

Energy-efficient CO₂ Capture with Chemical-Looping Combustion



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*CCSP - Final results seminar,
October 13, 2016
Helsinki*

TODAY:

- The need for BioCCS/BECCS
- Why CLC ?
- Status of CLC development
- Why Nordic Countries ?
- Are the costs reasonable ?

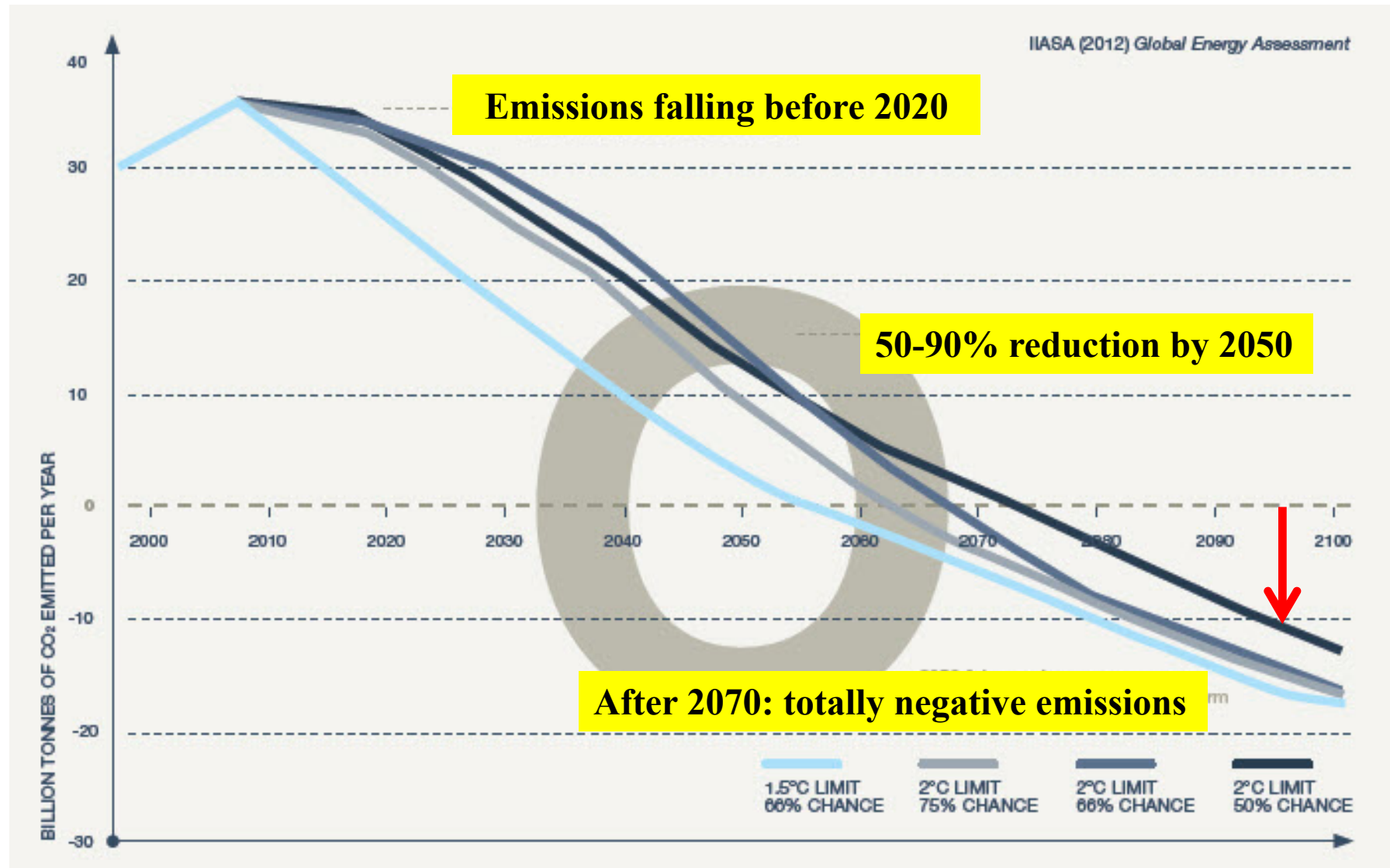
**Carbon budget for max 1.5°C and 2°C :
300 and 900 Gton CO₂**

Emissions today >35 Gton/yr :

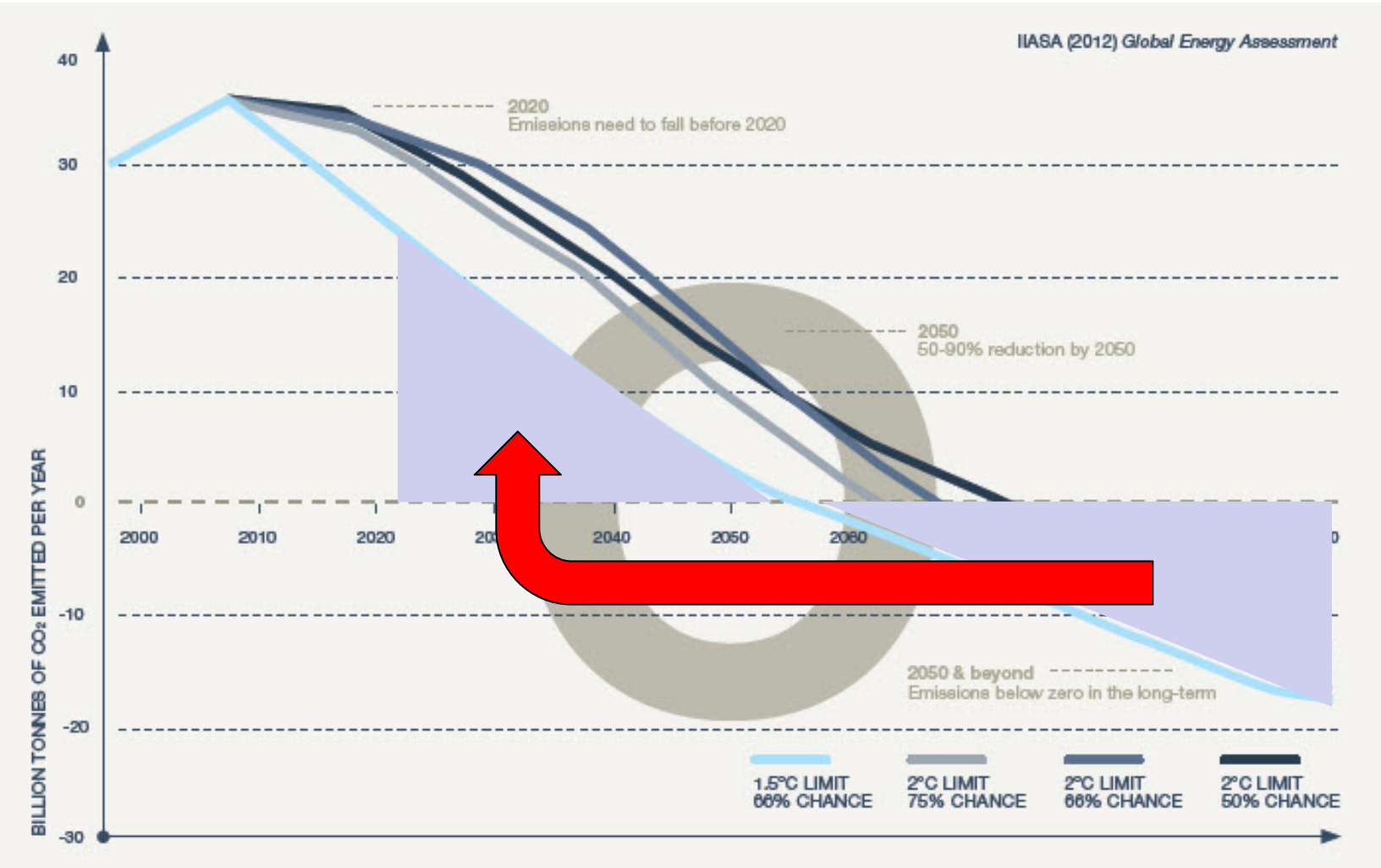
<10-30 years left of today's emissions!!

Climate goal "well below" 2°C - 20 years ?

To meet the 2°C target it is not sufficient to stop emissions of CO₂, most likely we need *negative* emissions by the end of the century.

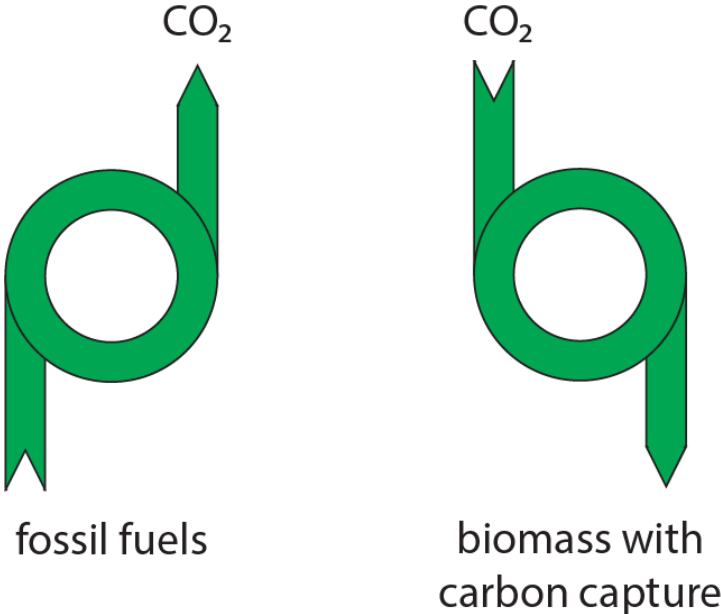


To meet the 1.5°C target, budget is very soon filled.



BECCS (Bioenergy Carbon Capture & Storage)

ATMOSPHERE



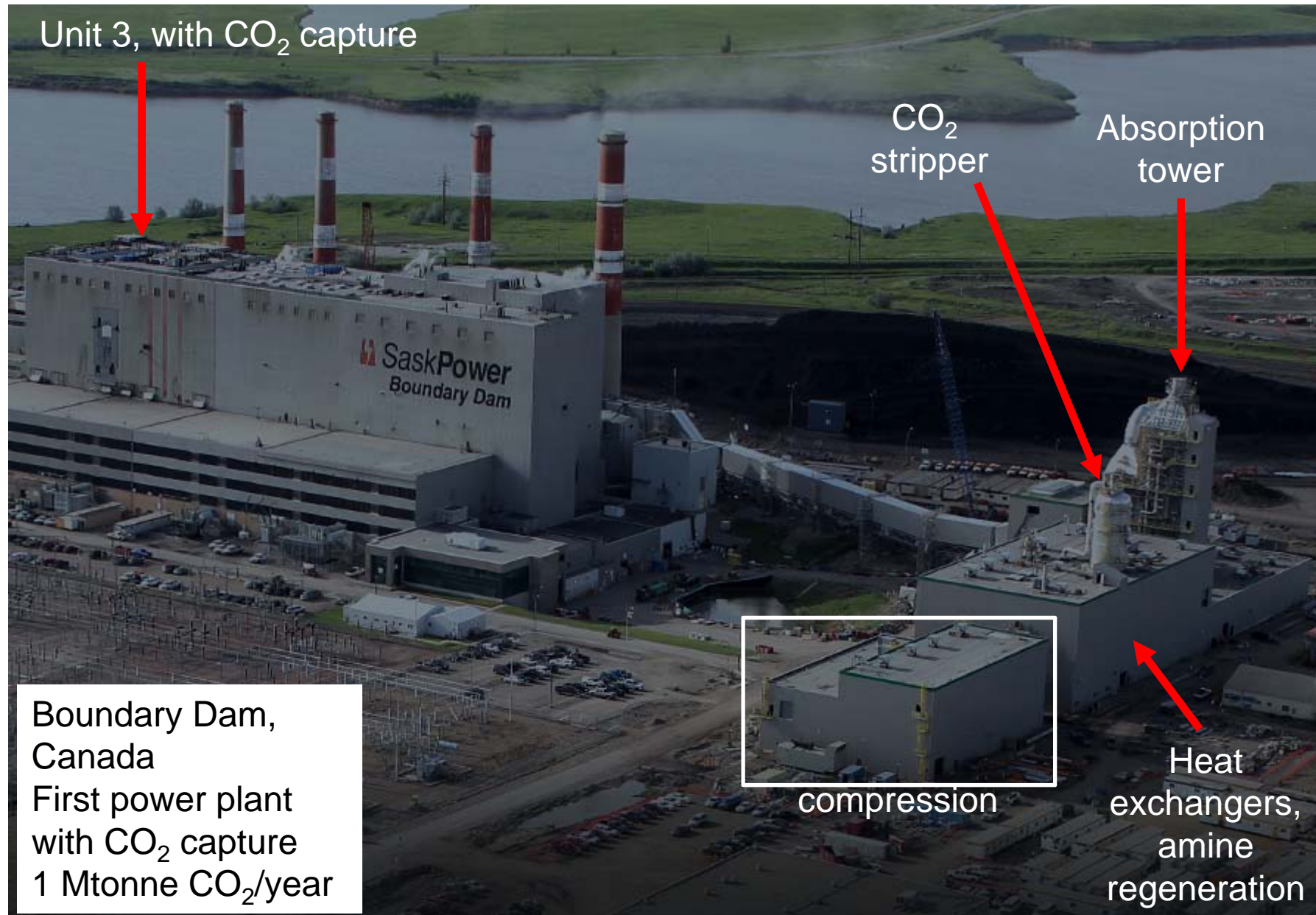
GROUND

Carbon Capture and Storage (CCS) status

Three main technologies¹, all having

- ❑ large energy penalties, around 10%-units**
 - ❑ significant need for gas-separation equipment**
 - ❑ cost normally estimated to 50 €/tonne CO₂ or more**
-
- First commercial large post-oxidation in operation
2 years (Boundary Dam, Canada)**

¹post-, pre- and oxycombustion

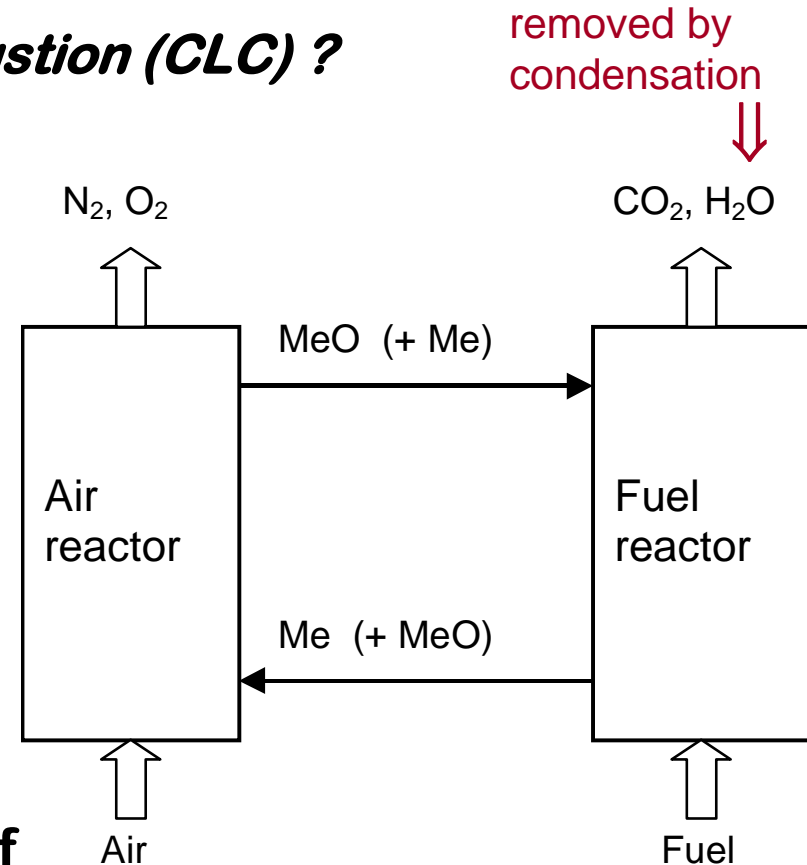


Why chemical-looping combustion (CLC) ?

Oxygen is transferred from air to fuel by metal oxide particles

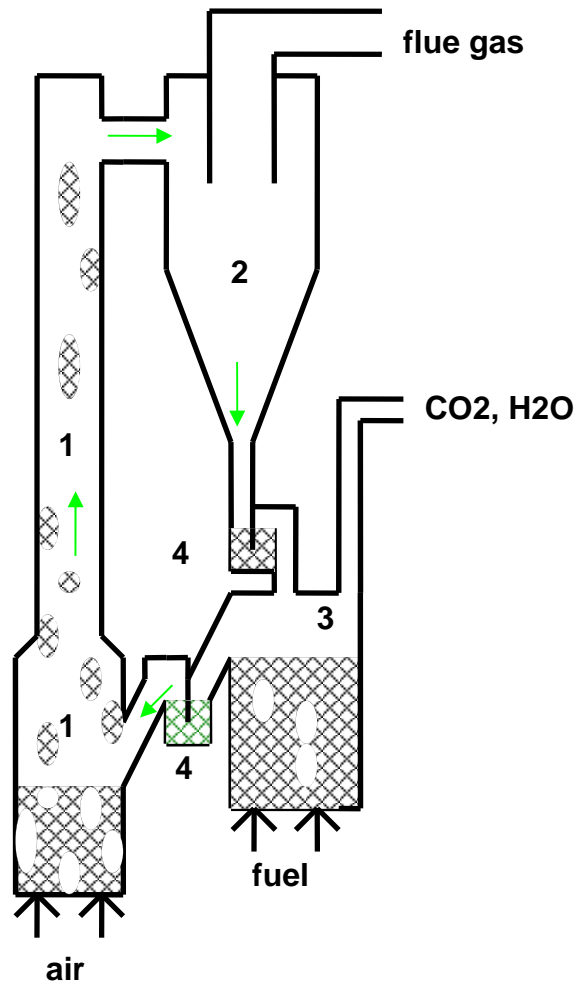
Inherent CO₂ capture:

- fuel and combustion air *never mixed*
- *no active gas separation needed*
- large costs/energy penalties of gas separation avoided



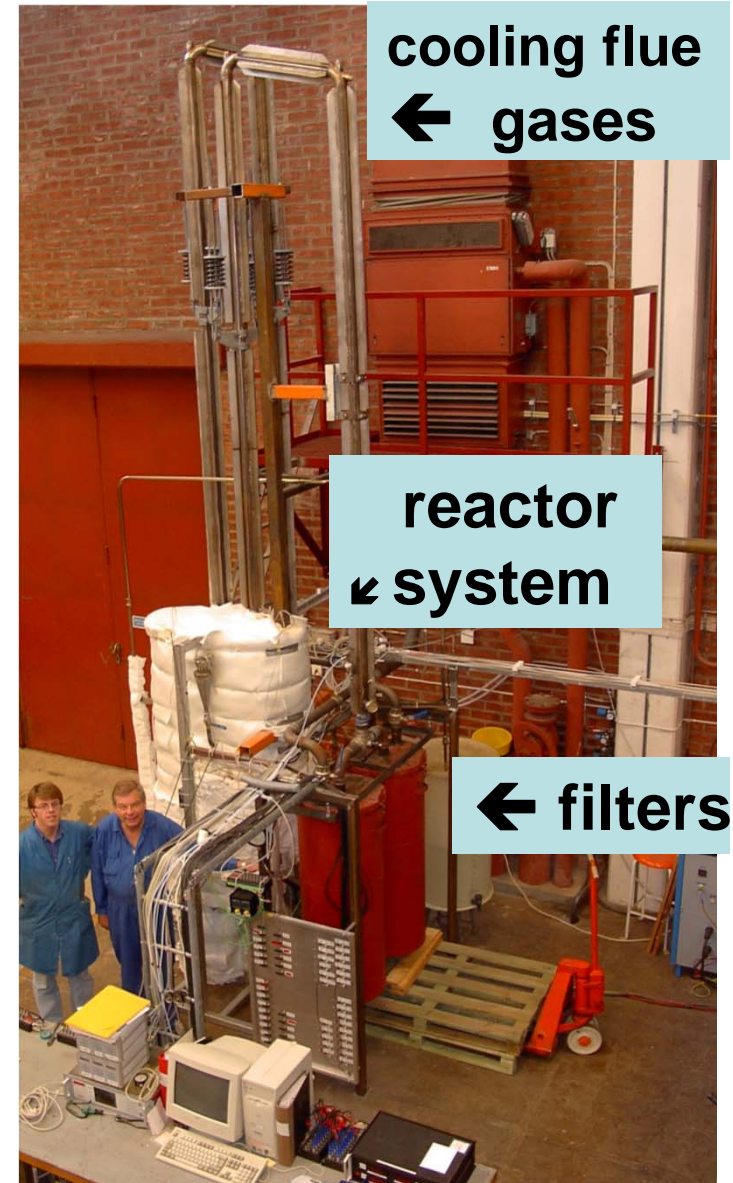
- Potential for real breakthrough in costs of CO₂ capture
- But, does it work in practice ?

Chalmers' 10 kW gas-CLC, 2003



1 air reactor, 2 cyclone
3 fuel reactor, 4 loop seals

without insulation

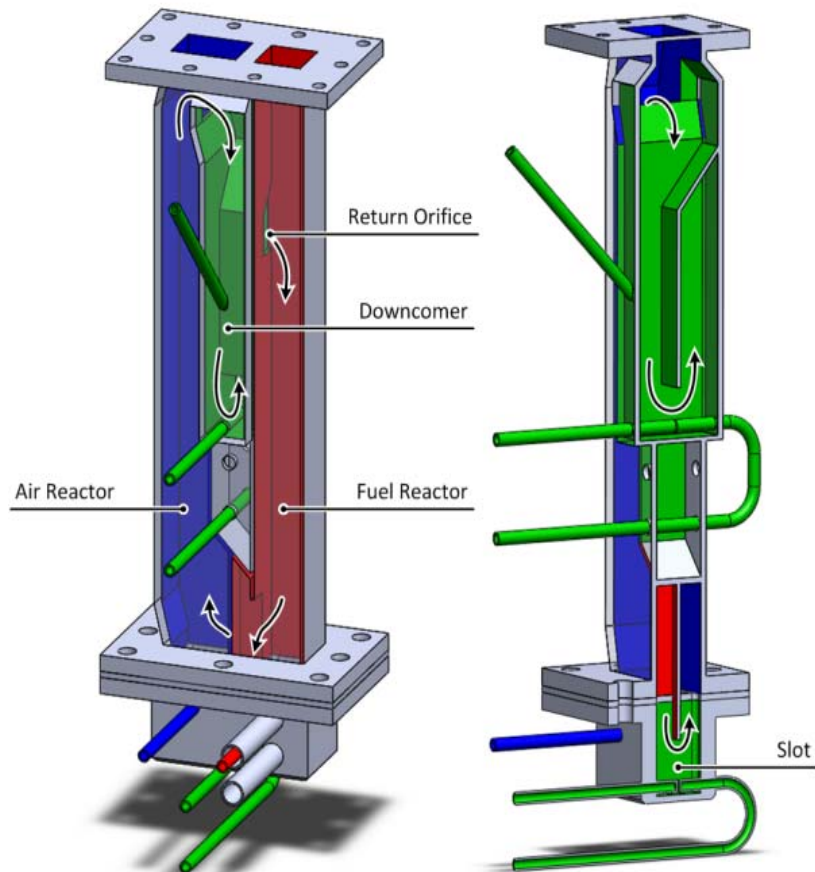


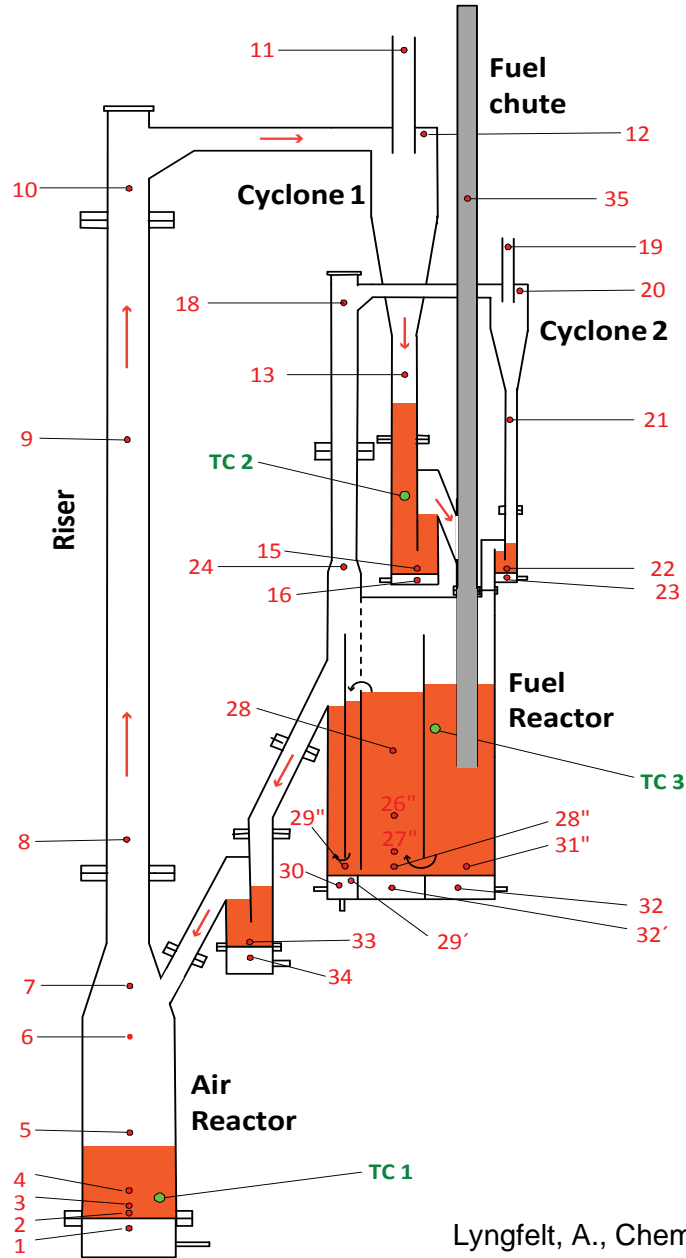
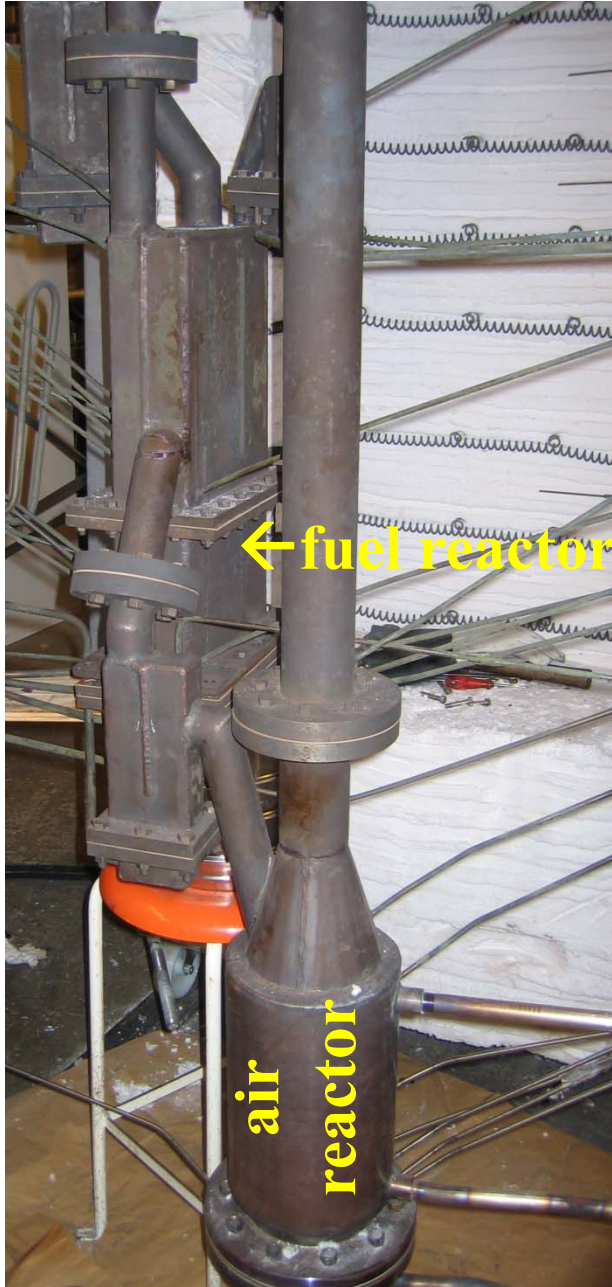
Chalmers 300 W gas-CLC, 2004

Dimensions:

Air Reactor: 25x35 mm, 25x25 mm

Fuel Reactor: 25x25 mm





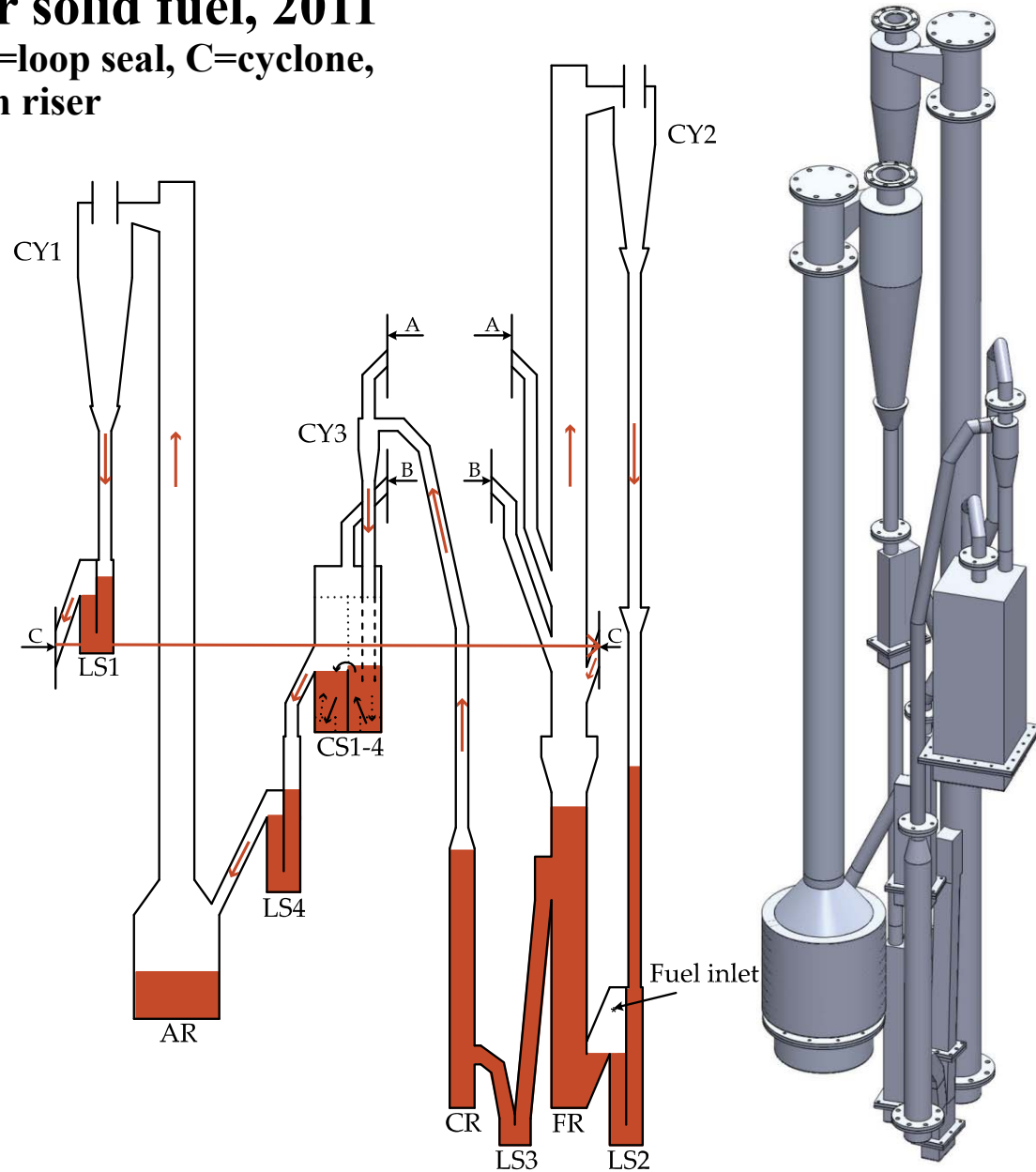
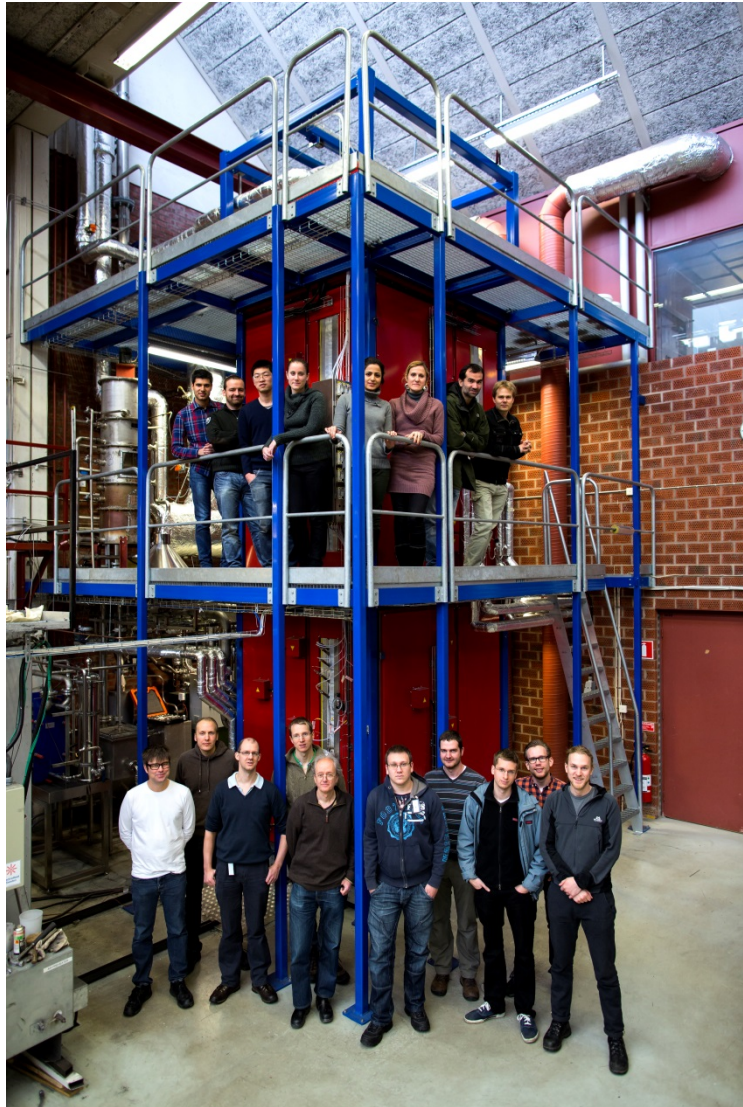
**Chalmers' 10 kW
chemical-looping
combustor
for solid fuels.
First operation 2006
Published 2008**



Lyngfelt, A., Chemical-looping combustion of solid fuels, *Greenhouse Gas Issues*, No. 87, September 2007, 9-10.

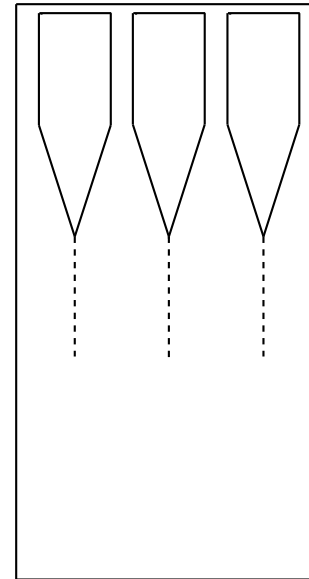
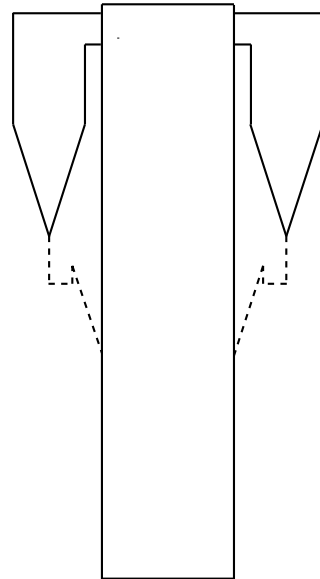
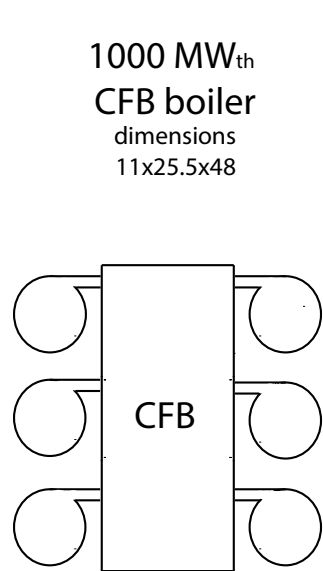
Chalmers' 100 kW CLC for solid fuel, 2011

AR=Air reactor, FR=fuel reactor, LS=loop seal, C=cyclone, CS=Carbon stripper, CR=Circulation riser



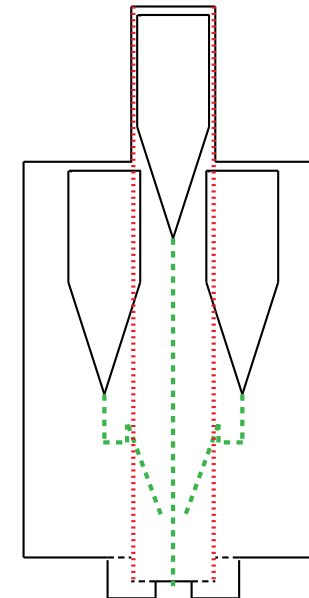
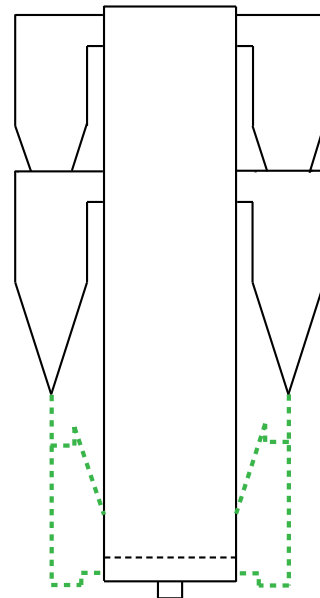
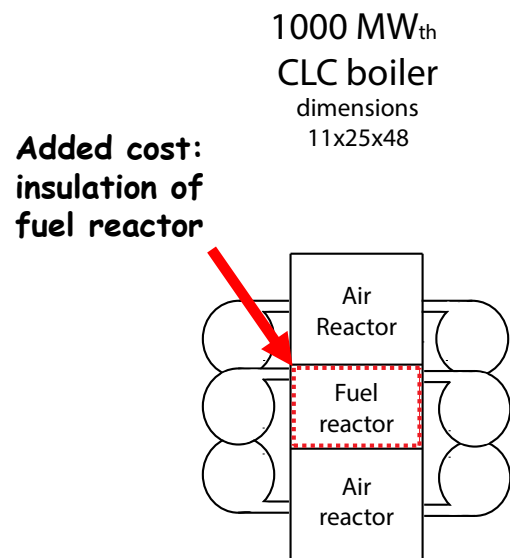
Where are we ?

- **CLC operation worldwide**
 - 34 small pilots : 0.3 kW – 3 MW
 - >9000 h with >70 oxygen carriers, >150 publications
 - 3600 h at Chalmers with >50 oxygen carriers
- **CLC with solid fuels**
 - Low cost oxygen carriers can be used
 - Incomplete gas conversion/char conversion
 - Some oxy-polishing needed, oxygen demand: 5-25%
 - Up to 98% CO₂ capture attained (little char leakage to air reactor)
 - Up to 90% fuel conversion (i.e. 10% char elutriated)
 - 3000 h operation in 17 units
 - 400 h at Chalmers 10 kW and 100 kW



**Fuel reactor,
cyclones, ducts and
post-oxidation
chamber: 2500 m²**

Cost: 1500 €/m²



**Added cost of fuel
reactor:**

4 M€

0.4 M€/year

2 Mton CO₂/year

= 0.2 €/ton CO₂

Added cost relative to CFB¹

Type of cost	estimation, €/tonne CO ₂	range, €/tonne CO ₂	Efficiency penalty, %
CO ₂ compression	10	10	3
Oxy-polishing	6.5	4-9	0.5
Boiler cost	1	0.1-2.3	-
Oxygen carrier	2	1.3-4	-
Steam and hot CO ₂ fluidization	0.8	0.8	0.8
Fuel grinding	0.2	0.2	0.1
Lower air ratio	-0.5	-0.5	-0.5
<u>Total</u>	<u>20</u>	<u>15.9-25.8</u>	3.9

Scale-up, first step without CO₂ capture, to assess technology

- Main costs: Downstream treatment and oxygen production not needed
- CO₂ capture could be added afterwards

Scale up, reduce/eliminate cost of boiler and surrounding system:

- Add fuel reactor to existing CFB boiler / Build dual purpose boiler (CFB/CLC)

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Fuel grinding	0.2	0.2	0.1
Lower air ratio	-0.5	-0.5	-0.5
<u>Total</u>	<u>3.5</u>	<u>1.9-6.8</u>	0.4

¹Lyngfelt, A., and Leckner, B., A 1000 MW_{th} Boiler for Chemical-Looping Combustion of Solid Fuels - Discussion of Design and Costs, *Applied Energy* 157 (2015) 475-487

Estimated cost of CLC, less than half of competing technologies

Should be suitable for biomass.

- **larger biomass boilers normally use CFB technology**

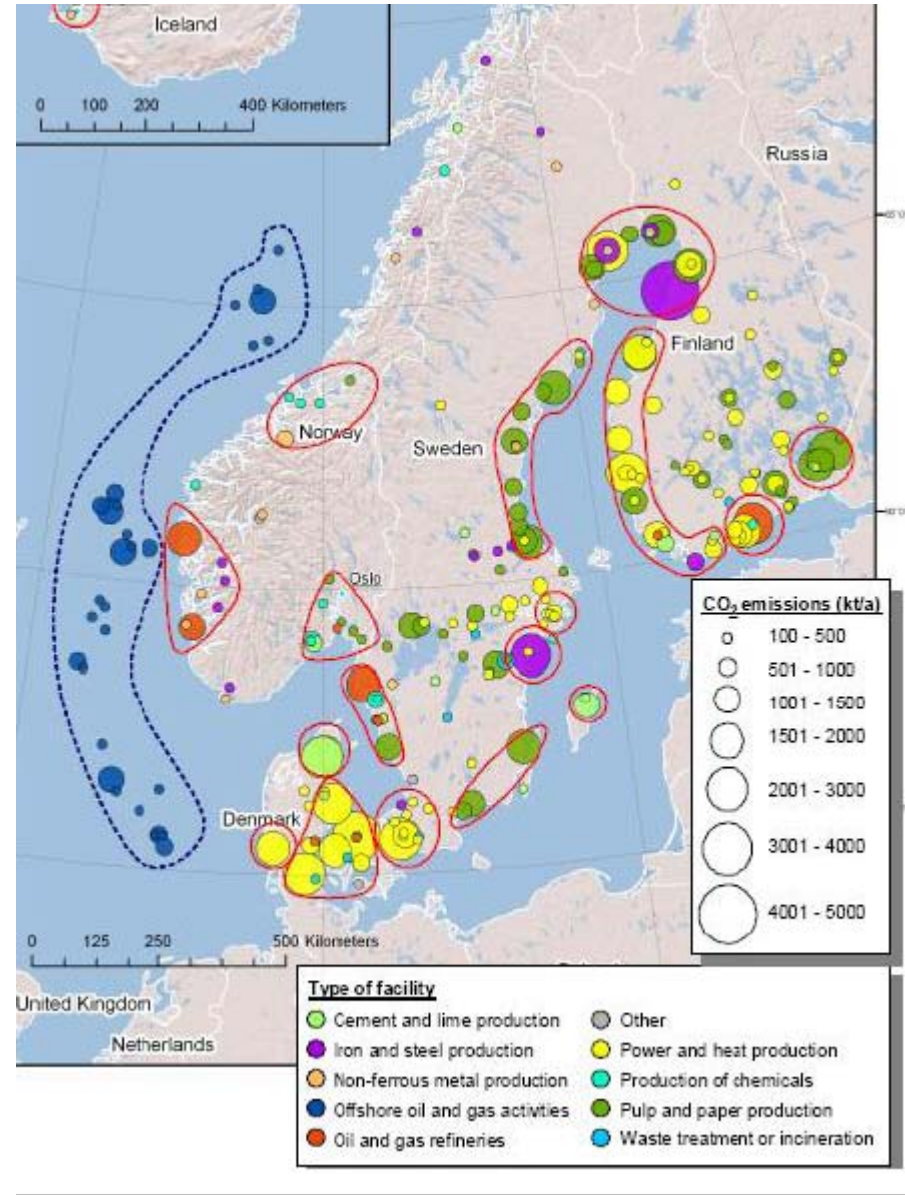
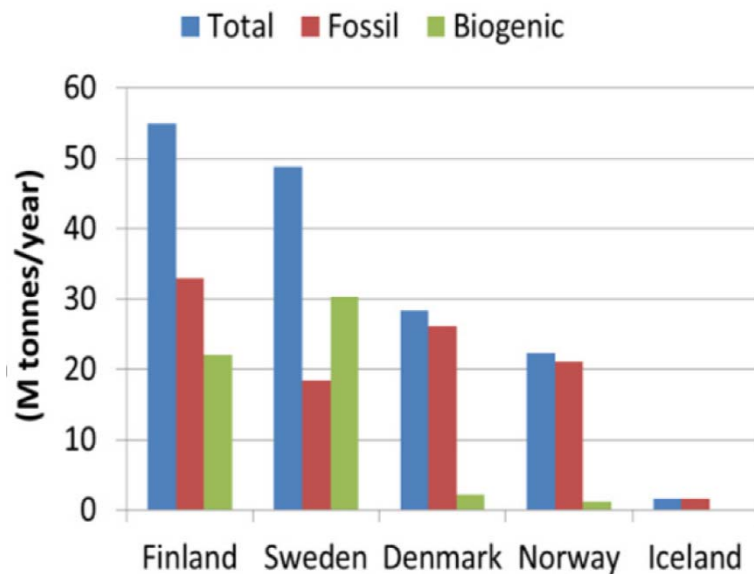
Additional potential advantages

- **No pollutants in flow from air reactor**
 - **Lower air ratio possible ?**
- **Pollutants, e.g. NO_x, concentrated in CO₂ flow**
 - **Possibility to eliminate NO_x emissions ?**
- **No alkali from air reactor ?**
 - **Alkali leaves with flue gases from fuel reactor ?**
 - **and/or is captured by the oxygen carrier ?**
 - **No corrosion ?**
 - **Higher steam data / efficiency ?**
 - **More research needed**
- **No other ash from air reactor ?**
 - **Reduced fouling ?**
 - **Problems concentrated in smaller flow from fuel reactor ?**

CO₂ capture and storage in Nordic countries

total Nordic fossil CO₂ emissions 200 Mt/year
 in addition:
 >50 Mt/year biogenic

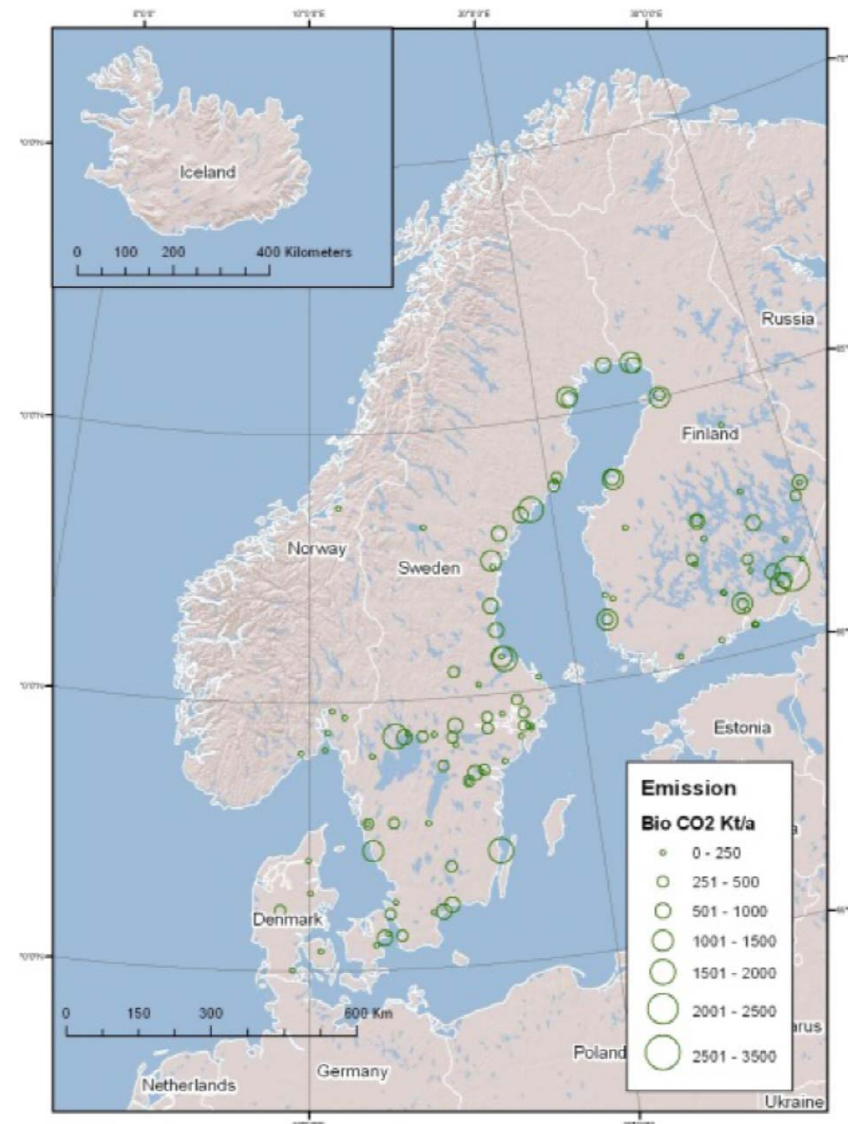
CO₂ emissions, sources >100 000 tons/year:



potential storage locations



CO₂ biofuel point sources



Ideas of port in western Norway with pipeline to storage, could receive CO₂ by boat from Sweden/Finland.

Nordic countries and BioCCS

- **Large biogenic emissions (25% of fossil)**
- **Very large and proven storage locations**
- **Key competence in storage, Norway worldleading**
- **Potential synergies with industrial emission that would need storage (cement, iron & steel...)**
- **Key competence in CLC**

- **Moral: Nordic countries have by far exceeded their "share of the atmosphere"**
- **We are rich, if we cannot afford it who can ?**

What is a reasonable cost ?

global carbon intensity $\approx \frac{1}{2}$ kg CO₂/€

=>

”avoidance cost” much less than 2 €/kg CO₂

Thus, avoidance cost < 0.1 €/kg CO₂

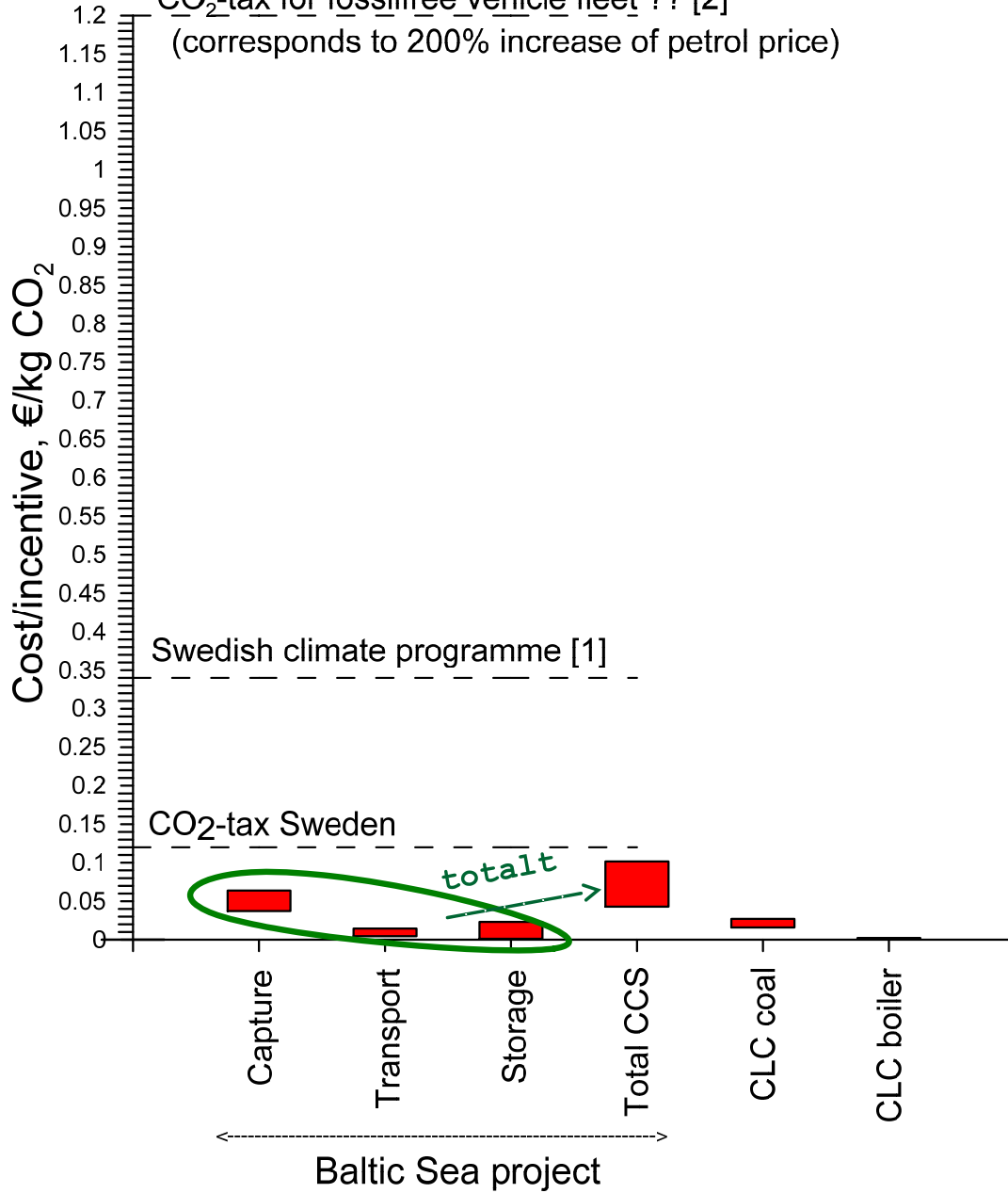
leads to cost <5% of GDP

Avoidance costs <0.1 €/kg preferred !!!

(<100 €/ton)

↑ 2 €/kg CO₂ (= global BNP/global emissions)

CO₂-tax for fossilfree vehicle fleet ?? [2]
(corresponds to 200% increase of petrol price)



Scale-up

Fuel size:

- Use intermediate size, 90-300 μm
 - High CO_2 capture and low loss of char

Reactor and system design:

- Use existing proven CFB technology when possible

Scale-up strategy, lower cost by

- First step without CO_2 capture
- Dual purpose unit, i.e. CLC that can be used as CFB.

Circulation system/control

- Key for successful operation

Pilot operation:

- >9000 h of operation and ~3000 h with solid fuels shows CLC is feasible.
- **Additional small-scale pilot operation will not answer key questions related to performance in full-scale**
 - Small pilots do not have relevant height to show conversion possible in full-scale riser, wrt. conversion of gas and char
 - High bottom beds possible, but will be slugging because of high ratio H/D
- ***Technology ready for scale-up !***



Negative CO₂







Nordic Energy Research
Flagship Project



norden
Nordic Energy Research

Negative CO₂

Enabling negative CO₂ emissions in the Nordic energy system through the use of Chemical-Looping Combustion of biomass (bio-CLC)

	Budget (kNOK)
 CHALMERS	Chalmers University of Technology 9258
 BELLONA	The Bellona Foundation 2080
 SIBELCO NORDIC	Sibelco Nordic AB 240
 SINTEF	SINTEF Energy Research 6555
	SINTEF Materials and Chemistry 2787
 VTT	VTT Technical Research Centre of Finland Ltd 6667
 Åbo Akademi	Åbo Akademi University 3337
	Sum: 30924

Conclusions

- BioCCS will be needed in large scale to meet climate targets**
- CCS has reasonable costs**
- Nordic countries are very suitable for developing BioCCS**
- Chemical-Looping Combustion has unique potential for dramatically reduced cost of CO₂ capture**

QUESTIONS ?

*>290 publications on chemical-looping on:
<http://www.entek.chalmers.se/lyngfelt/co2/co2publ.htm>*