Energy-efficient CO_2 Capture with Chemical-Looping Combustion

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CCSP – Final results seminar,
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Helsinki

TODAY:

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

Carbon budget for max 1.5ºC and 2ºC :

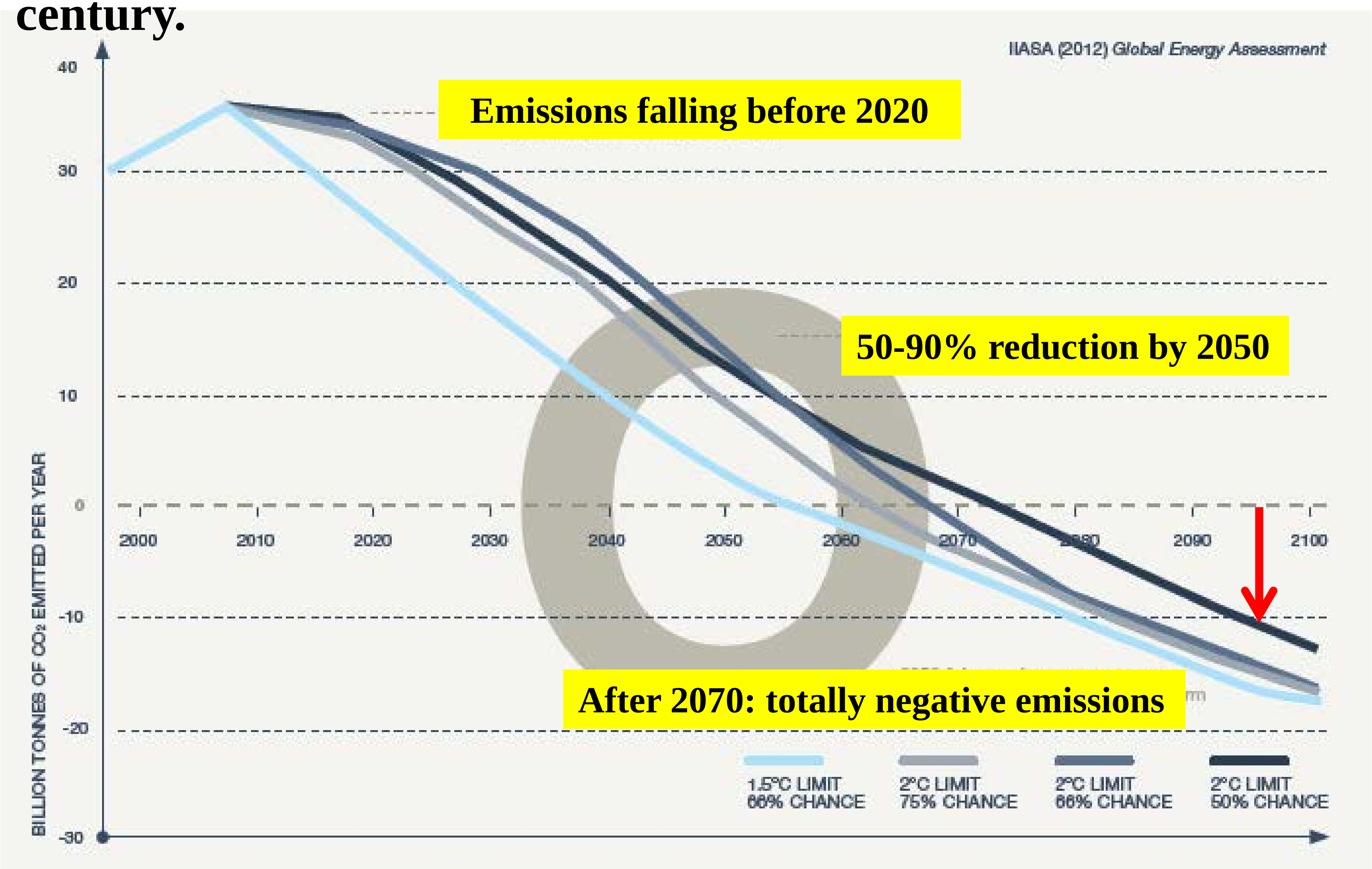
300 and 900 Gton CO_2

Emissions today >35 Gton/yr :

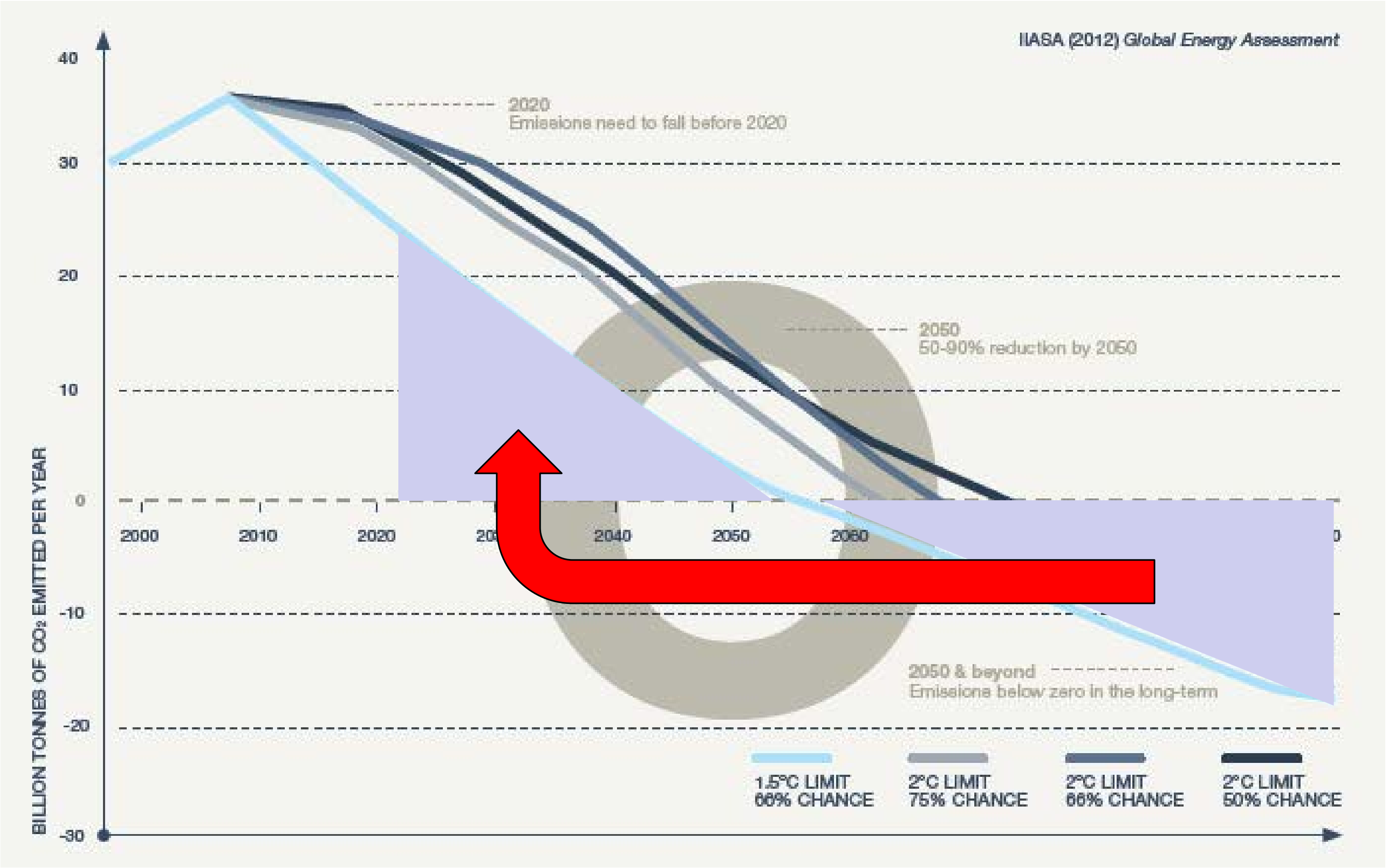
<10-30 years left of todays emissions!!

Climate goal ”well below” 2ºC - 20 years ?

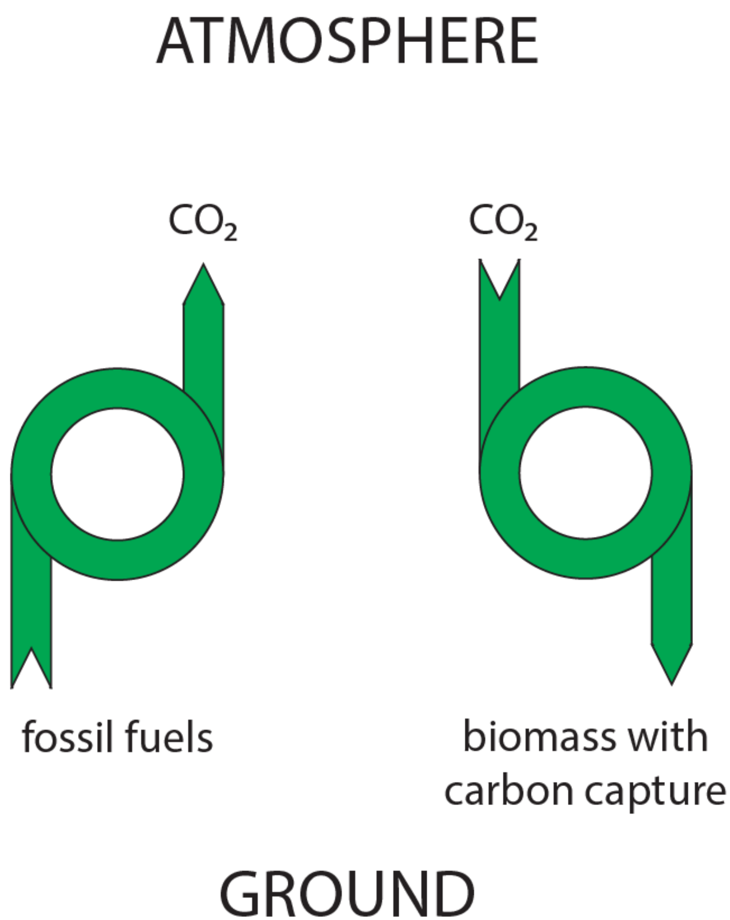
To meet the 2°C target it is not sufficient to stop emissions of CO_2, most likely we need *negative* emissions by the end of the century.



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



BECCS (Bioenergy Carbon Capture & Storage)



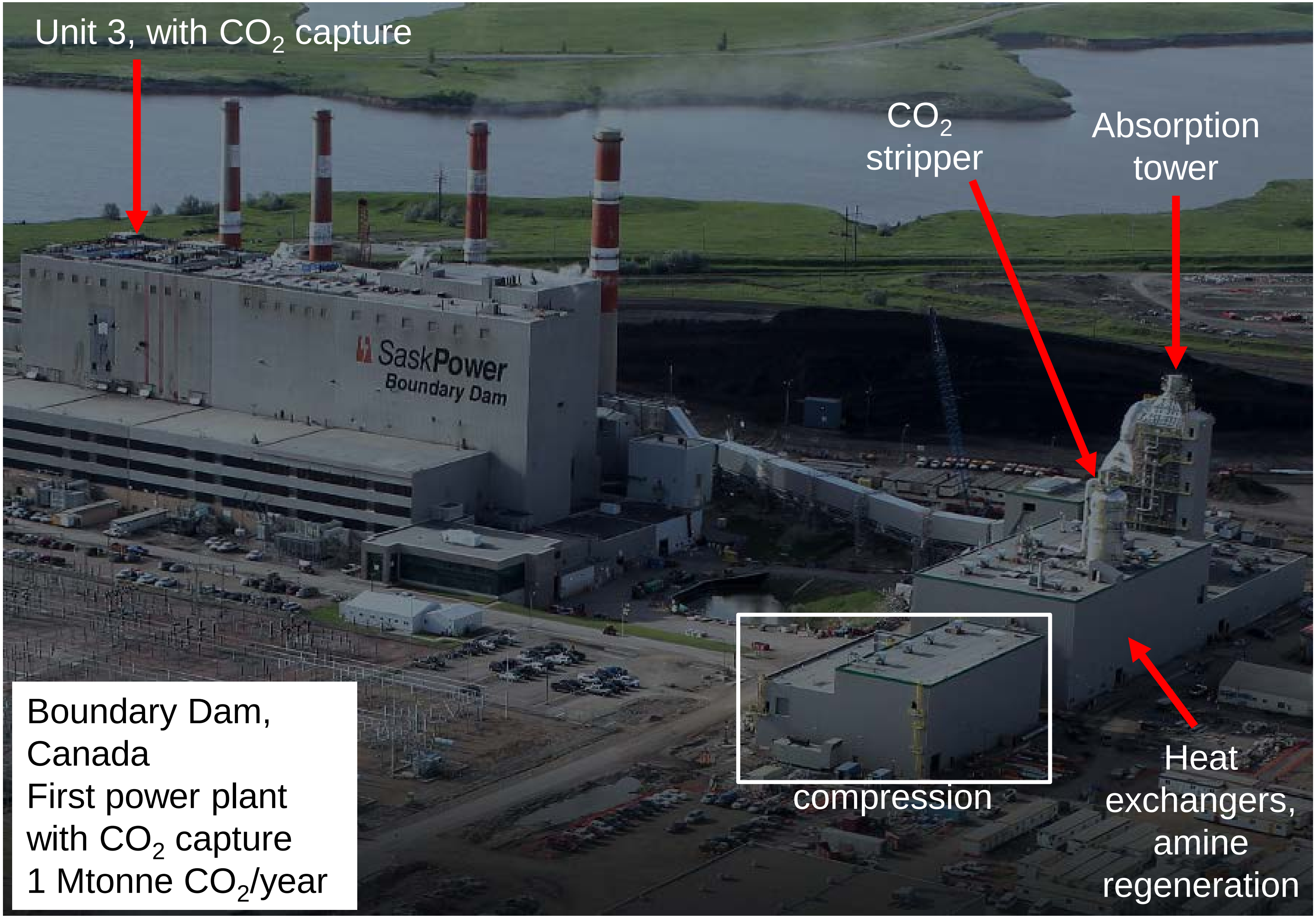
Carbon Capture and Storage (CCS) status

Three main technologies[1], all having

- ❑ **large energy penalties, around 10%-units**
- ❑ **significant need for gas-separation equipment**
- ❑ **cost normally estimated to 50 €/tonne CO_2 or more**

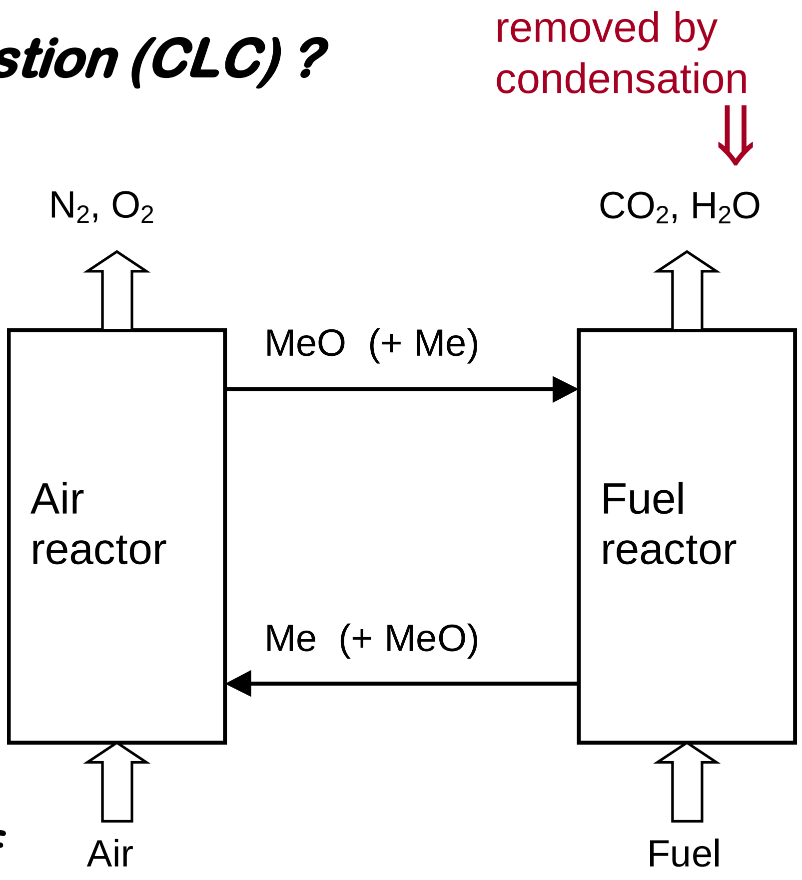
- **First commercial large post-oxidation in operation 2 years (Boundary Dam, Canada)**

[1] post-, pre- and oxycombustion


Unit 3, with CO_2 capture
CO_2
stripper
Absorption
tower
SaskPower
Boundary Dam
compression
Heat
exchangers,
amine
regeneration
Boundary Dam,
Canada
First power plant
with CO_2 capture
1 Mtonne CO_2/year

Why chemical-looping combustion (CLC) ?

Oxygen is transferred from air to fuel by metal oxide particles

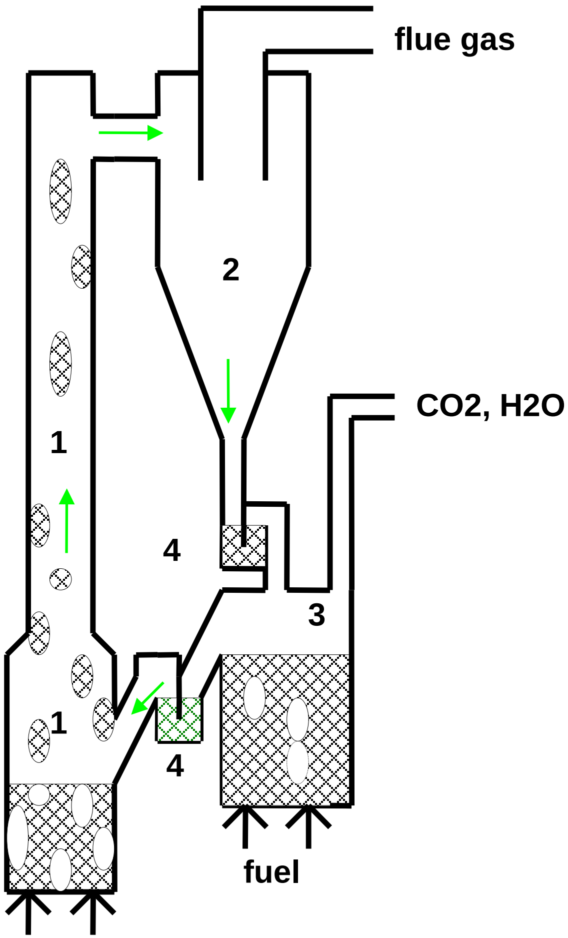


Inherent CO_2 capture:

- **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 CO_2 capture**
- **But, does it work in practice ?**

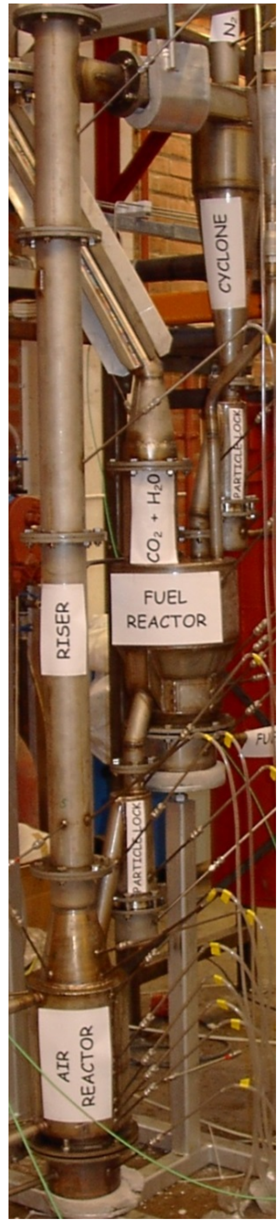
Chalmers' 10 kW gas-CLC, 2003

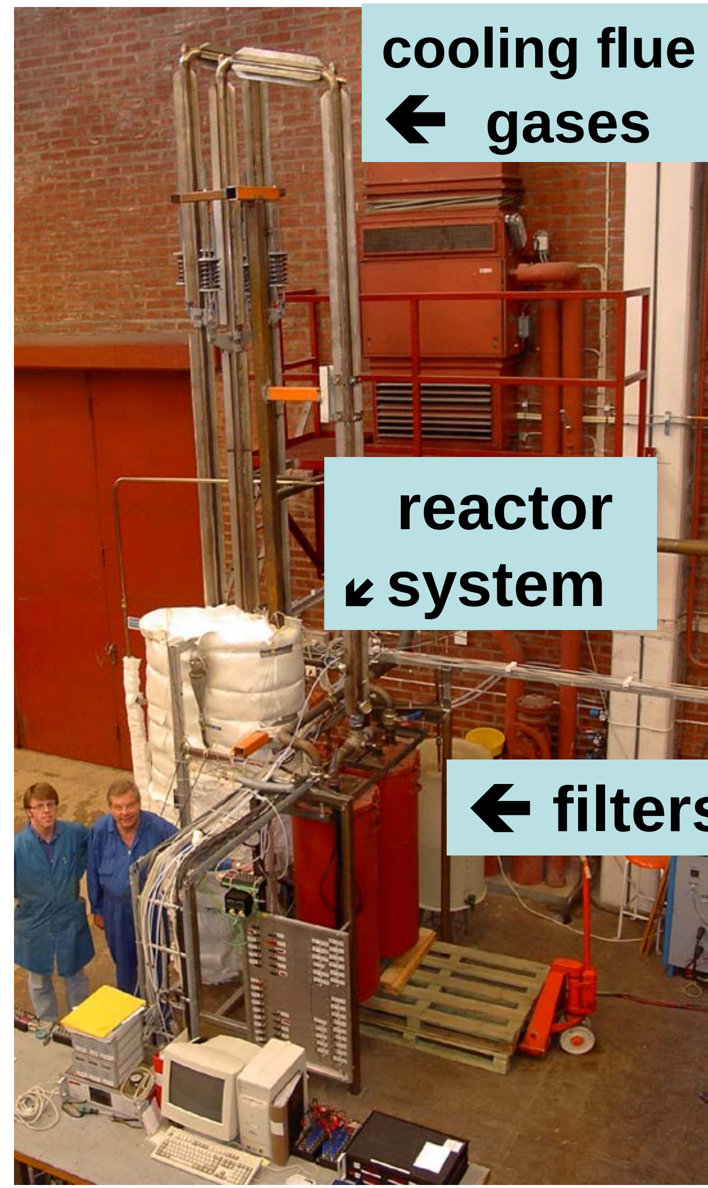


1 air reactor, 2 cyclone

3 fuel reactor, 4 loop seals

without insulation



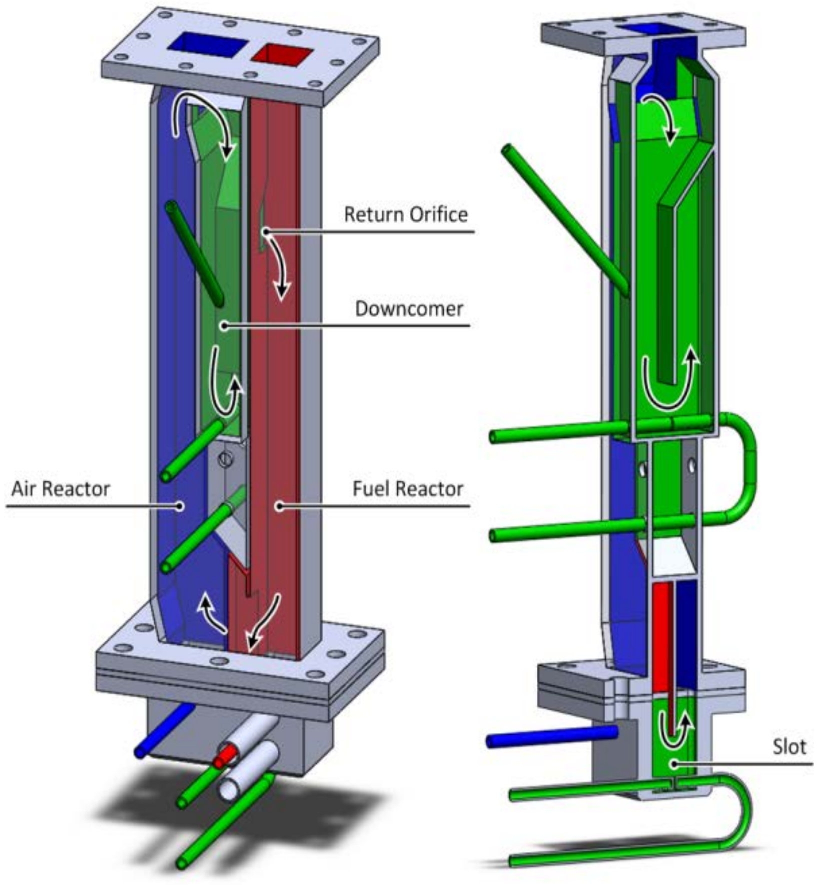


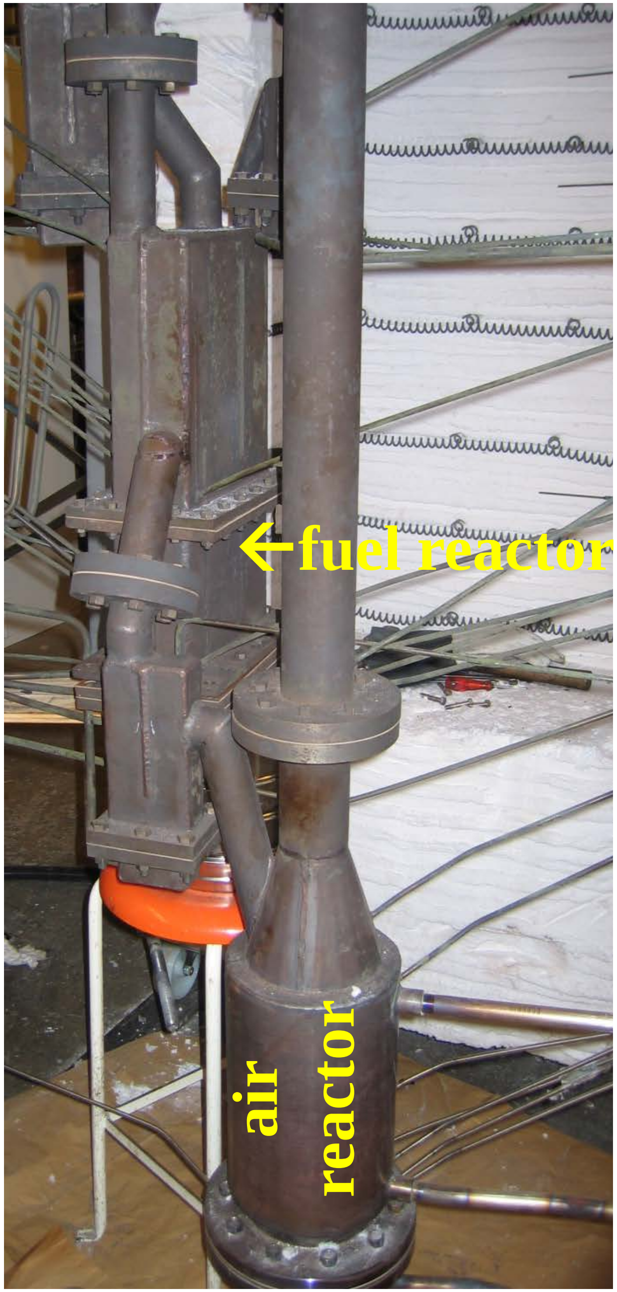
Chalmers 300 W gas-CLC, 2004

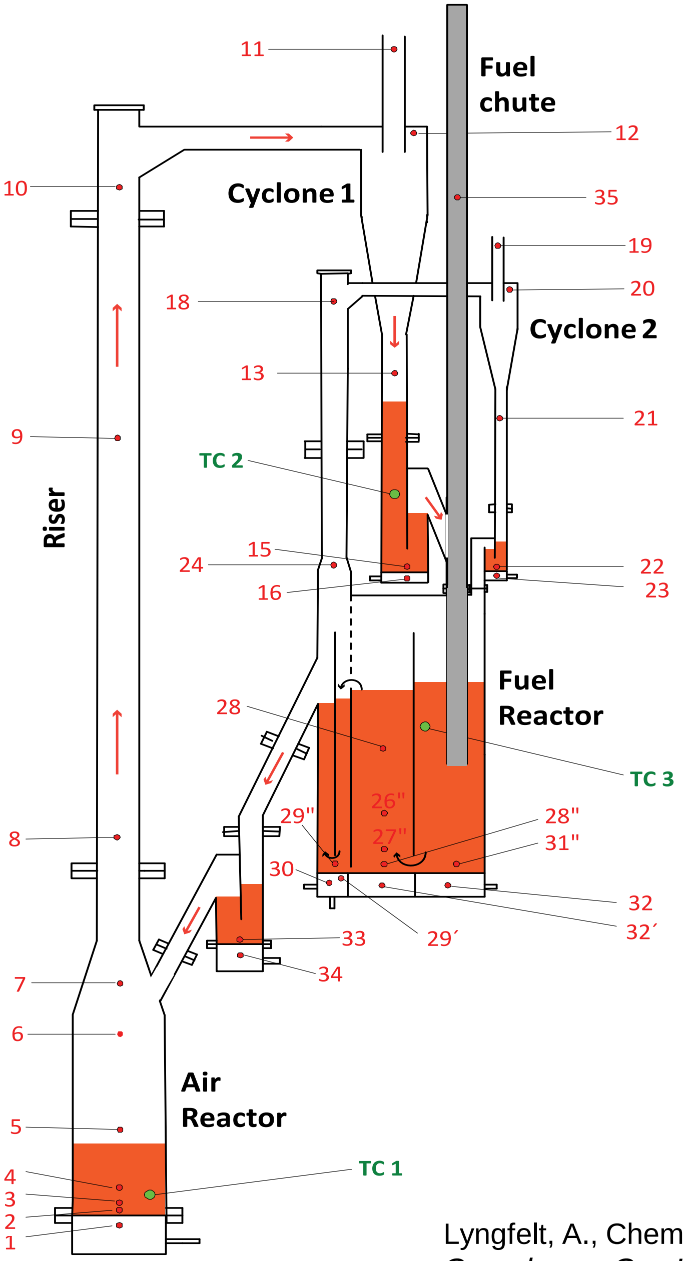
Dimensions:

Air Reactor: 25x35 mm, 25x25 mm

Fuel Reactor: 25x25 mm





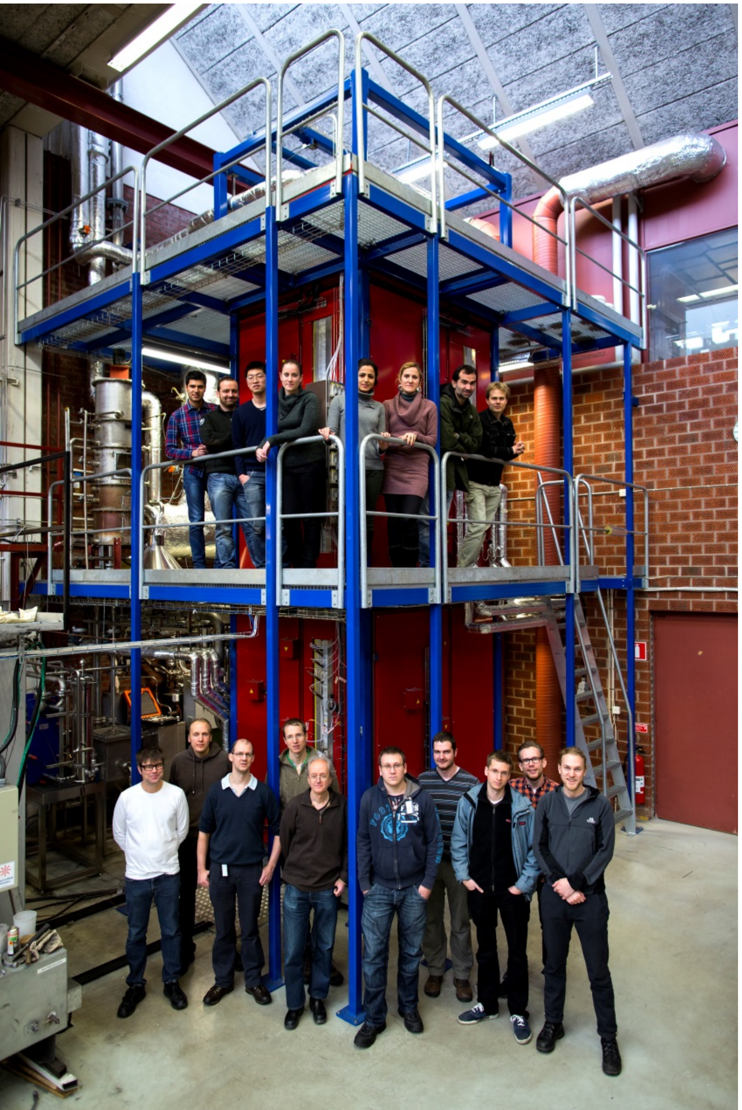


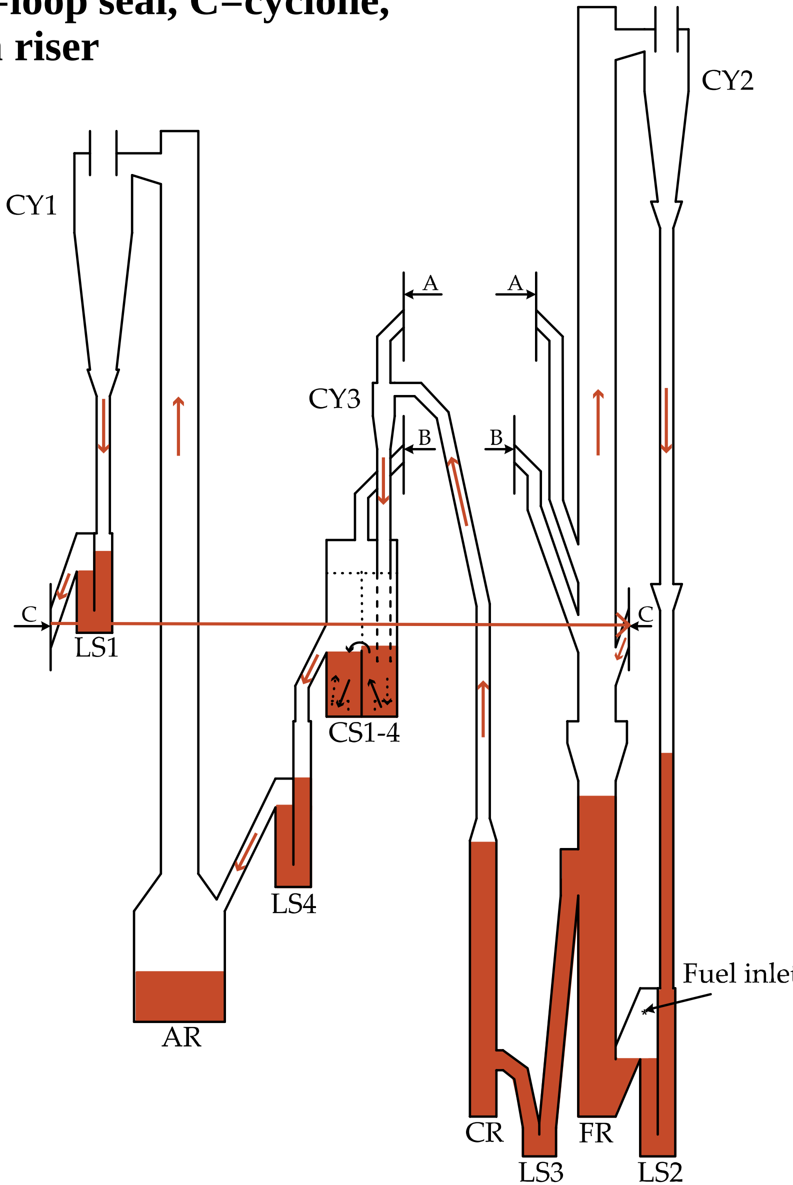
Chalmers' 10 kW chemical-looping combustor for solid fuels.
First operation 2006
Published 2008

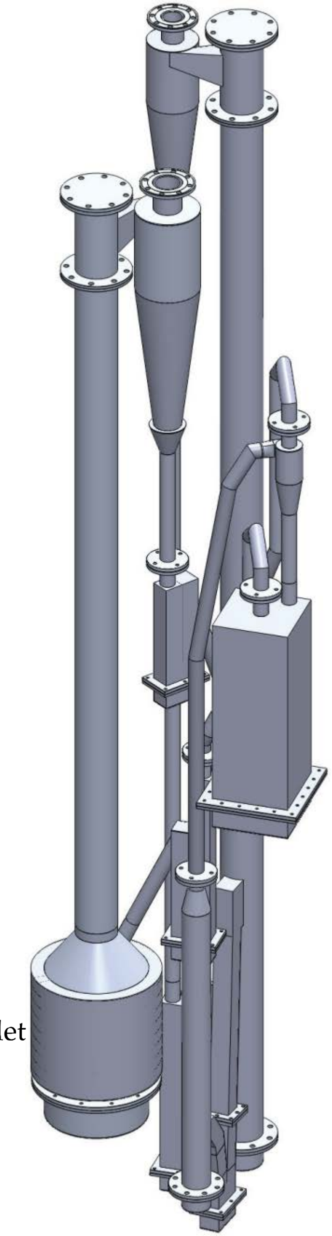
Lyngfelt, A., Chemical-looping combustion of solid fuels, *Greenhouse Gas Issues*, No. 87, September 2007, 9-10.

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



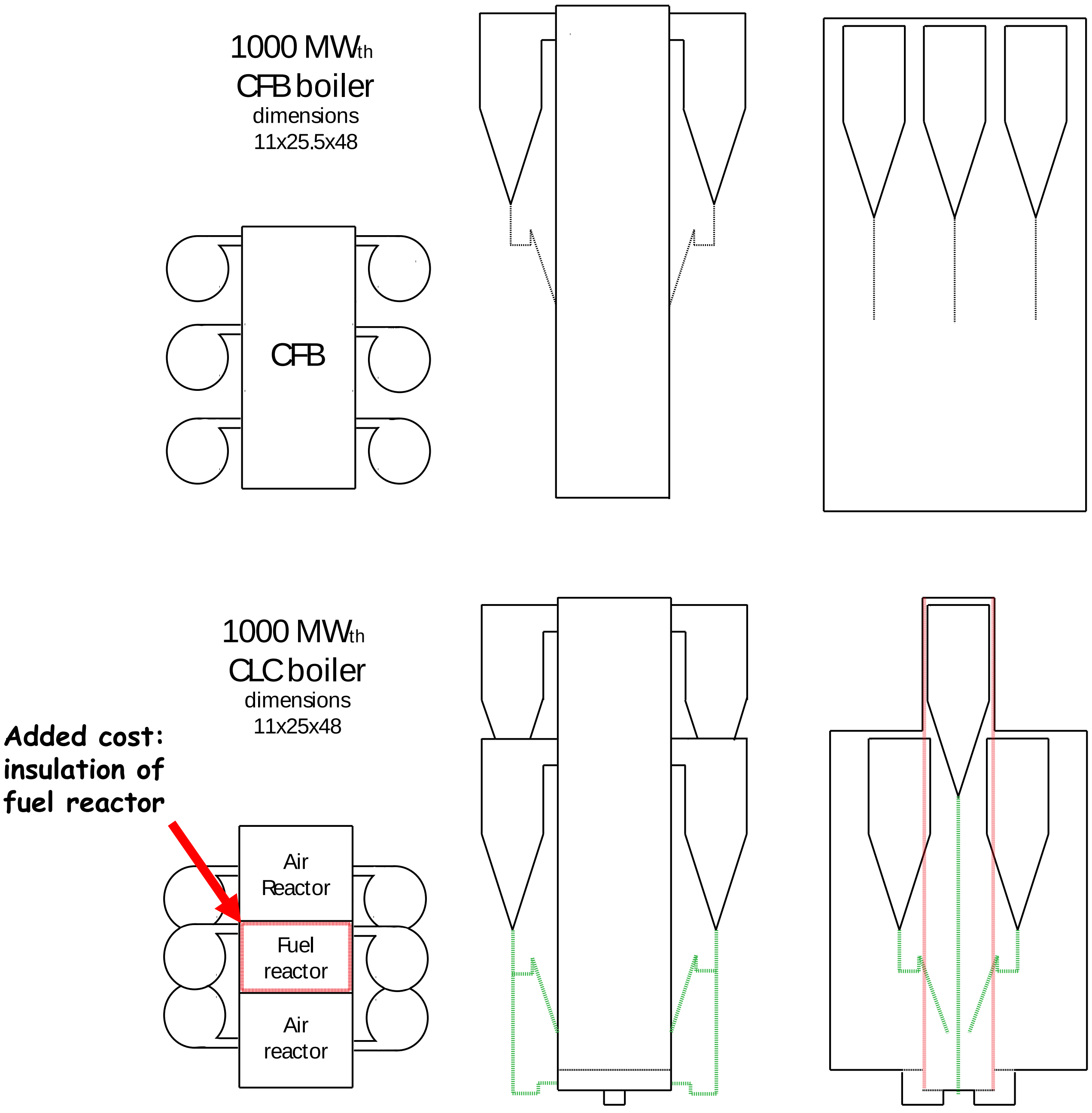




Where are we ?

- **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% CO_2 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 m^2

Cost: 1500 €/m^2

Added cost of fuel reactor:

4 M€

0.4 M€/year
2 Mton CO_2/year

= 0.2 €/ton CO_2

From: Lyngfelt, A., and Leckner, B., A 1000 MWth Boiler for Chemical-Looping Combustion of Solid Fuels - Discussion of Design and Costs, *Applied Energy* in press *(available on-line)*

Added cost relative to CFB[1]

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
Total	20	15.9-25.8	3.9

Scale-up, first step without CO_2 capture, to assess technology

- **Main costs: Downstream treatment and oxygen production not needed**
- **CO_2 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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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
Total	3.5	1.9-6.8	0.4

[1]Lyngfelt, 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 CO_2 flow
    - Possibility to eliminate NOx 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 ?

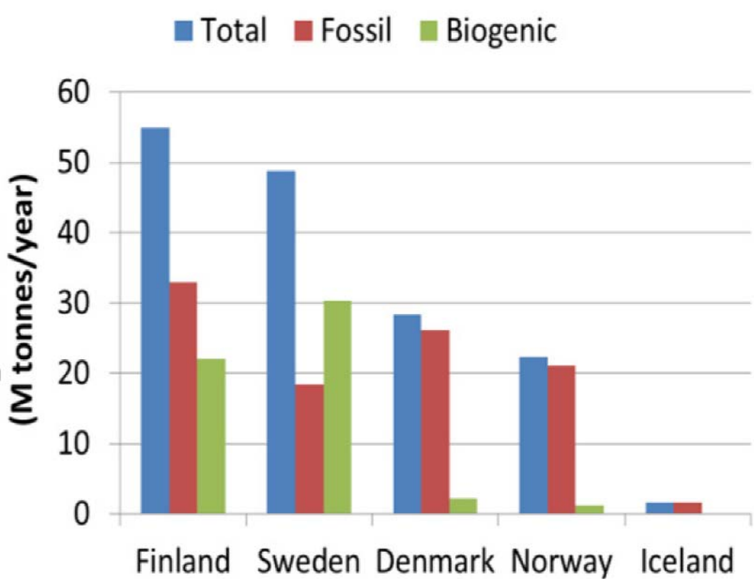
CO_2 capture and storage in Nordic countries

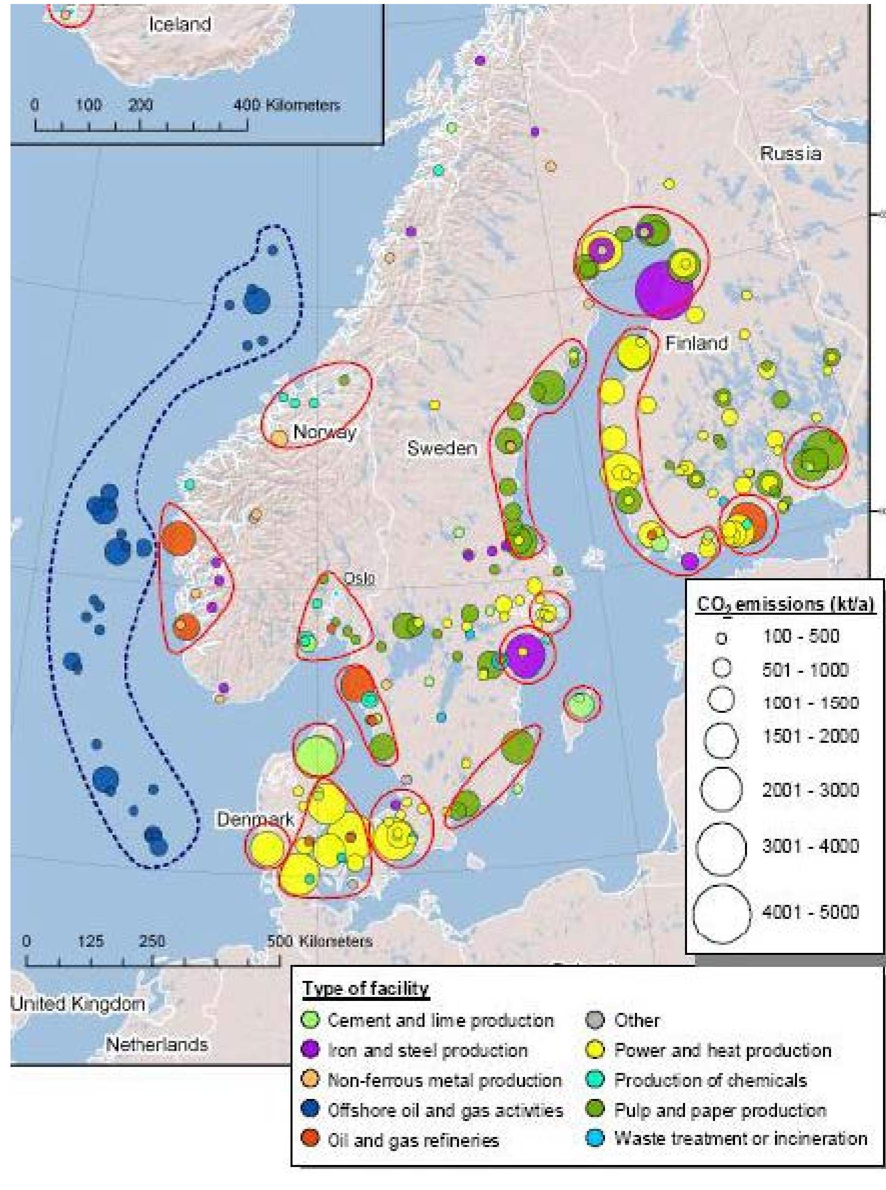
total Nordic fossil CO_2 emissions 200 Mt/year

in addition:

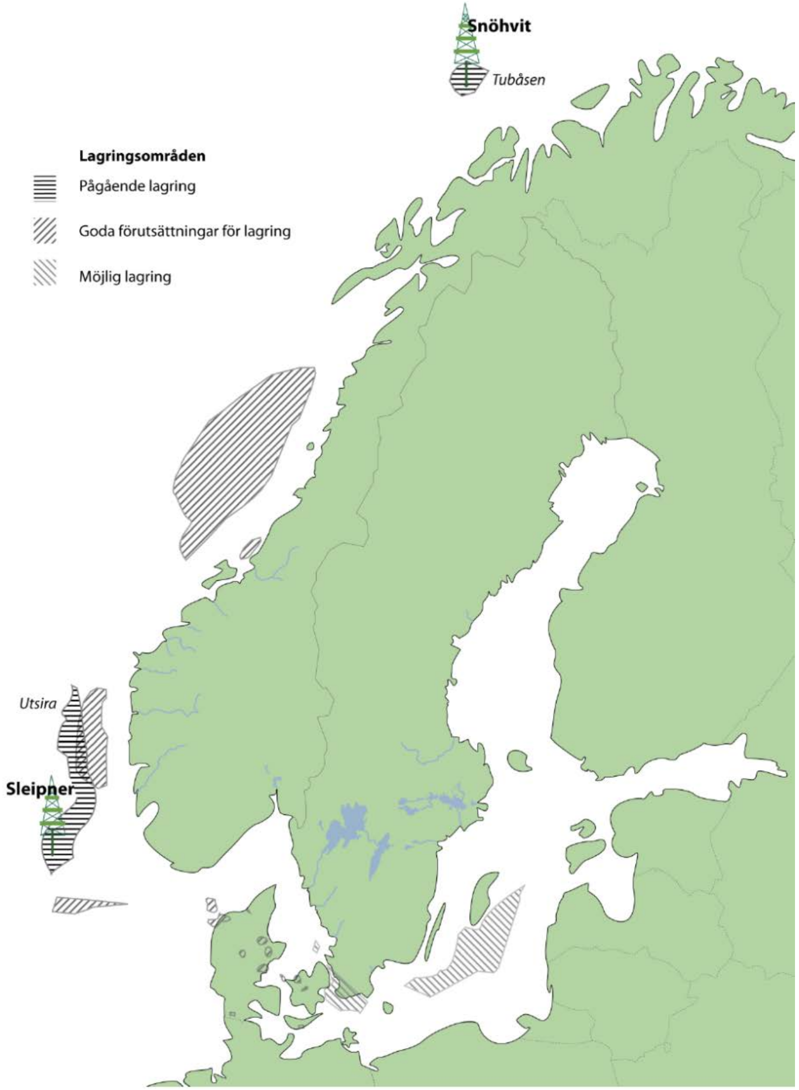
>50 Mt/year biogenic

CO_2 emissions, sources >100 000 tons/year:

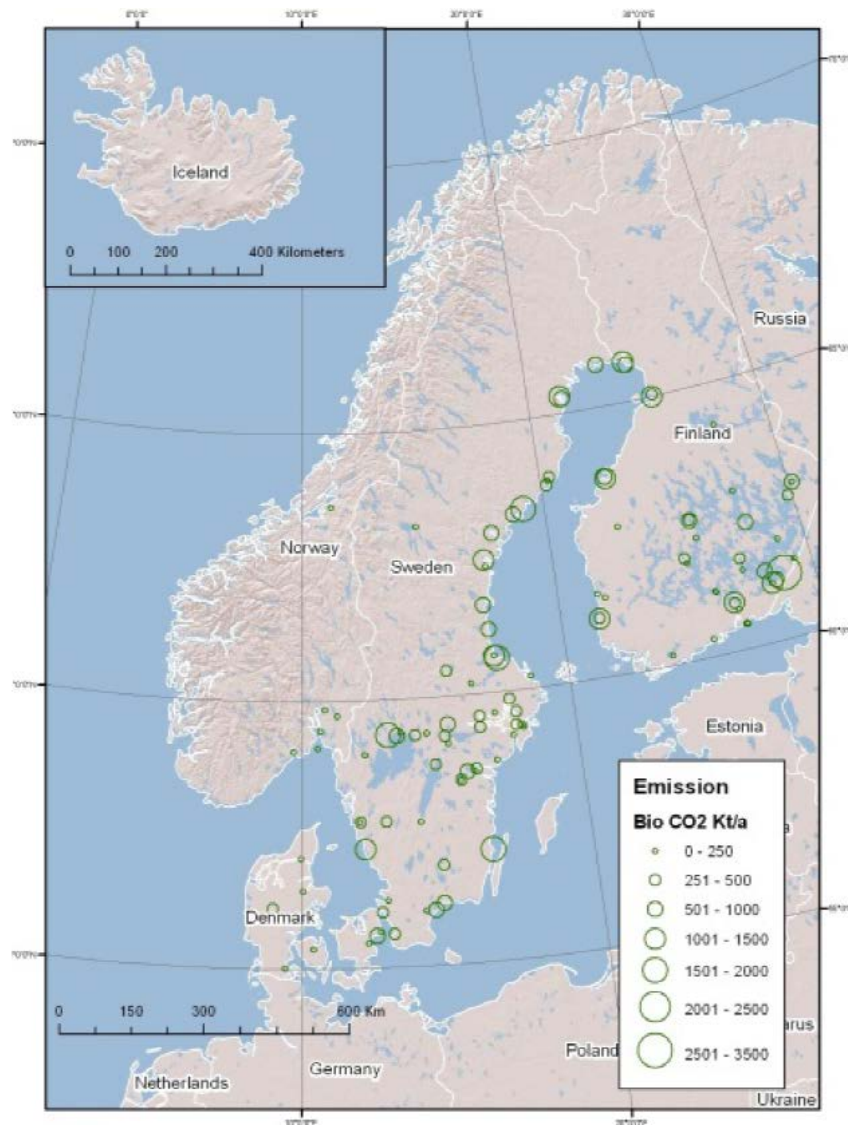




potential storage locations



CO_2 biofuel point sources



Ideas of port in western Norway with pipeline to storage, could receive CO_2 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 ?

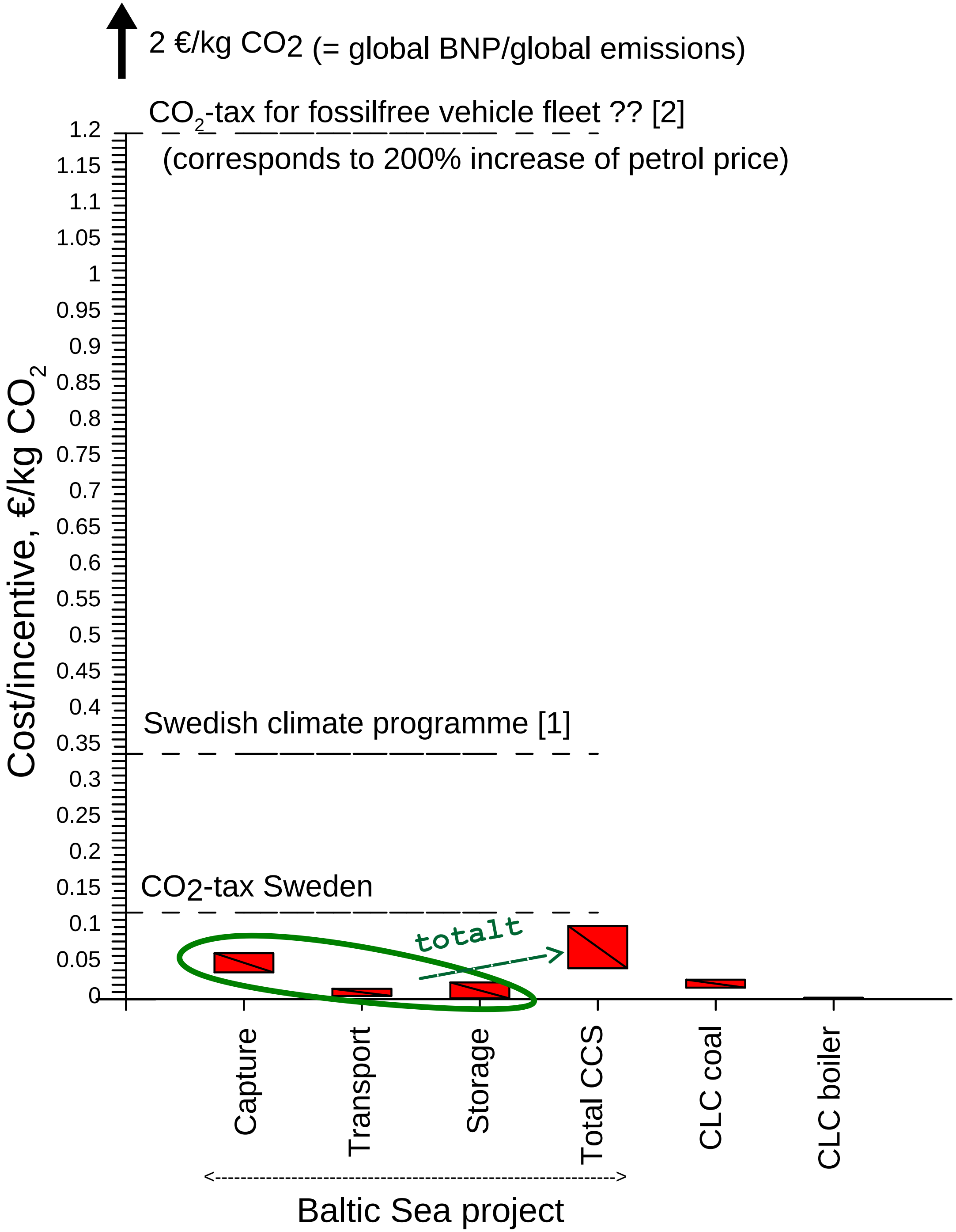
global carbon intensity ≈ ½ kg CO_2/€

=>

”avoidance cost” much less than 2 €/kg CO_2

Thus, avoidance cost < 0.1 €/kg CO_2
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)
Swedish climate programme [1]
CO2-tax Sweden
totalt
Cost/incentive, €/kg CO2
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Capture
Transport
Storage
Total CCS
CLC coal
CLC boiler
Baltic Sea project

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 *<u>not</u>* 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 !*

Nordic Energy Research

Flagship Project

Nordic Energy Research

Negative CO_2

Enabling negative CO_2 emissions in the Nordic energy system through the use of Chemical-Looping Combustion of biomass (bio-CLC)

	Budget (kNOK)
Chalmers University of Technology	9258
The Bellona Foundation	2080
Sibelco Nordic AB	240
SINTEF Energy Research	6555
SINTEF Materials and Chemistry	2787
VTT Technical Research Centre of Finland Ltd	6667
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 CO_2 capture**

Questions ?

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