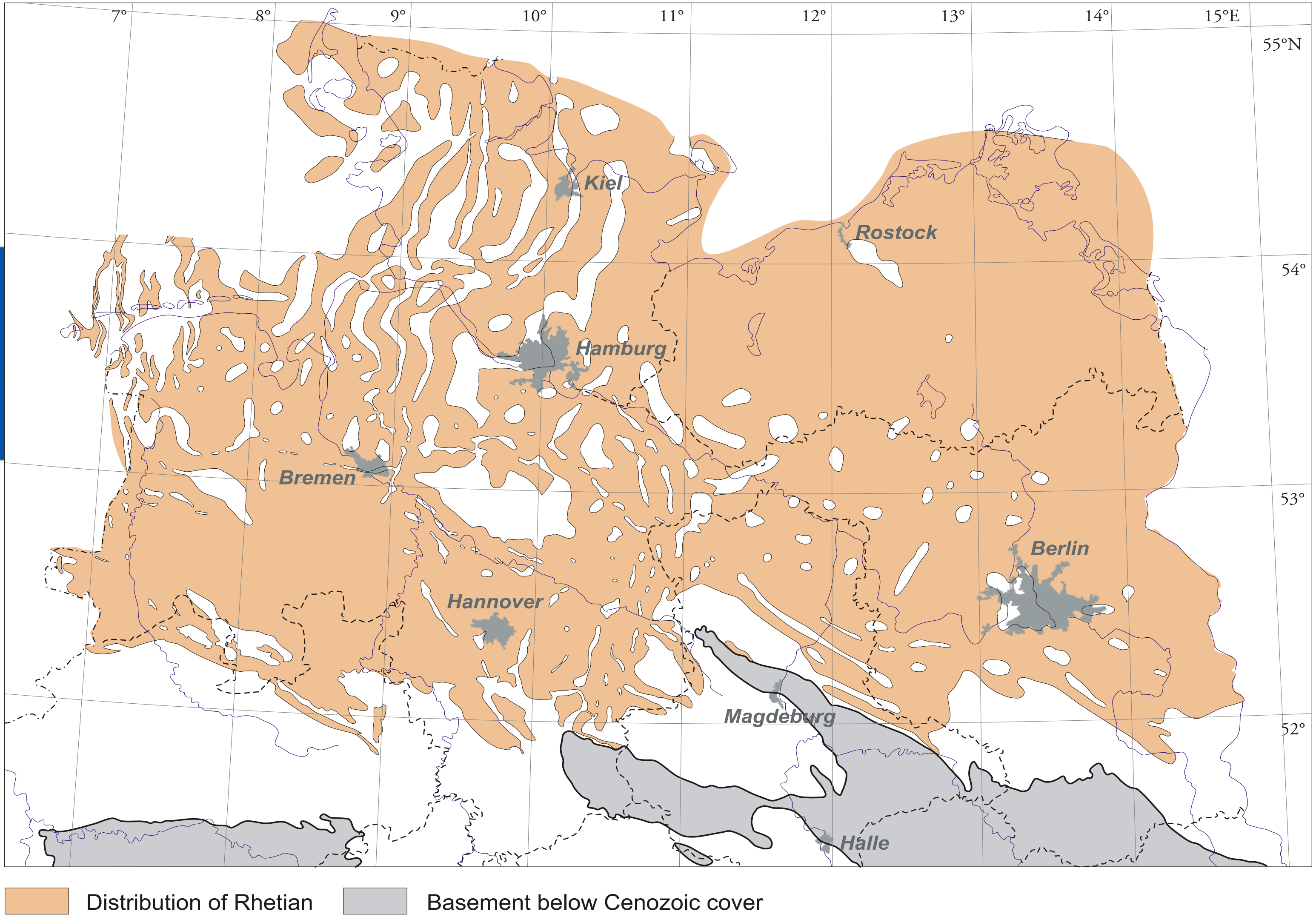
Sleipner CO2 Injection



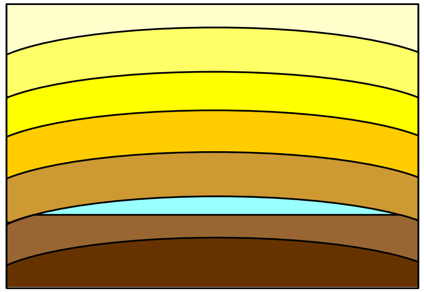
STATOIL

CO2 storage capacity in northern Germany: Large saline aquifers deep underground



Present day distribution of the Rhetian - aquifers (a. DIENER et al. 1984, FRISCH & KOCKEL 1998)

There exists more storage capacity for CO_2 in Europe (and worldwide) than the remaining fossil fuels



Source:

Franz May, Peter Gerling, Paul Krull

Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover

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CO_2 pipelines in operation in the USA:
already existing for various industrial applications

Electricity generation costs with CO_2 capture
(assuming 30 €/ton CO_2)

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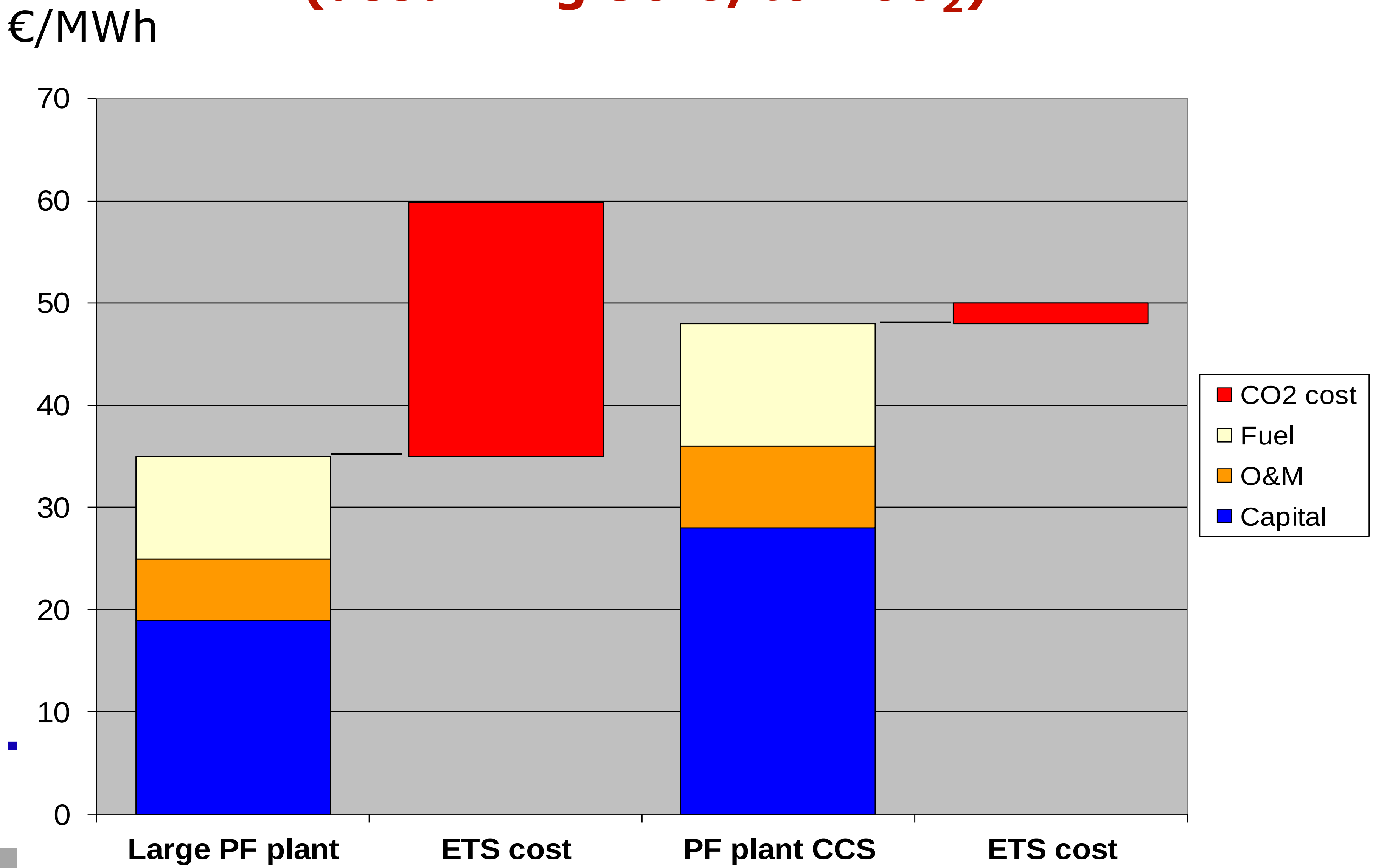
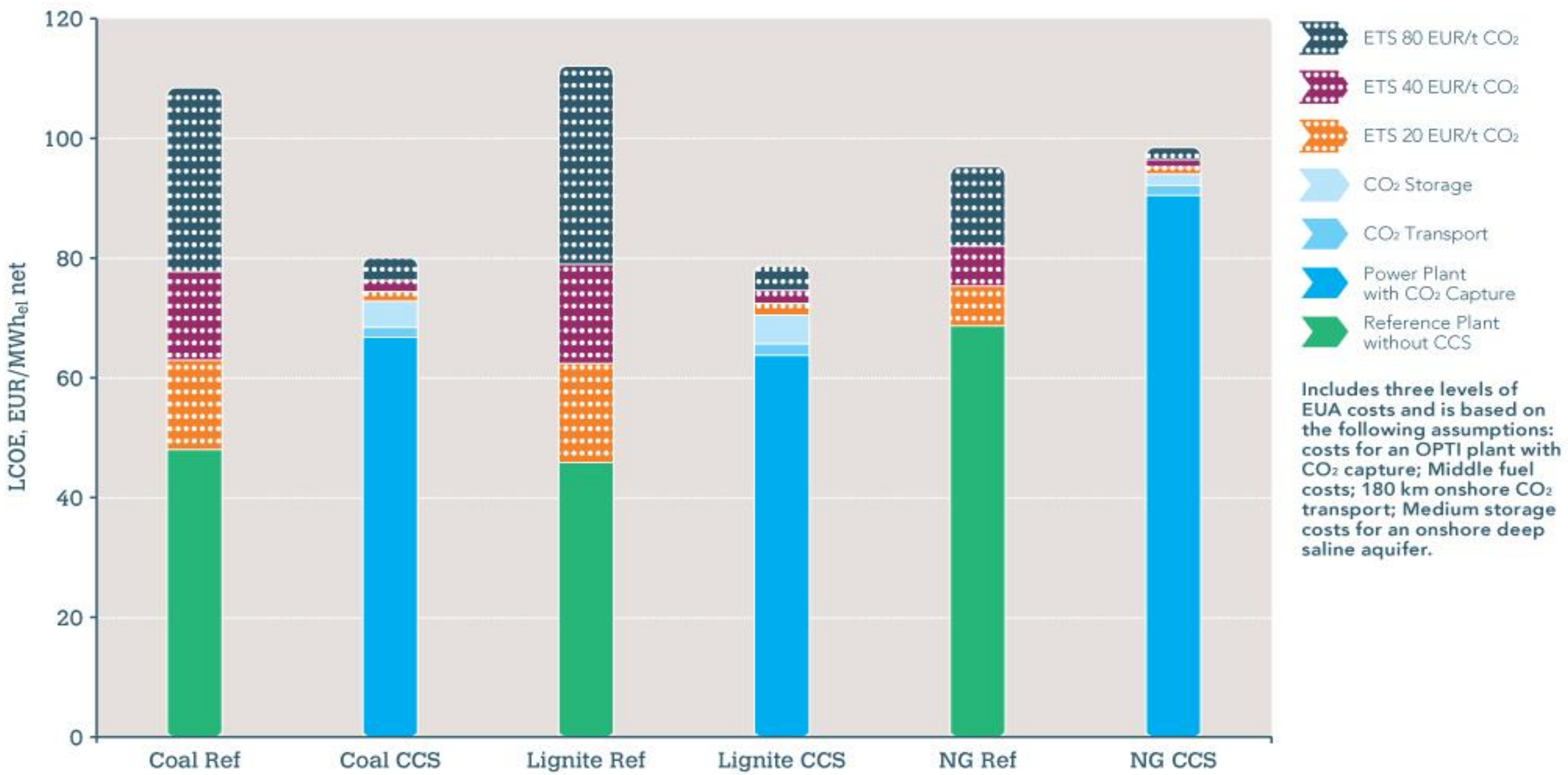


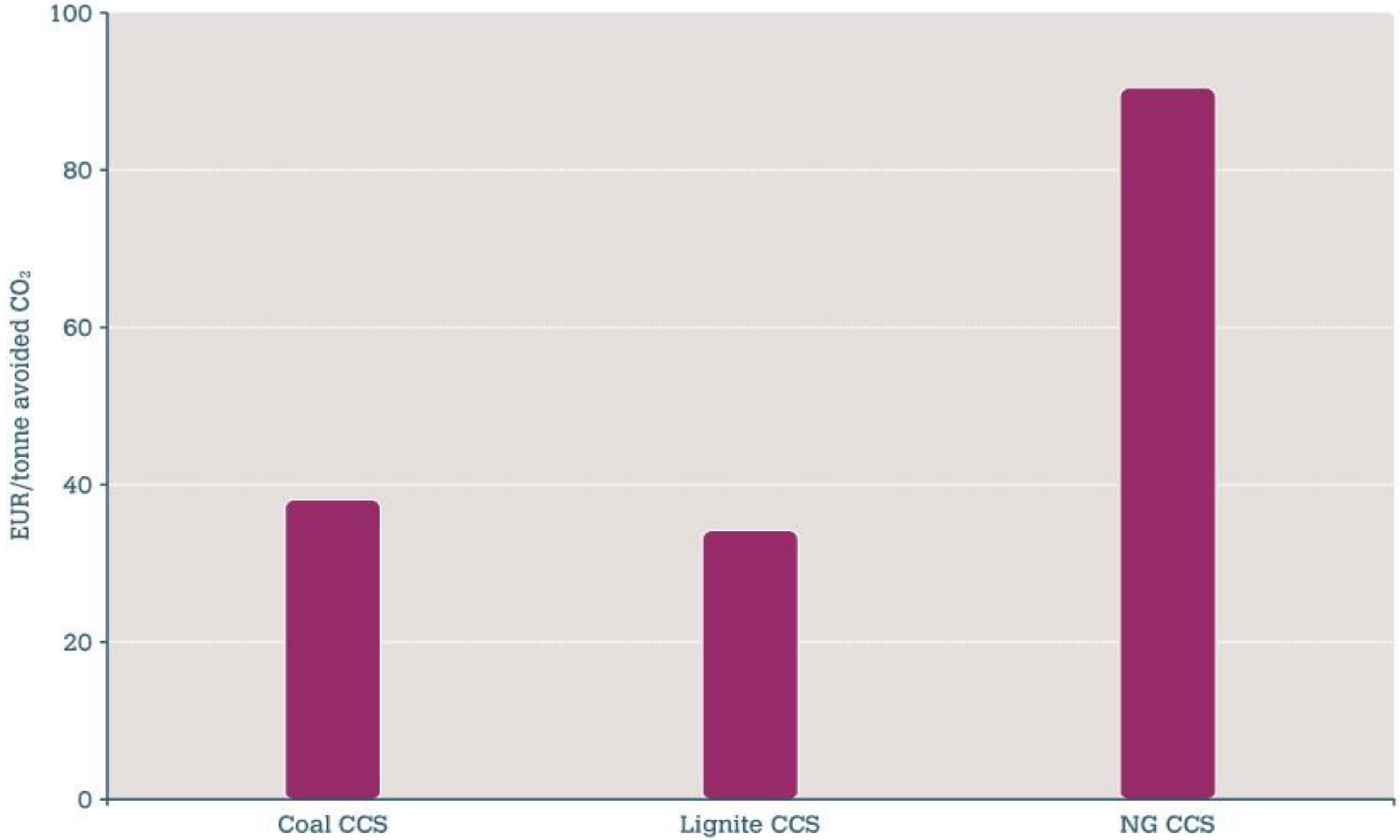
LCOE for integrated CCS projects (coal and gas)

Figure 1: The Levelised Cost of Electricity (LCOE) of integrated CCS projects (blue bars) compared to the reference plants without CCS (green bars)



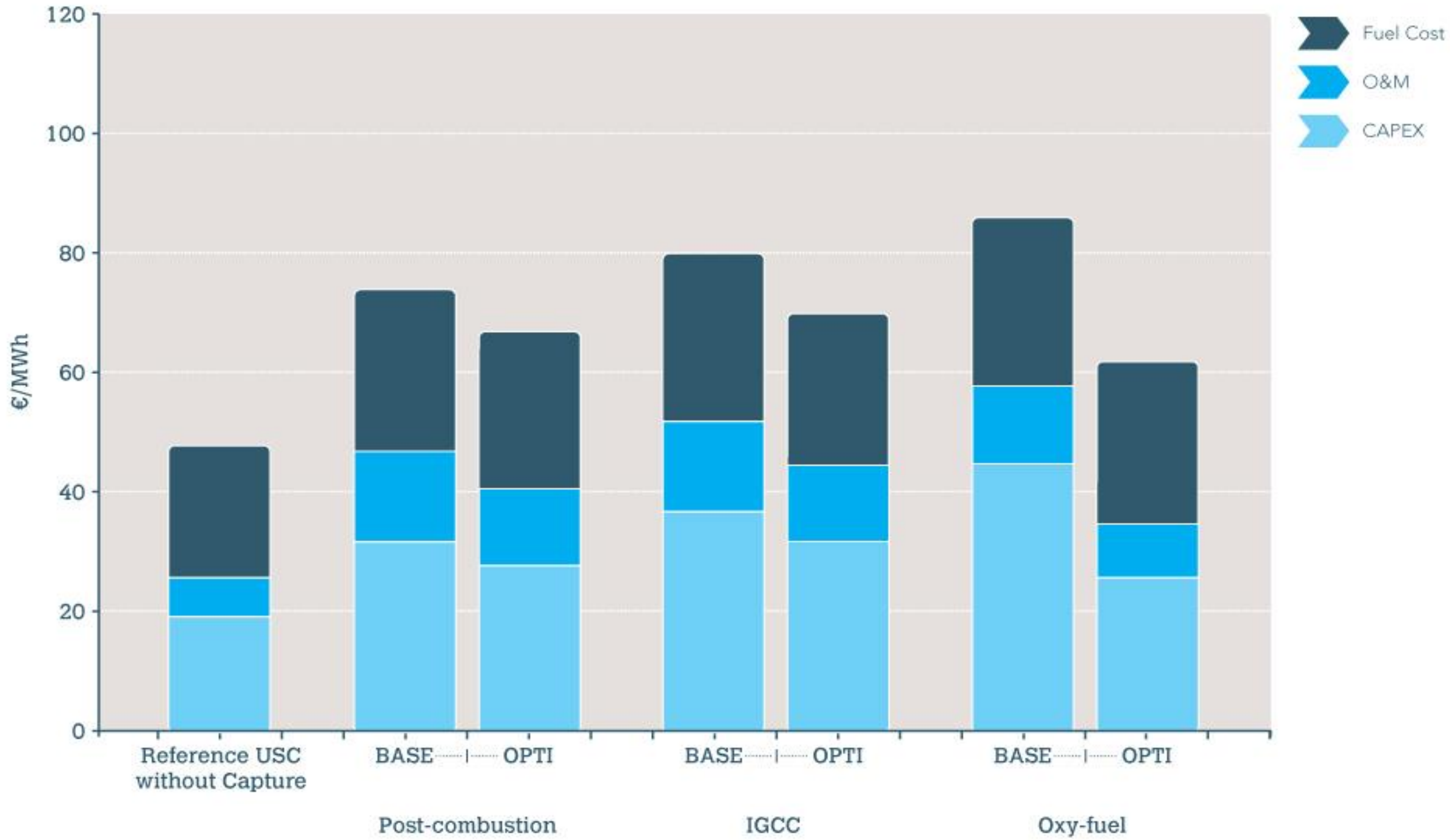
CO_2 Avoidance Costs:
Price to Justify Building CCS Projects vs. plants w/o CCS

Figure 13: CO_2 avoidance costs for possible plants commissioned in the mid 2020s – the price of EUAs required to justify building CCS projects vs. a plant without CCS from a purely economic point of view (calculated on the same basis as Figure 12)



LCOE for Coal Plants with CO_2 capture
(capture-cost only)

Figure 14: The LCOE for hard coal-fired power plants with CO_2 capture (using Middle fuel costs)



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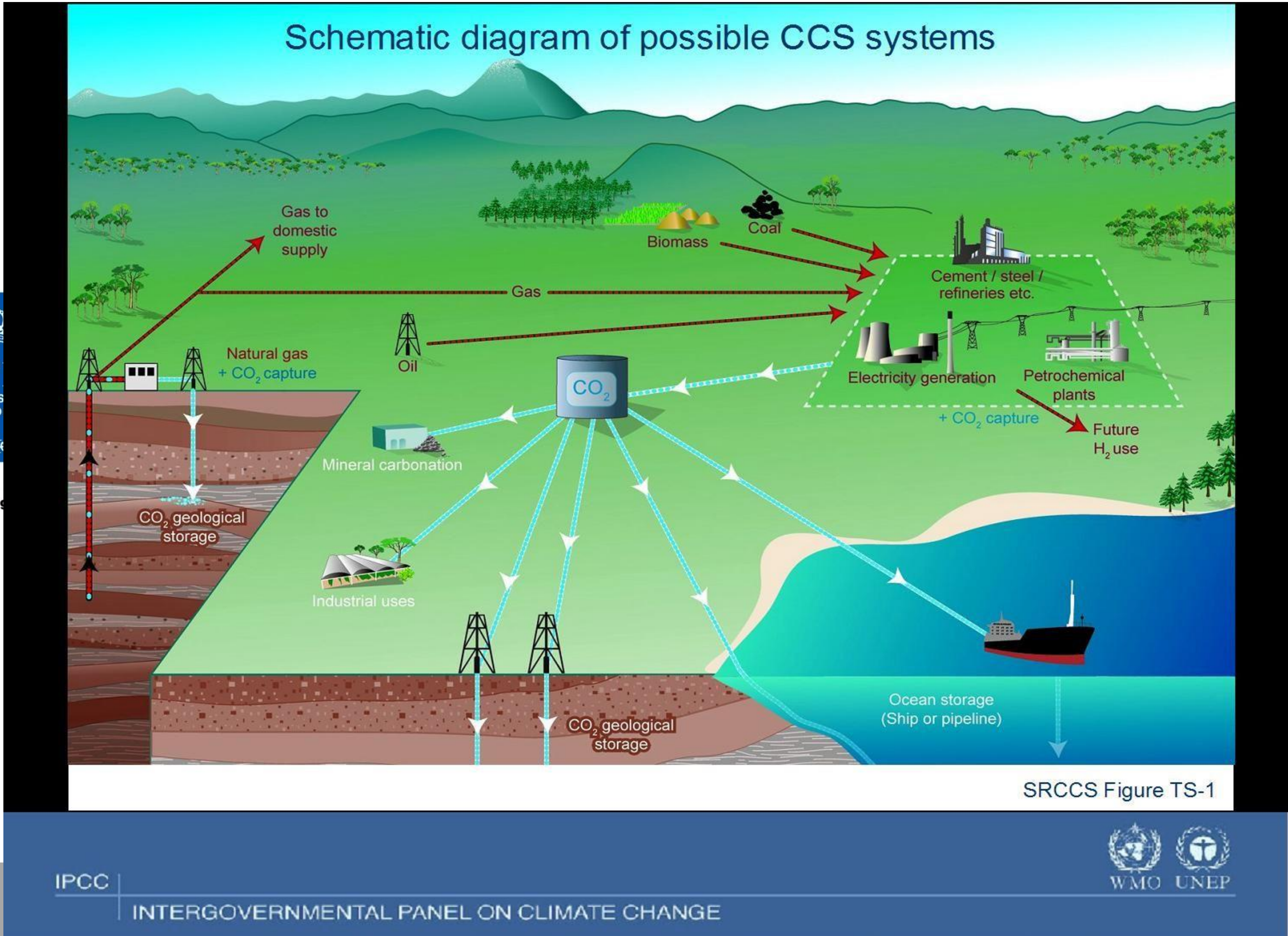
Summary of CCS alternatives



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New projects & technology innovations

Several projects in the U.S. and Canada, primarily for Enhanced Oil Recovery (EOR) by injecting CO2 in oil fields:

- The **Kemper County coal gasification** project, a 580MW lignite plant with pre-combustion carbon capture, in Mississippi. Suffers from problems and delays.
- The 240MW **Petra Nova** project in western Texas. When completed in 2018, it will be the world's largest post-combustion CCS project. Unique business model - the utility NRG delivers the CO2 for EOR against receiving a share of the oil revenue.
- A 1MW post-combustion pilot plant with low-temperature CO2 absorption process is being tested by Linde and BASF in Alabama. When enlarged to full-scale, it will serve a 880MW coal-fired plant.
- The **Sask Power** Boundary Dam project in Saskatchewan, Canada – post-combustion capture on a 110MW coal-fired unit. First successful commercially operating CCS in the world, since 2014!
- The **Callide Oxyfuel** project in Australia – a $245 million international joint venture.
- **Flameless Pressurized Oxy-Combustion** (FPOC) technology by the Italian company Itea SpA. Originally developed for waste-to-energy applications, it has recently been demonstrated at a pilot scale of 5 MWth. The FPOC process is fuel-flexible and can handle low-rank lignite coal. Scale-up to 50 MWth pilot is planned at a research center in Sardinia.
- The **Advanced Superimposed Cycle** (ASIC) for solid fuels, with an inbuilt carbon separation process and minimum loss of efficiency.
  By Dr. Hisatome Masatoshi from Japan's Hisatome Power & Environment Engineering
- The **Allam Cycle** – pressurized oxyfuel combustion of natural gas with CO2 expansion in a gas turbine and/or combined cycle at high efficiency.
  By Dr. Rodney Allam. Demonstration plant of 25MW size is under construction in Texas.
- *…and many other examples planned for the near future at various locations…*

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Kemper County project – victim of an endless cost carousel

After a long struggle against rising costs (~7 billion $) and facing countless technical problems, the **Kemper County coal gasification** project with pre-combustion carbon capture was ultimately doomed to fail. The plant was converted to a regular natural gas combined cycle in 2017.

Towards the climate goals

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In order to meet the climate targets set out in the Paris Agreement (if possible at all):

- Over 2000 CCS facilities will be needed around the world by 2040! Currently, there are only 17 operational full-scale CCS facilities, with 4 more expected to come online in 2018.
- 14% of emissions reduction must come from CCS! The remainder should be achieved by various other energy conservation or efficiency measures.
- The CCS facilities should operate around the clock and capture 37 million tonnes CO2 per year!
- If the carbon targets should be reached within the stipulated time: The world should **decrease not only the use of fossil fuels but also of biomass and biofuels** (!!) and rather allow the biomass to act as a carbon sink, not as fuel. This includes also the application of CCS projects to biomass-fired plants.