Negative CO_2

norden
Nordic Energy Research

Negative CO_2 Emissions in the Nordic Countries

Anders Lyngfelt
Chalmers University
of Technology
Göteborg

CHALMERS

Nordic Flame Days 2019

Åbo Akademi, August 28-29

Key Messages

Carbon dioxide budget soon exhausted - large negative emissions are needed

Several principles for negative emissions - several needed (but don't rely on Direct Air Capture)

BECCS / Bio-CCS safest
- capture of CO2 from biomass + geological storage

Storage - eternal storage is not needed, less safe storage also relevant ("e.g. forestation")

Bio-CCS
- climate-efficient use of limited resource
- biogenic carbon dioxide is valuable waste (can give minus emissions) - significant potential
- technology well known (simple), but few large-scale plants

Key Messages

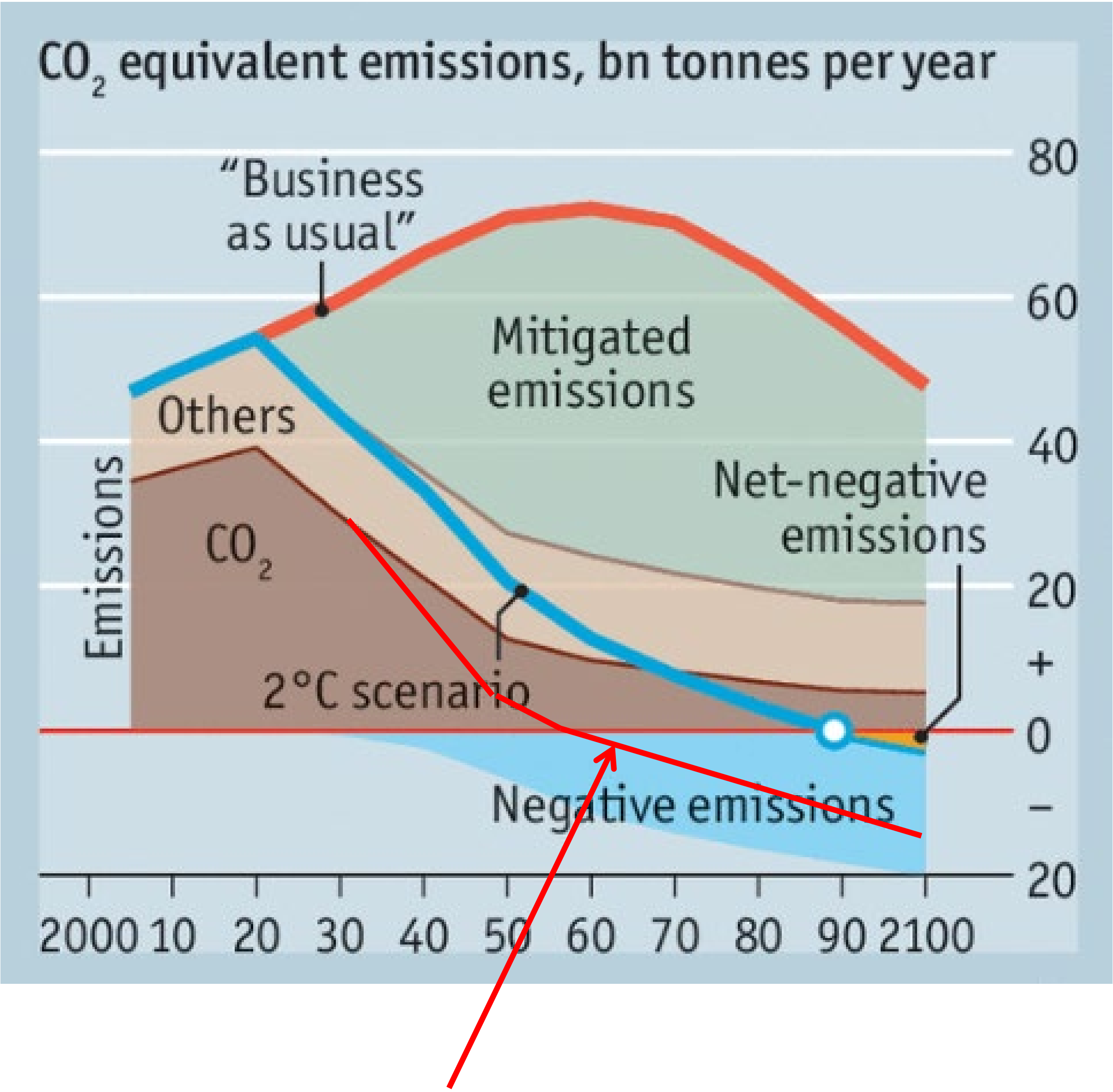
Negative emissions must be financed

CCS not really expensive - corresponds to a few% of GDP

-Rational solution, "producer liability “, emitters pay for removing the CO_2 from the atmosphere

Chemical-Looping Combustion of biomass, Bio-CLC, has potential for dramatic reduction of CO_2 Capture cost

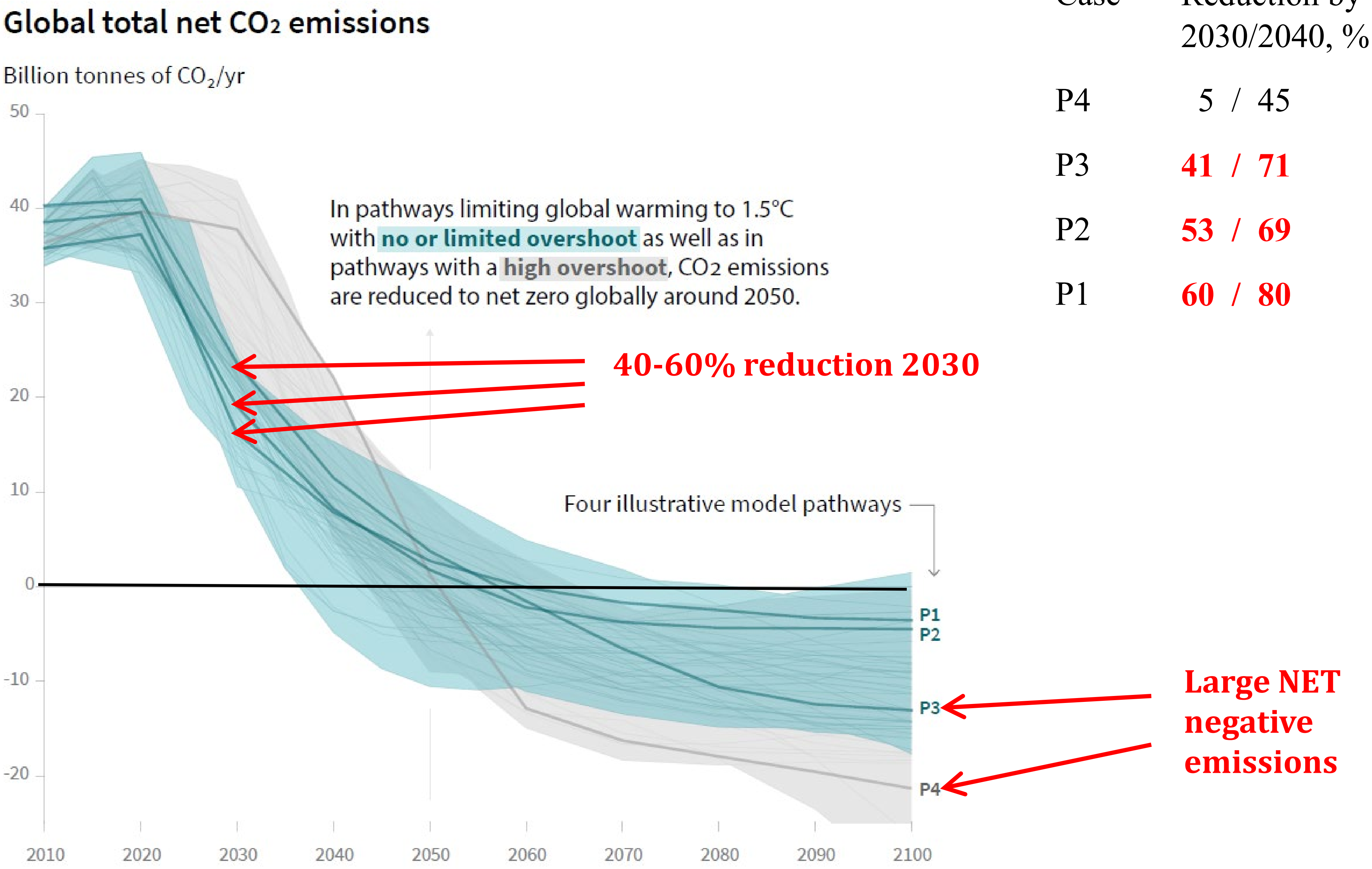
The Nordic region - great potential for bio-CCS, plus very good storage facilities.



Net CO_2 emissions

A major fraction of the CO_2 emissions will need to be removed from the atmosphere by negative emissions.

1,5 degree target



Case	Reduction by 2030/2040, %	Negative emissions, Gt
P4	5 / 45	**-770**
P3	**41 / 71**	**-370**
P2	**53 / 69**	-160
P1	**60 / 80**	-90

Principles of Negative Emissions

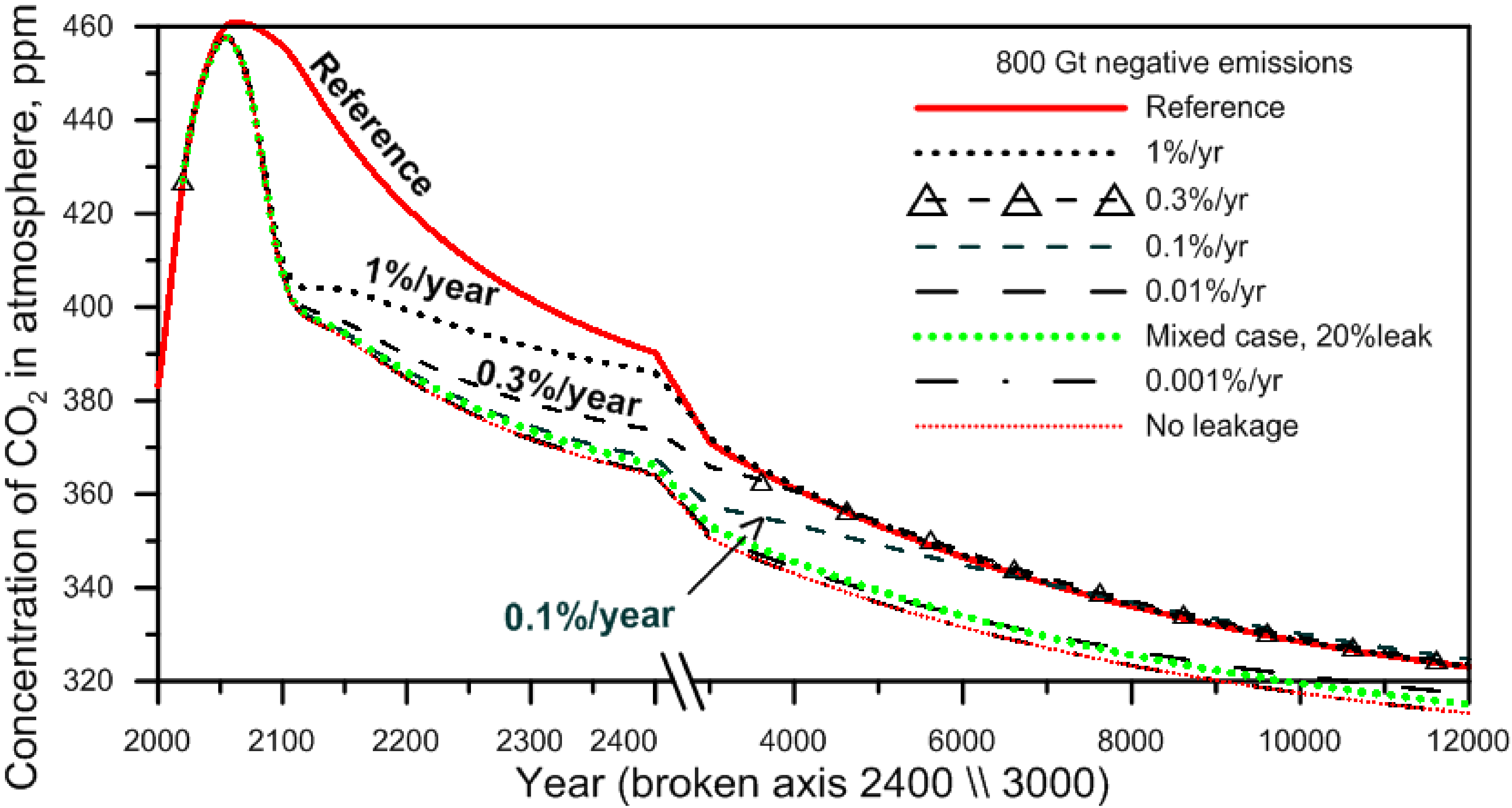
Plants are good at capturing CO_2. Ways of preventing CO_2 from returning to atmosphere:

- **Capture and storage of CO_2 from combustion of biomass/biowaste**
- **Afforestation/Reforestation**
- **Bio-char for soil improvement**
- **Agricultural practices to increase carbon content in soil**

Non-biogenic paths:

- **Enhanced weathering**
- **Ocean liming (CO2 capture and storage from lime calcination plus distribution of lime)**
- **Direct Air Capture (~300 times lower concentration as compared to chimney)**

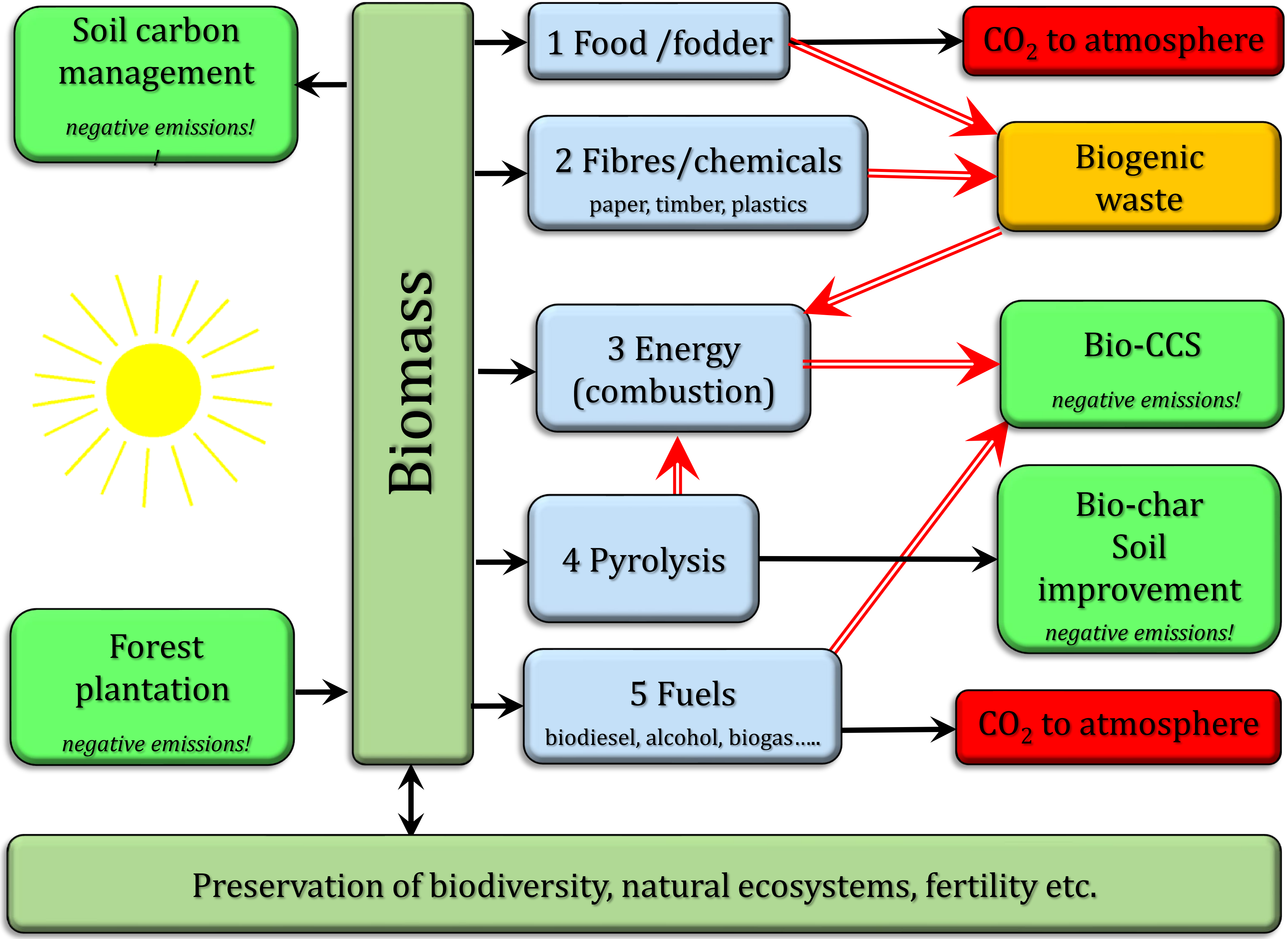
How long does CO_2 need to be stored ?



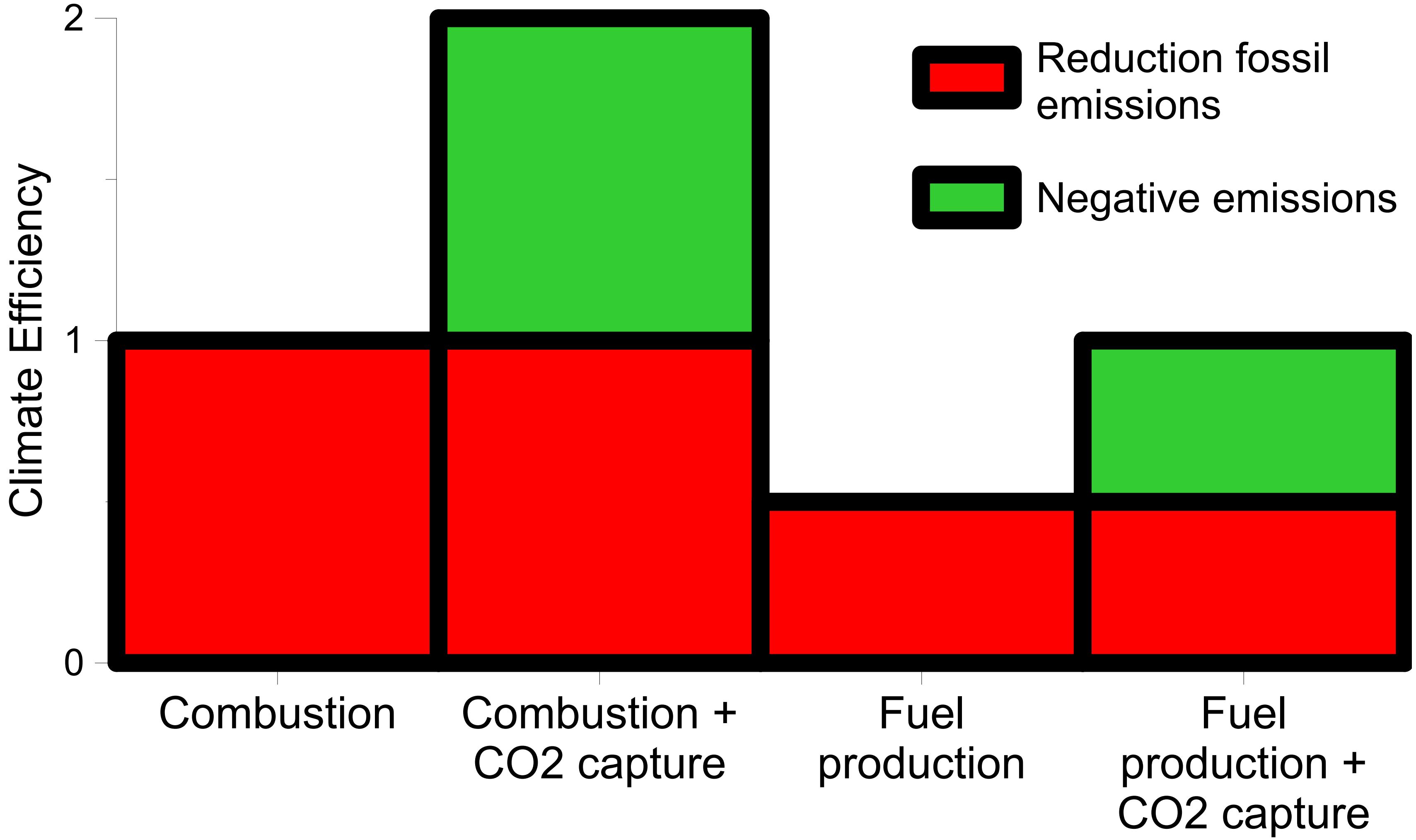
Bio-CCS/BECCS
Making good use of waste from our employment of biomass

Total biomass extraction today 20 Gt/year (as CO_2) (fossil emissions >35 Gt/år)

Of these 20 Gt is 1/3 respiration (human beings + live stock)
Ideally the rest could be used for negative emissions



How is the carbon captured by the biomass used most efficiently for the climate ?

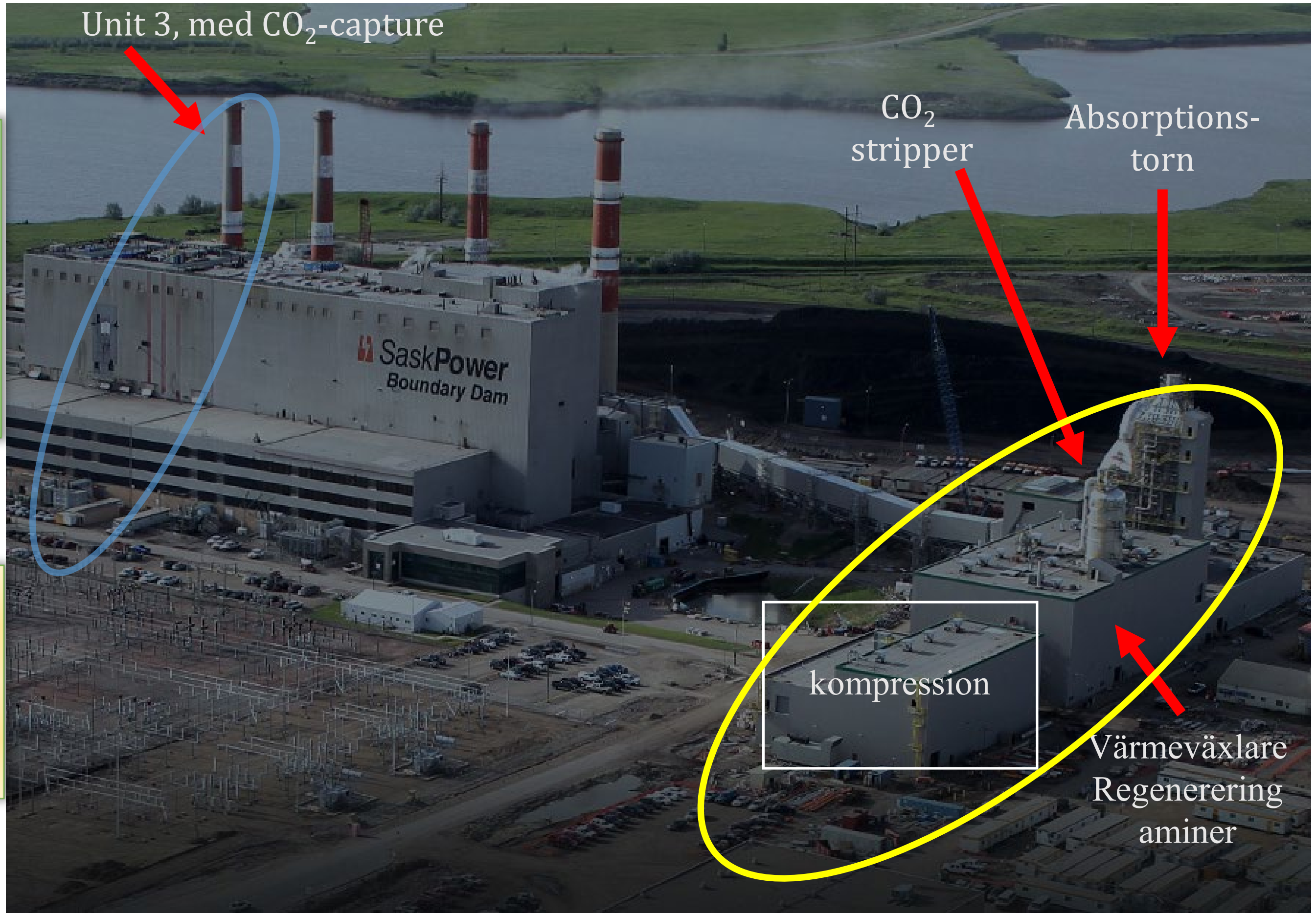


CO2 capture, an example

Boundary Dam, Canada. 115 MW_e

Coal power plant with CO_2-capture:
1 Mton CO_2/year

In operation since october 2014.



Owner (Sask Power) says:

Next time 1/3 of cost:

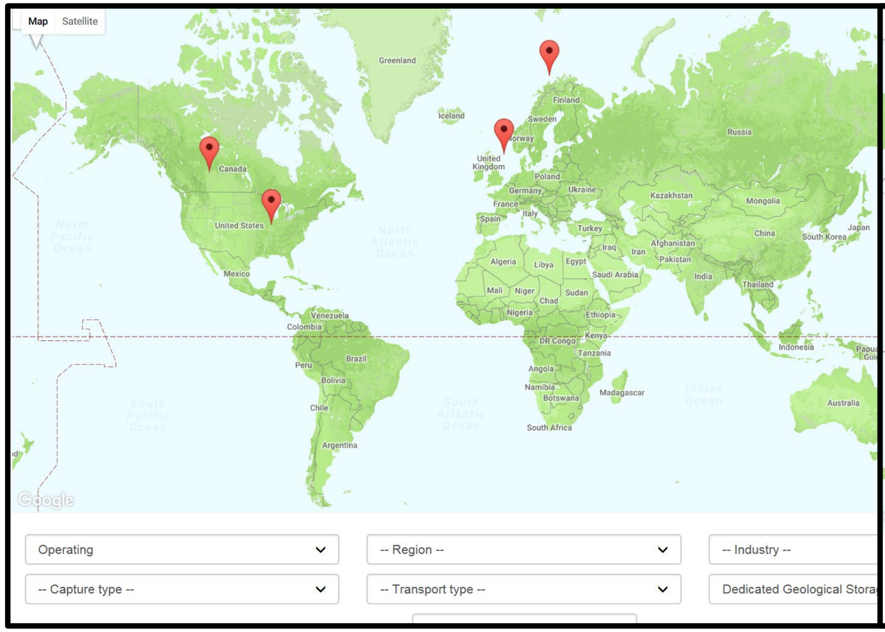
45 $/ton CO_2

Significant cost and energy penalty of gas separation

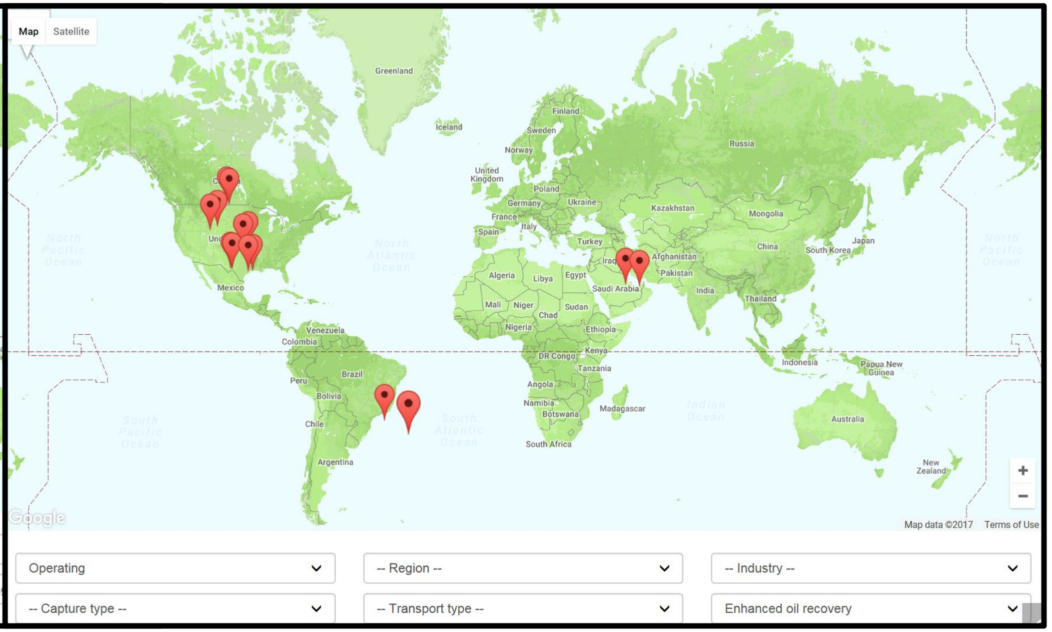

Petra Nova, Texas,
coal fired power plant
>1 Mton/year
Operation since
January 2017

Large-scale storage today

For climate only



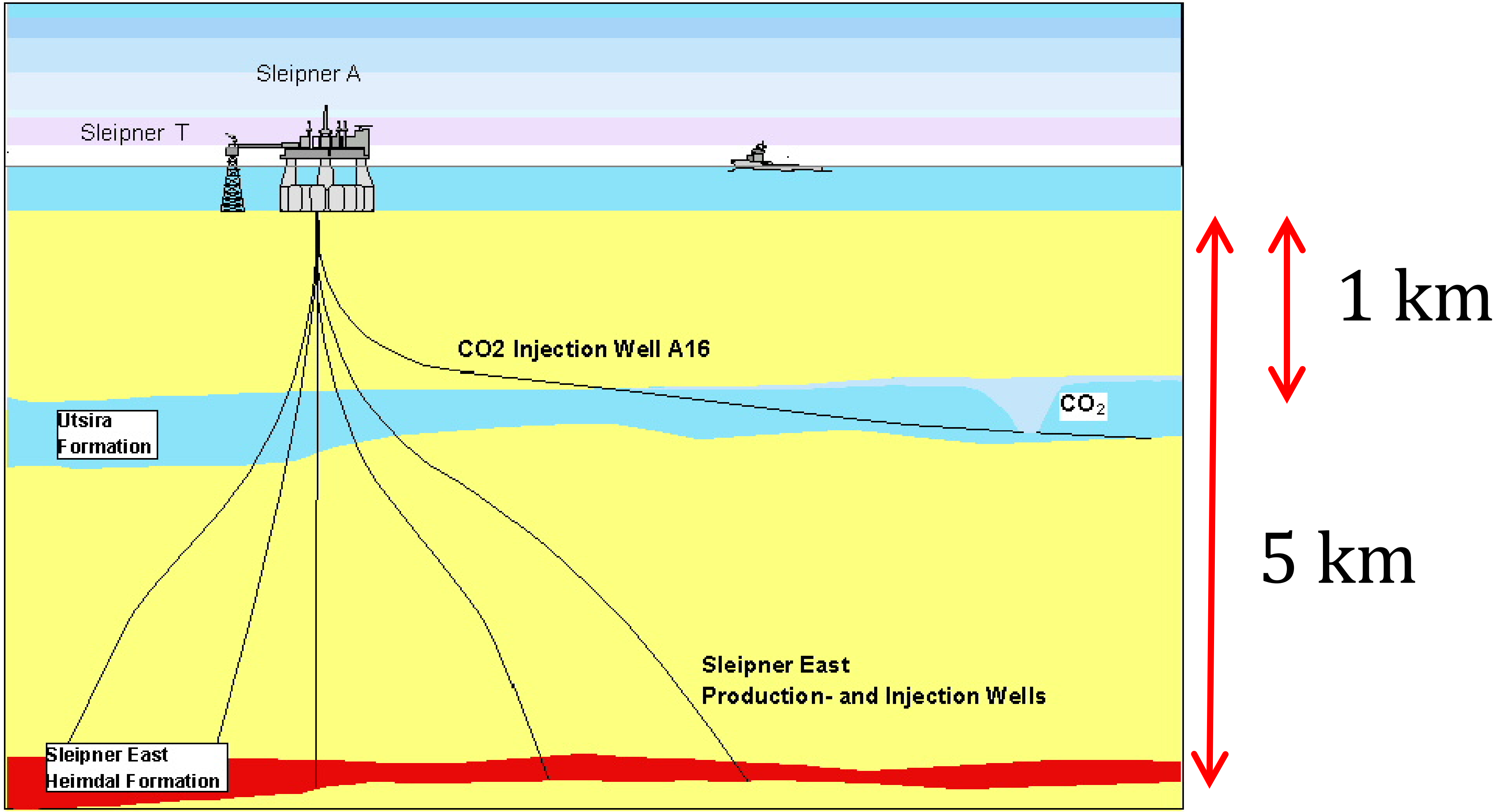
Enhanced oil recovery

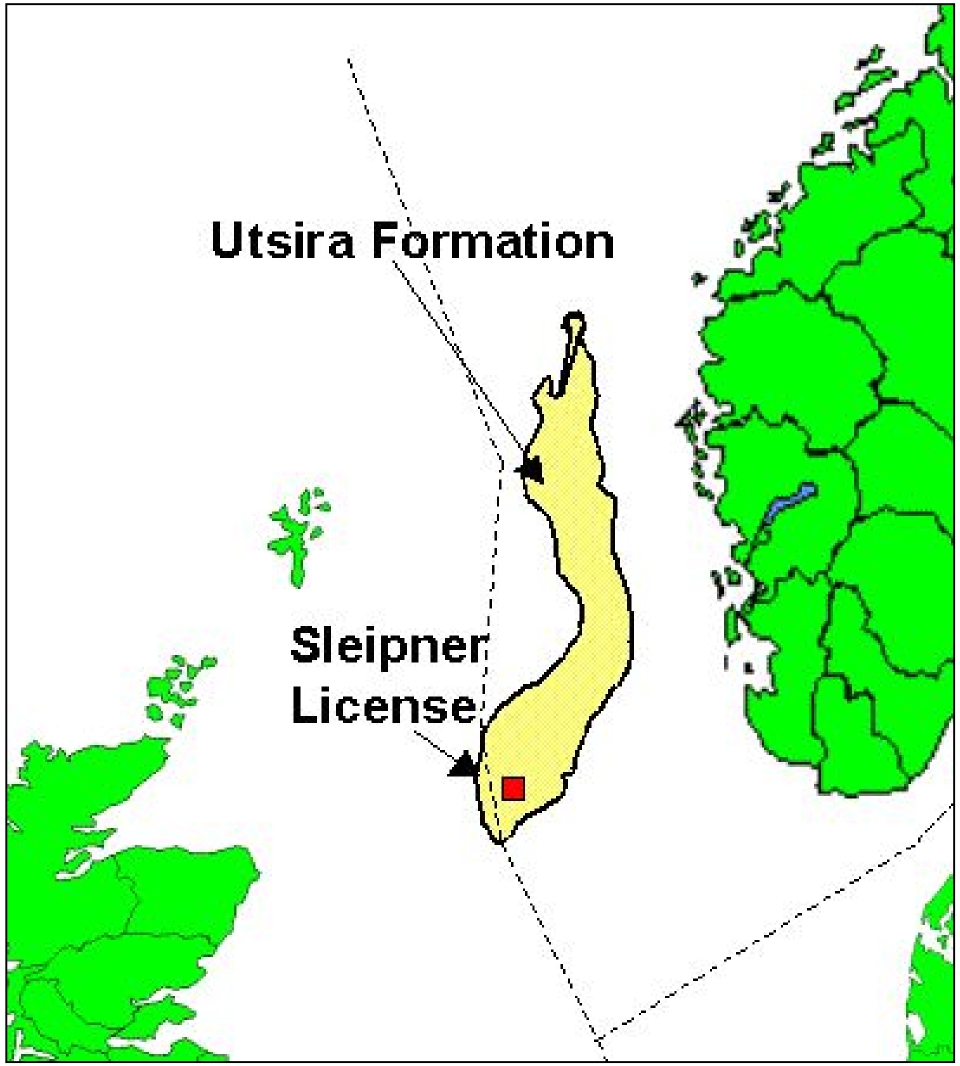


Totally stored 30 Mton CO_2/year
Appr. 0.1% of global emissions

Sleipner gas platform

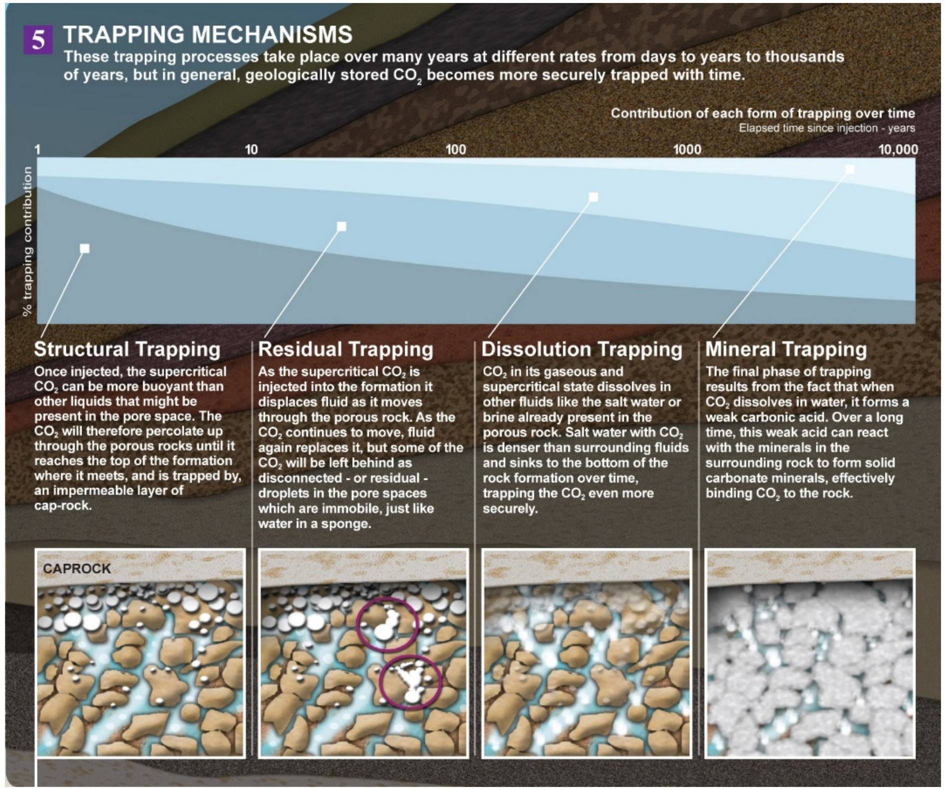
SLEIPNER AQUIFER CO2 STORAGE





Storage started 1996
1 million ton CO_2/year
(3% Norway's total emission)

Area: 26 000 km^2
Depth: 550 to 1500 m
Height: 200-300 m
Porosity: 30-40%

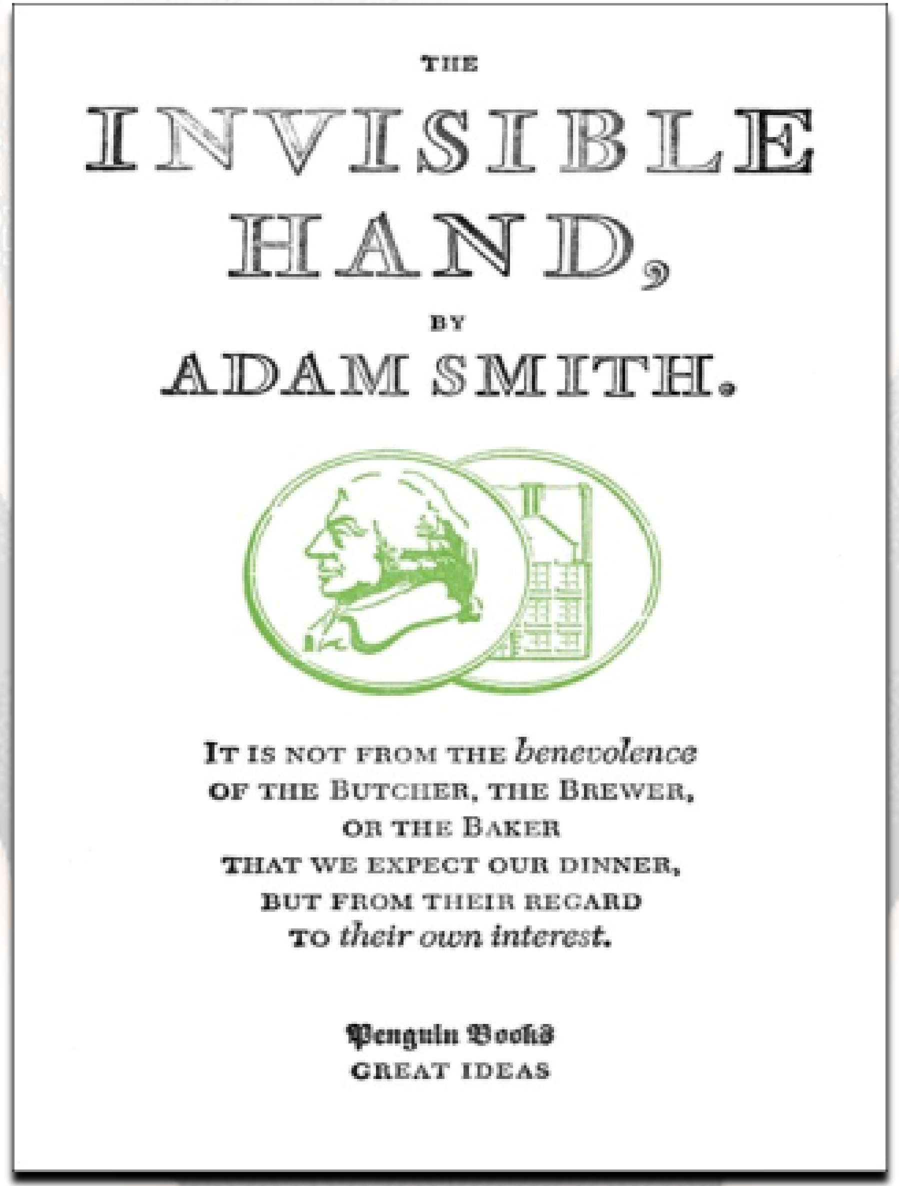


Trapping mechanisms:

1) Structural: Tight roof / caprock
2) Residual: gets stuck in pores
3) Dissolution: dissoved in water
4) Mineral: reacts with minerals

Expected leakage: <1% per thousand years

Greatest risk: other wells (gas, oil)



To meet climate targets we need the help of the "invisible hand" of the market.

Fossil fuels are too cheap. So we need a price on CO2 emissions.

A more difficult challenge is to find someone to pay for negative emissions.

Who will be willing … ?

Cost CCS/BECCS: ≈0.1 €/kg CO_2
Reasonable ?

Carbon dioxide intensity in global economy: 0.5 kg CO_2/€

Thus: 0.1 €/kg CO_2 corresponds to 5% of global economy

Proposal: Introduce "*producer liability*". Emitters are responsible, and need to pay, for removing any emitted CO_2 from atmosphere.

Normally, the cost to avoid CO_2 emission is lower than atmospheric CO_2 capture.

Thus: The cost for the economy could be considerably less than 5%.

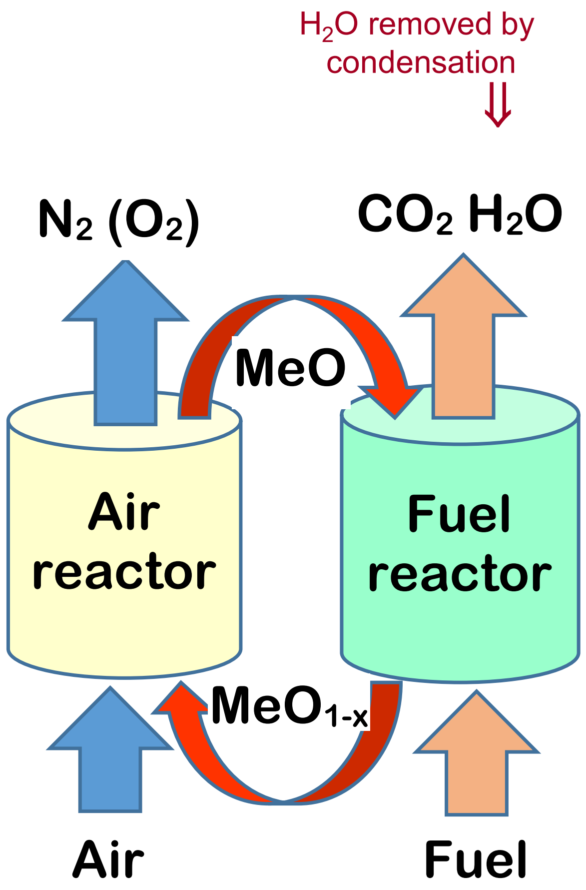
Chemical-Looping Combustion (CLC)

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*

But does it work in practice ??



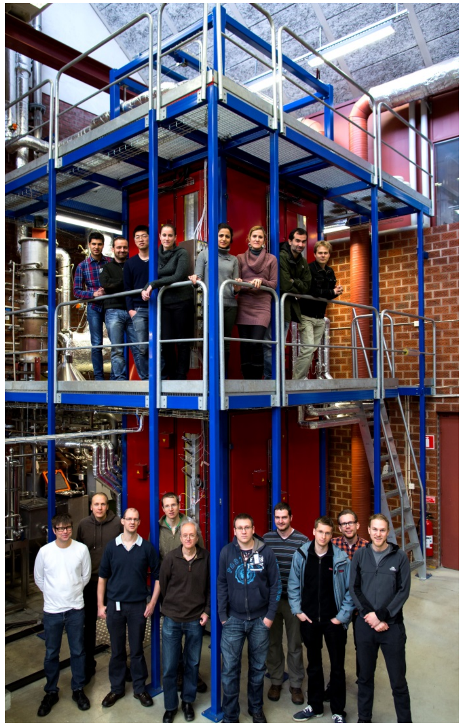
Yes, it works!!

Total chemical-looping operation
at Chalmers:
4 000 h in four pilots

10 kW gas, 2003

300 W gas, 2004

10 kW solid fuel, 2006



100 kW solid fuel, 2011

Worldwide: 11 000 h in 46 pilots

Type	Oxygen carrier	Gaseous fuel	Liquid fuel	Solid fuel	**Total**	%
Manufactured	NiO	2677	377	237	**3291**	29%
	CuO	1130	122	173	**1425**	13%
	Mn_3O_4	74	17	0	**91**	1%
	Fe_2O_3	617	77	1072	**1766**	16%
	CoO	178	0	0	**178**	2%
	Combined oxides	918	10	289	**1217**	11%
Natural ore or waste material	Fe ore	488	0	576	**1064**	9%
	Ilmenite	538	150	788	**1496**	13%
	Mn ore	354	0	381	**735**	6%
	CaSO4	0	0	75	**75**	1%
Total manufactured		5594	603	1771	**7968**	70%
Total natural/waste		1380	150	1820	**3370**	30%
Total		6974	753	3591	**11338**	100%
Publications					212	

Table 12. Operation of 46 chemical-looping combustors/ gasifiers.

	Operator	Unit	Hours of operation	Typical fuels used, selected references	First reported
1	Chalmers	10 kW	1570	nat. gas [36] [37]	2004
2	KIER	50 kW	31	nat. gas [40]	2004
3	CSIC	10 kW	120	nat. gas [93]	2006
4	Chalmers	0.3 kW-GL	1359	nat. gas, syngas, kerosene [42]	2006
5	Chalmers	10 kW–SF	337	coal, petcoke, biomass pellets, wood char [260] [208]	2008
6	CSIC	0.5 kW-GL	1812	nat. gas, acid gas, sour gas, ethanol [47]	2009
7	KAIST	1 kW	8	CH_4 [61]	2009
8	Vienna UT	140 kW	660	nat. gas, CO, H_2 [67]	2009
9	Alstom, Fr	15 kW	100	nat. gas [74]	2009
10	Nanjing	10 kW –SF	260	coal, biomass. [261]	2009
11	KIER	50 kW	300	nat.gas, syngas [78]	2010
12	Nanjing	1 kW – SF	195	coal, biomass, sew. sludge [170] [171]	2010
13	IFP-Lyon	10 kW-GSF	453	CH_4 ,coal, syngas [262] [250]	2010
14	Stuttgart	10 kW	1	syngas [215]	2010
15	Xi'an Jiaotong	10 kW- Pr	15	coke oven gas [155]	2010
16	CSIC	1.5 kW-SF	729	coal [217]	2011
17	Chalmers	100 kW – SF	217	coal, petcoke, wood pellets, wood char [223] [224]	2012
18	Hamburg	25 kW –SF	95	coal, CH_4 [263]	2012
19	Ohio	25 kW –SF	980	coal [127] [264]	2012
20	Nanjing	50 kW-Pr	19	coal [192]	2012
21	WKentuU	10 kW	24	nat. gas, syngas [111]	2012
22	Tsinghua	0.2 kW	322	CO [236]	2013
23	Alstom, US	3 MW –SF	75	coal [259]	2014
24	CSIC	50 kW-SF	69	coal, lignite, anthracite [232]	2014
25	Chalmers	10 kW-LF	80	diesel, heavy fuel oil [162]	2014
26	Darmstadt	1 MW –GSF	195	coal [234] [235]	2015
27	Huazhong	5 kW-GSF	200	CH_4 coal [189]	2015
28	Guangzhou	10 kW-G	62	saw dust [133]	2015
29	Nanjing	25 kW-G	13	rice husk [83]	2015
30	KIER	200 kW	100	nat. gas [84]	2016
31	Huazhong	50 kW-SF	8	coal [194]	2016
32	SINTEF	150 kW	9	CH_4, biomass [113]	2016
33	VTT	20 kW-SF	130	biomass [238]	2016
34	NETL	50 kW	2	CH_4 [265]	2016
35	Chalmers	1.4/10 MW	93	biomass [237]	2016
36	Nanjing	20 kW-SF	70	coal [193]	2016
37	Zabrze	10 kW	3	CH_4 [195]	2017
38	Nanjing	5 kW-SF/s	16	coal, sewage sludge [200]	2017
39	Nanjing	5 kW-SF/i	6	biomass, CO, [203]	2018
40	Nanjing	2 kW-SF	12	syngas, nat. gas [204]	2018
41	Nanjing	25 kW-G	2	coal [205]	2018
42	CSIRO	25 kW-SF	35	brown coal [240]	2018
43	Tsinghua	30 kW-SF	100	coal [241]	2018
44	JCOAL	100 kW-GSF	73	NG, coal [242]	2018
45	Vienna UT	80 kW-SF	20	wood pellets [243]	2018
46	NCCC	250 kW Pr WS	360	syngas+propane [118]	2018

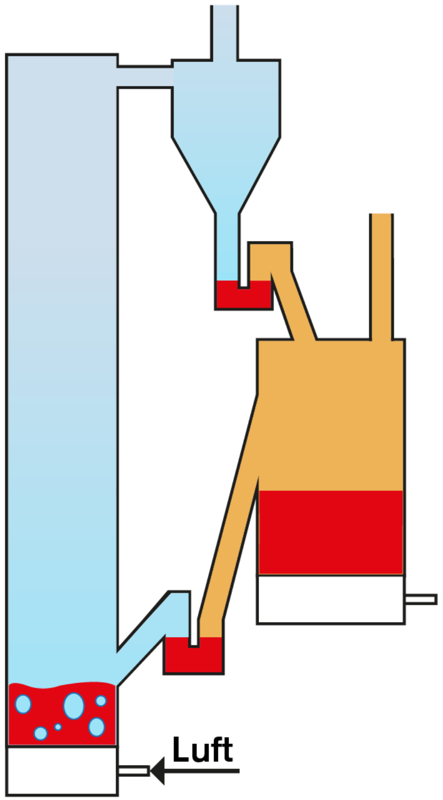
SF-solid fuel, GSF-gaseous & solid fuel, Pr-pressurized, LF-liquid fuel, GL=gaseous/liquid fuel, G-Gasification, WS=water splitting, /s=staged, /i=with internals

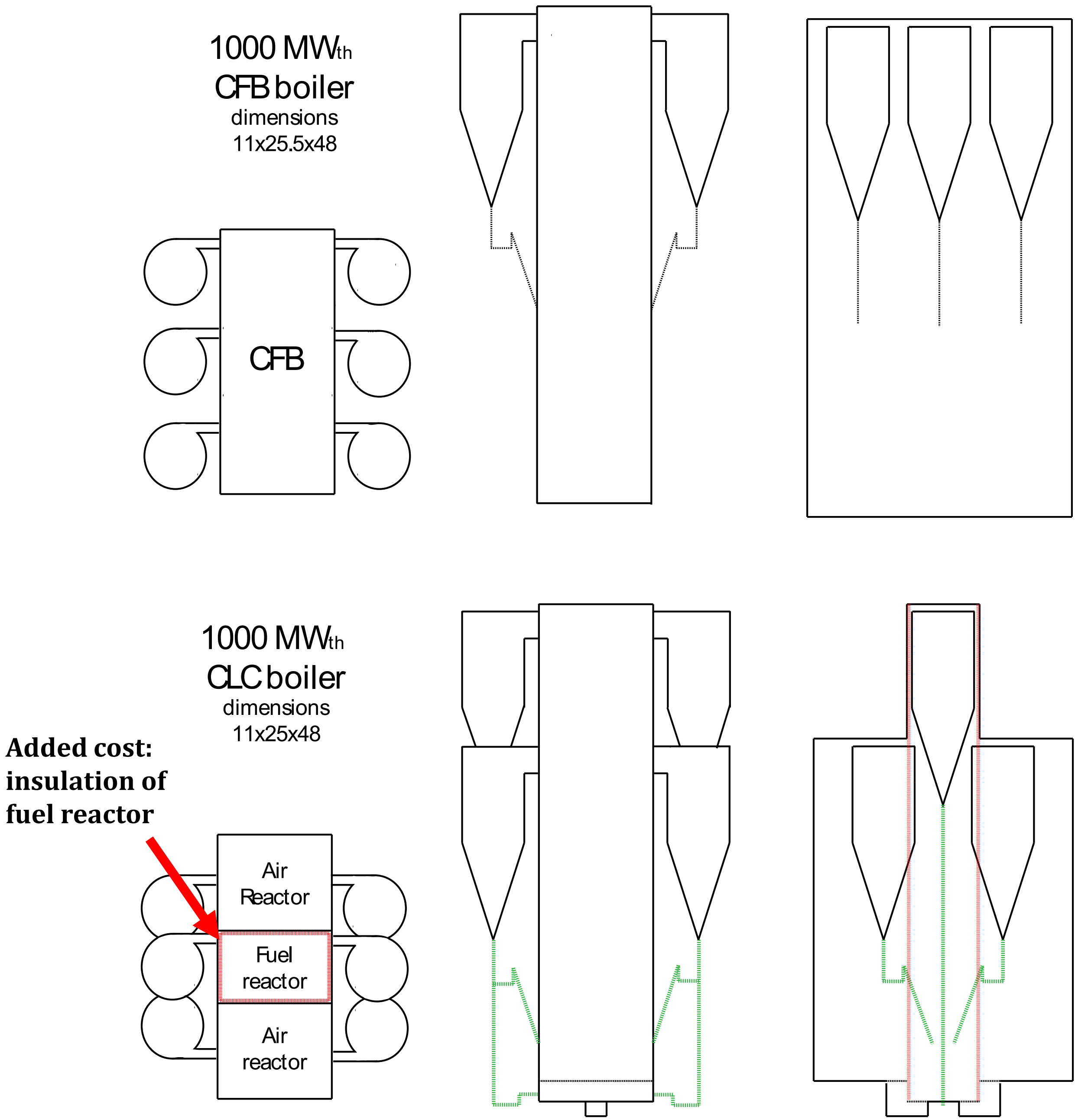
In addition to >11 000 h of operation in smaller CLC pilots there is

>20 000 h of operation of Oxygen Carrier Aided Combustion (OCAC) in fluidized bed boilers.

Circulating fluidized-bed boiler

Chemical Looping Combustion





Walls of fuel reactor, cyclones, ducts and post-oxidation chamber:
→ 2500 m^2

Cost: 1500 €/m^2

<u>Thus, added cost of CLC fuel reactor:</u>

≈ 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* 157 (2015) 475-487 *(Open Access)*

Ways to scale-up

big cost

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

small cost

Demonstration without CO_2 capture can significantly reduce costs.

1) Verify concept, and potential advantages wrt. alkali and NO_x
2) Add CO_2 capture

[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

Pilot operational results with biomass pellets

Nordic Negative CO_2 project

Oxygen demand

VTT, 50 kW
- Ilmenite: 29-41%
- Mn ore: 27-31%

Chalmers, 100 kW
- Mn ore: ≈ 25%
- $CaMnO_3$ ≥3%

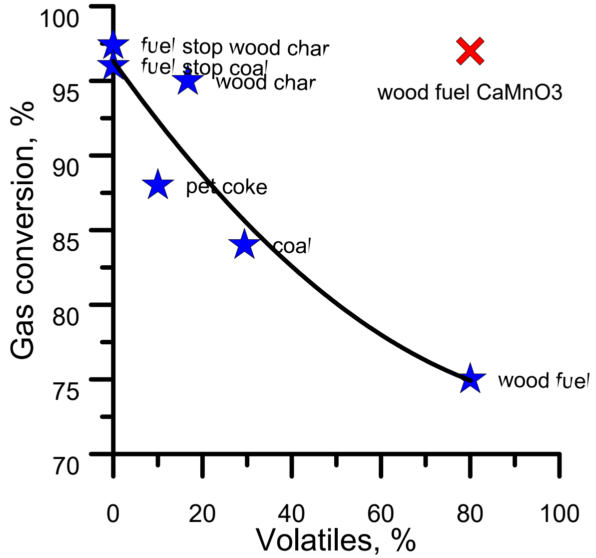
SINTEF, 150 kW
- Ilmenite: 16-26%

Chalmers 10 MW CFB*
- Mn ore: ≈40%

*with gasifier used as fuel reactor

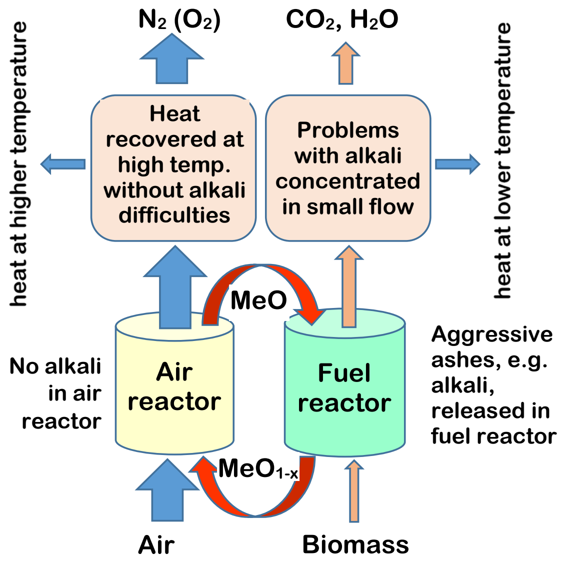
Biomass in CLC

High volatiles content could give problems with gas conversion



Could low ash content make manufactured oxygen carriers possible ?

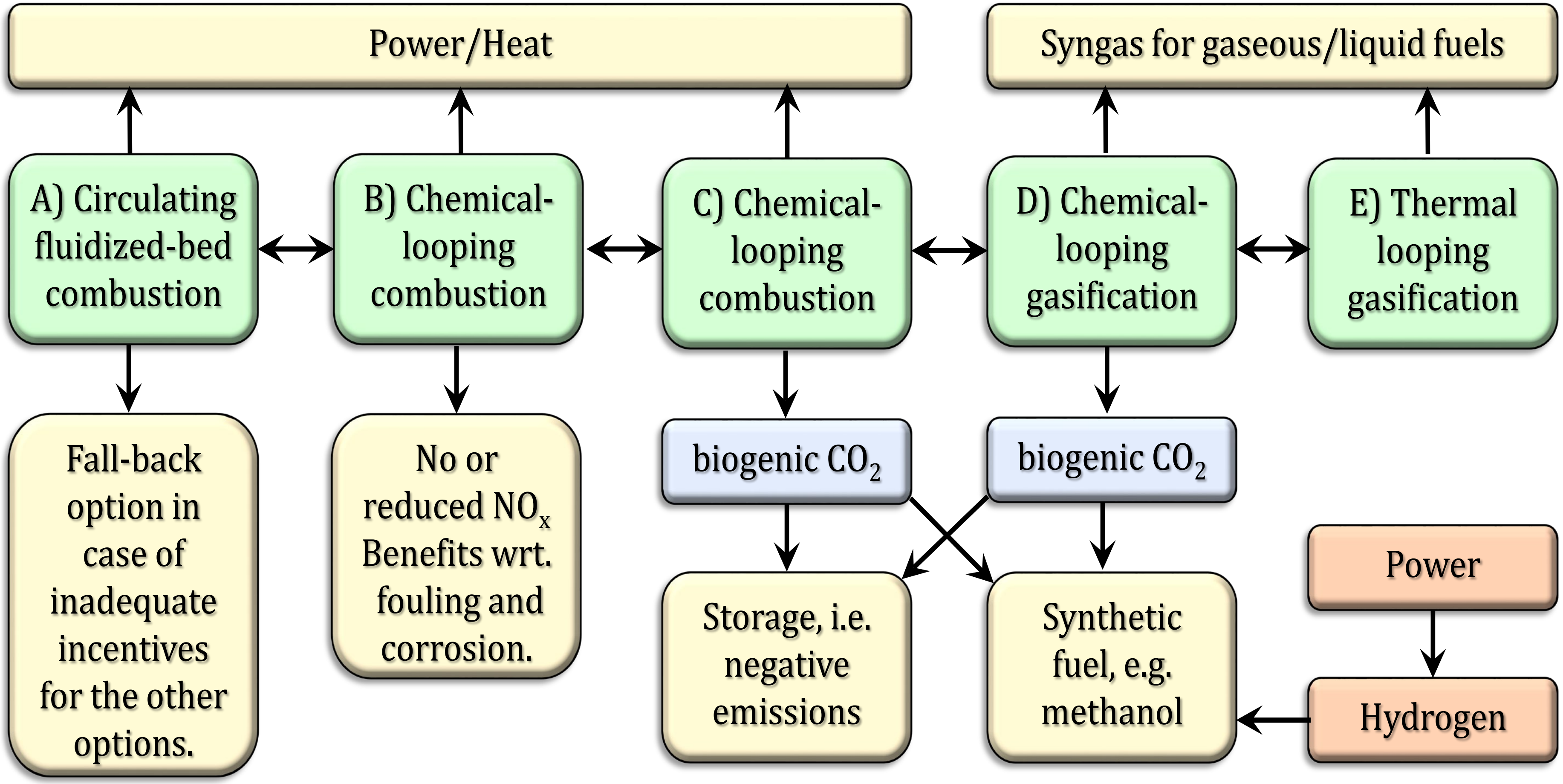
Biomass difficult fuel alkali gives low ash-melting temperature



Could CLC facilitate the use of biomass in boilers ?
(positive experience with OCAC)

Could range of possible fuels be extended?

Multipurpose Dual Fluidized Bed



STATUS OF CLC

>11 000 h of operation in 46 pilots with >70 different oxygen carrier materials, of which >3000 h with low-cost materials (e.g. ores of ilmenite, iron and manganese)

SOLID FUELS:

- >3000 h of operation in 20 pilots
- major cost of CO_2 capture, i.e. gas separation, is uniquely avoided (depending on gas conversion)
- unique potential for low energy penalty
- transparent cost evaluation based on difference compared to circulating fluidized bed available, 16-26 €/ton
- cost expected less than half of competing technologies
- could likely be demonstrated at low moderate cost using existing biomass gasifier (e.g. GobiGas)
- poor interest from coal industry
- no incentives for negative emissions

Conclusions CLC

CLC boiler very similar to CFB boiler (=circulating fludized-bed boiler)

Highly concentrated CO_2 stream can be obtained at small added cost

Major cost likely downstream

CLC can be demonstrated at lower cost w/o capture

Swedish CO_2 emissions from biomass, (larger point sources):
31 Mt/år

Sweden's domestic fossil CO_2 emissions are:

43 Mt/year

If fossil CO_2 emissions are stopped and CO_2 from biomass is captured, we can reduce emissions by

more than 150% !!!

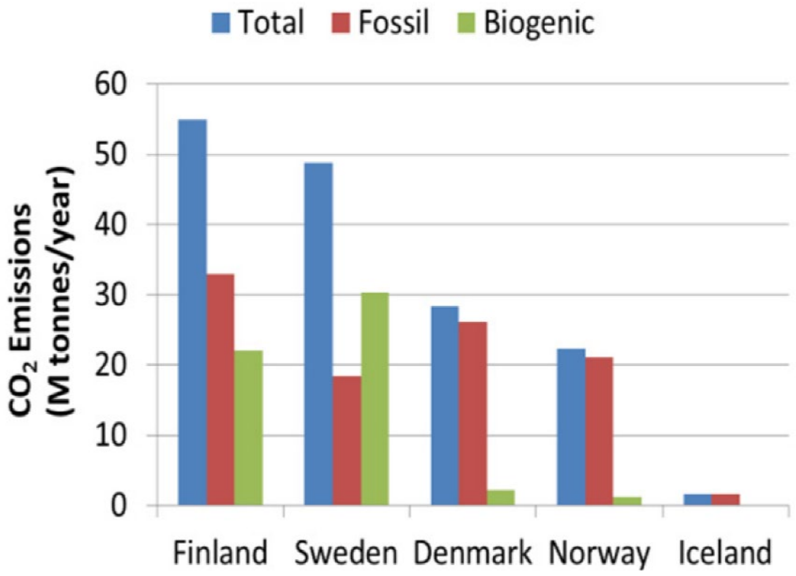
and start the clean-up of the atmosphere !

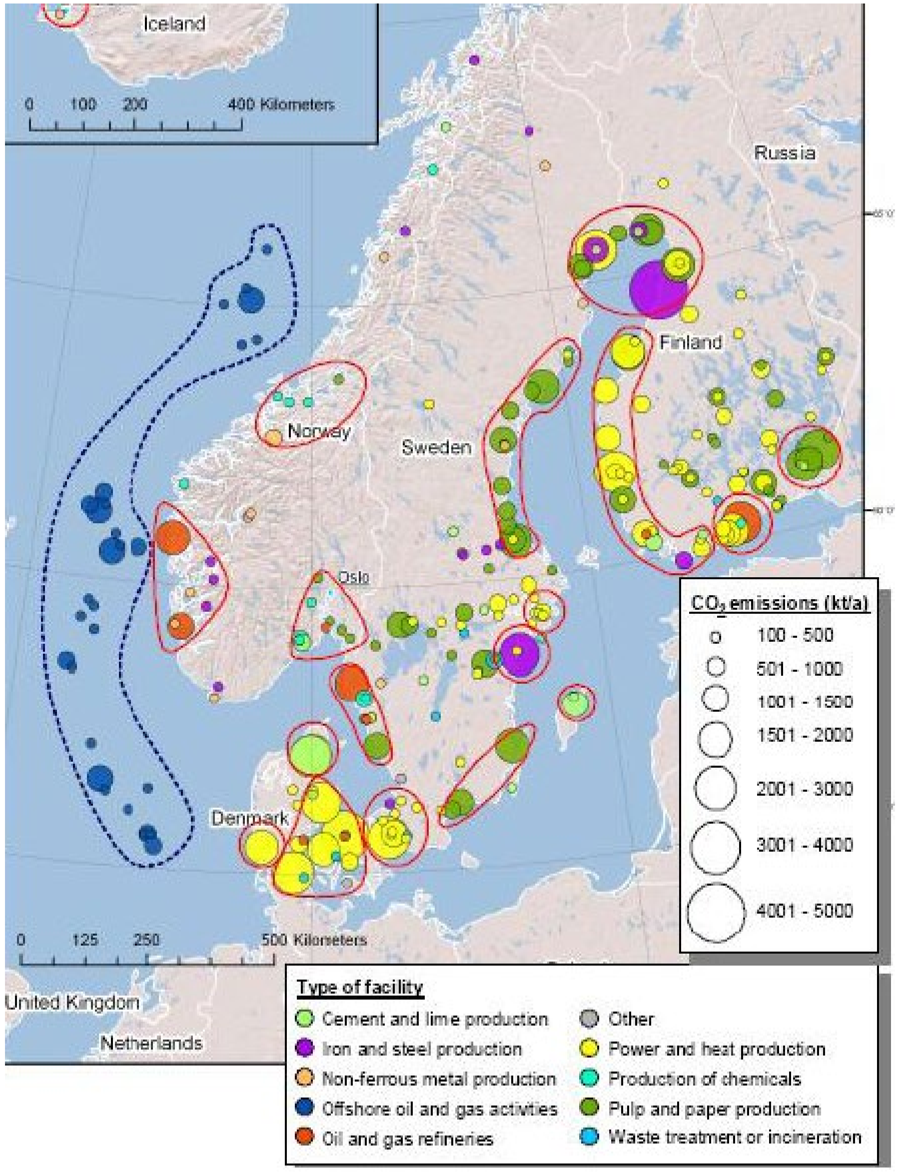
Finland has similar opportunities!

CO_2 capture and storage in Nordic countries

- total Nordic fossil CO_2 emissions 200 Mt/year
- in addition:
- >50 Mt/year biogenic

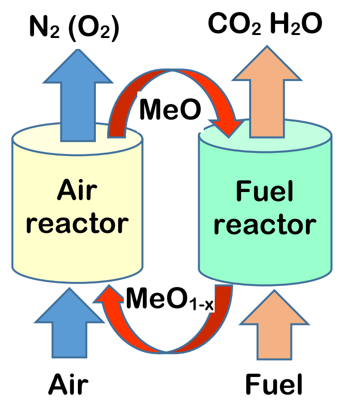
CO_2 emissions, sources >100 000 tons/year:

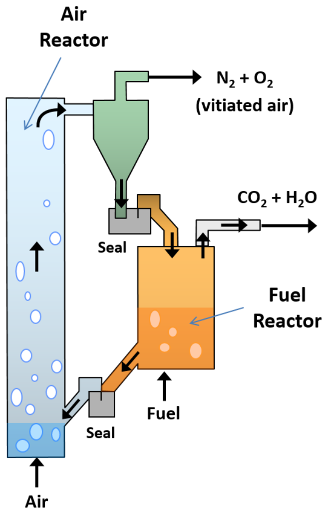




Smeaheia
Onshore facility, Kollsnes
The Waste-to-Energy Agency, Klemetsrud in Oslo
Heimdal
Johansen-formationen
Yara Ammonia plant, Porsgrunn
Utsira Sør
Ship for CO_2 transport
Norcem AS, cement factory, Brevik

http://negativeco2emissions2020.com/





PRINCIPLE

metal oxide (MeO) transfers oxygen from air to fuel

⇒

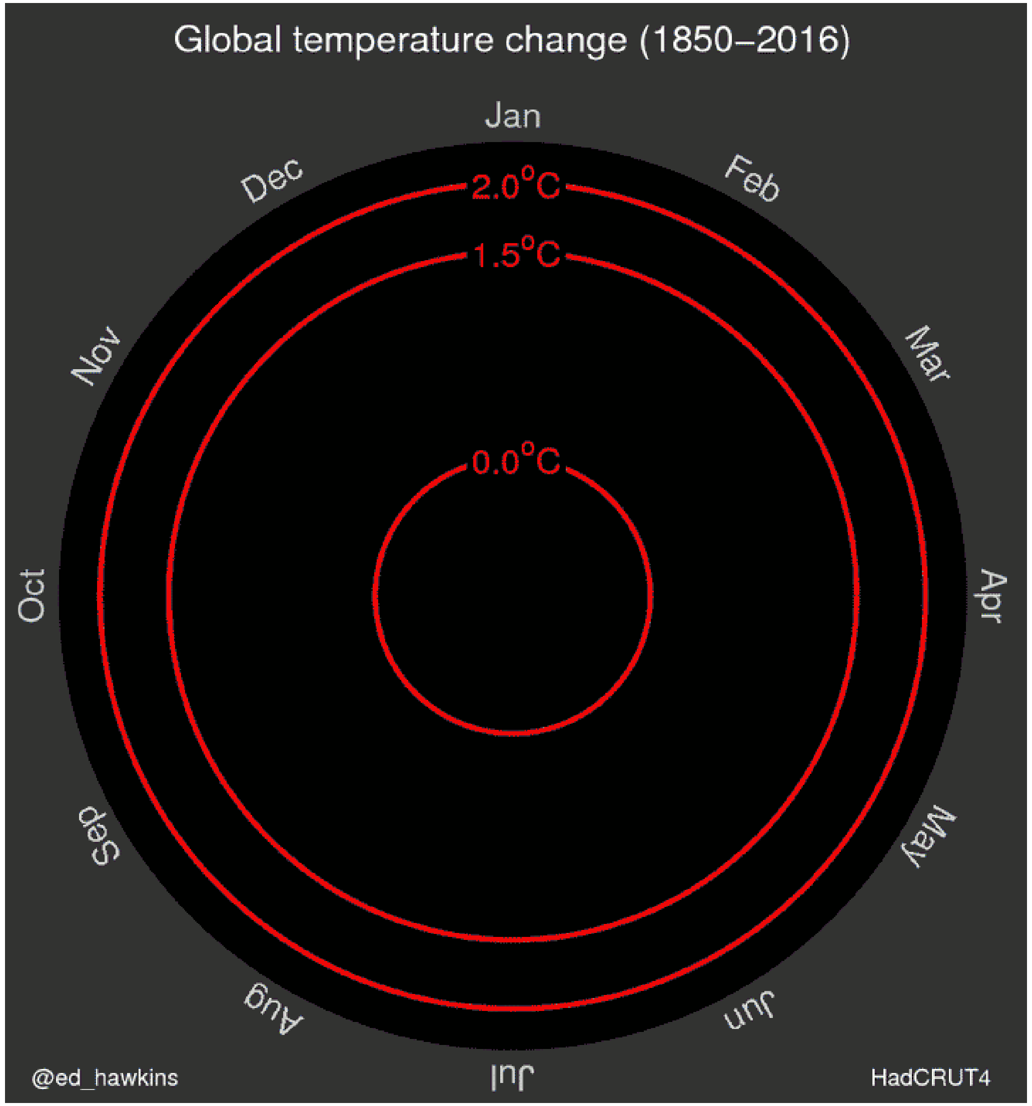
no separation needed

PRACTICE

well established circulating fluidized-bed technology

PURPOSE

Thank you!!! Questions



More climatesongs on *www.climatesongs.com*