Bioenergy with Carbon Capture (L6)

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Tracks course: TRA105

Chalmers

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Removal of CO_2 from the atmosphere
=
Negative Emissions

Bio-CCS

Growing trees/plants remove CO_2 from the atmosphere.

BUT, the CO_2 can be prevented from returning:

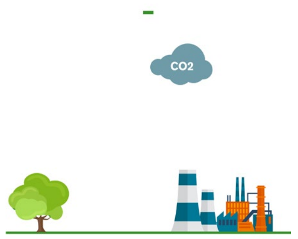
Capture and storage of CO_2 from combustion of biomass/biowaste

Bio-CCS (BECCS)
(BioEnergy Carbon Capture and Storage)

Principles of Negative CO_2 Emissions

Atmospheric CO_2 removal based on photosynthesis

- Capture and storage of CO_2 from combustion of biomass/biowaste, Bio-CCS



- Bio-char for soil improvement

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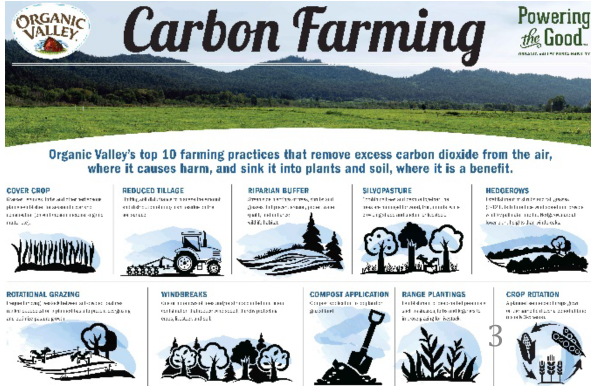
- Planting forests (afforestation/reforestation)

Agricultural practices to increase carbon content in soil



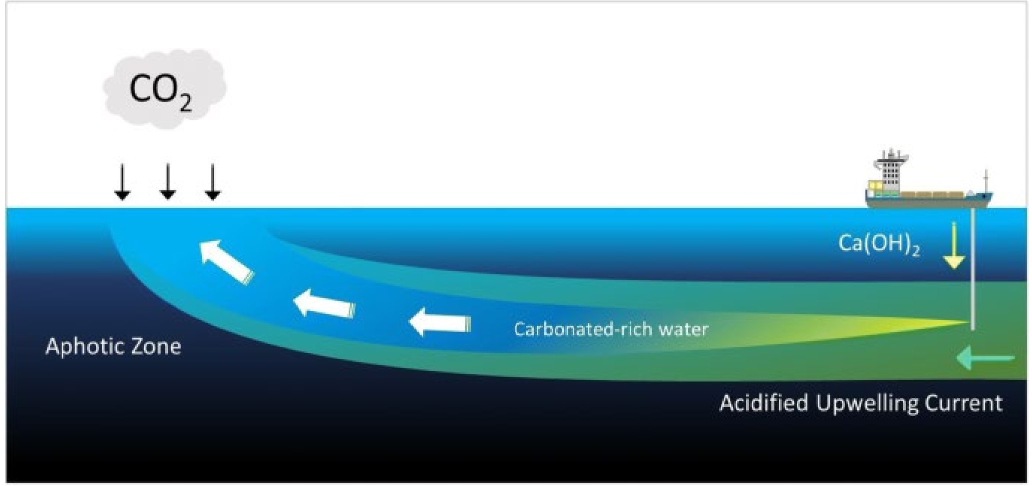
Negative Emissions, non-biogenic paths:

Enhanced weathering

Crushing of and spreading
rock minerals
that react with CO_2
(dissolved in water as
carbonic acid)
to form carbonate minerals

Ocean liming

CO_2 capture and storage from limestone calcination
($CaCO_3$ > CaO + CO_2) + distribution of lime (CaO)



Direct Air Capture (L7)

(~400 times lower concentration as
compared to ”capture in chimneys”)

Summary

Negative CO_2 Emissions (CDR, Capture Dioxide Removal):

Biomass based:

- BioEnergy Carbon Capture and Storage (Bio-CCS/BECCS)
- Planting forests (afforestation/reforestation)
- Bio-char for soil improvement
- Agricultural practices to increase carbon content in soil

The "natural sink "

Enhanced weathering

Ocean liming

Direct air capture

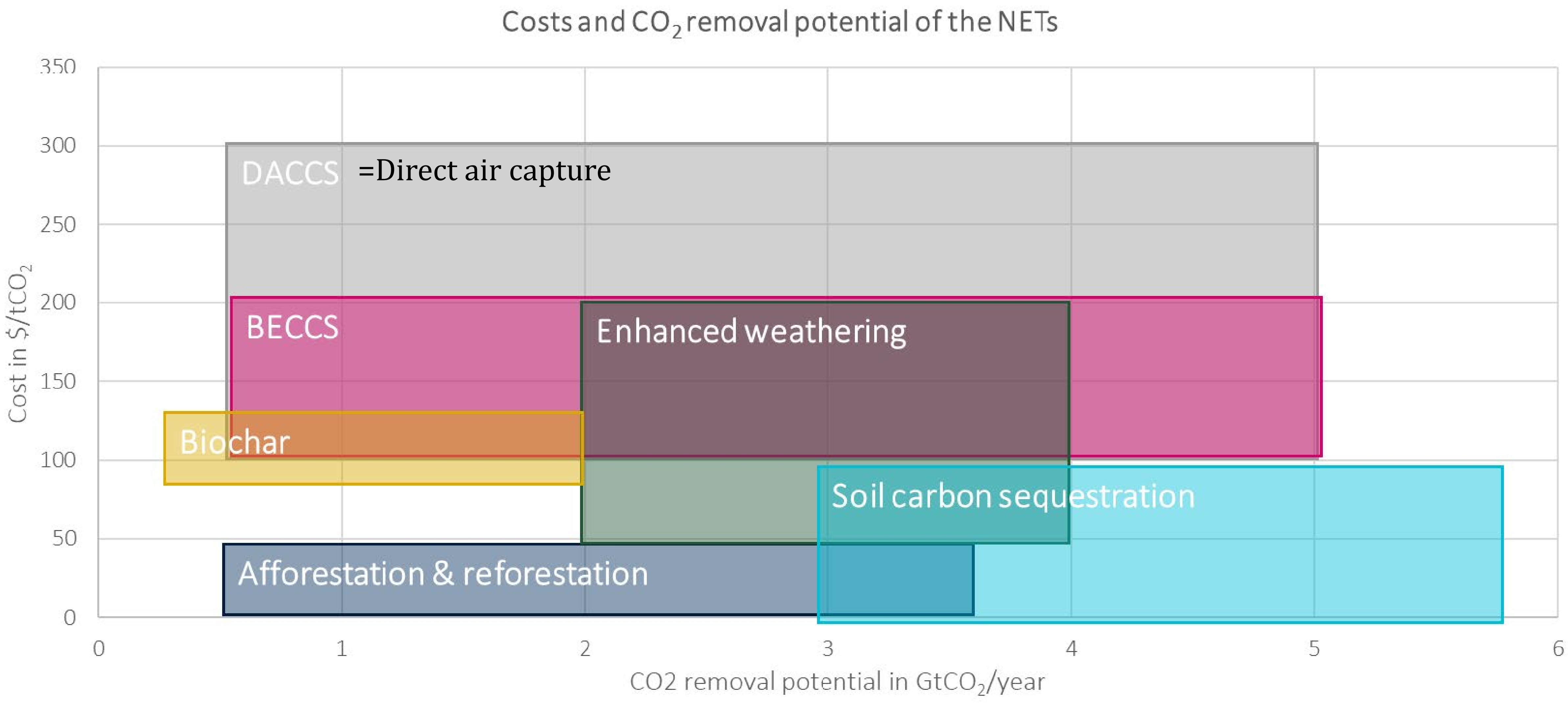
BioEnergy Carbon Capture:

BioEnergy Carbon Capture and Storage (Bio-CCS/BECCS)

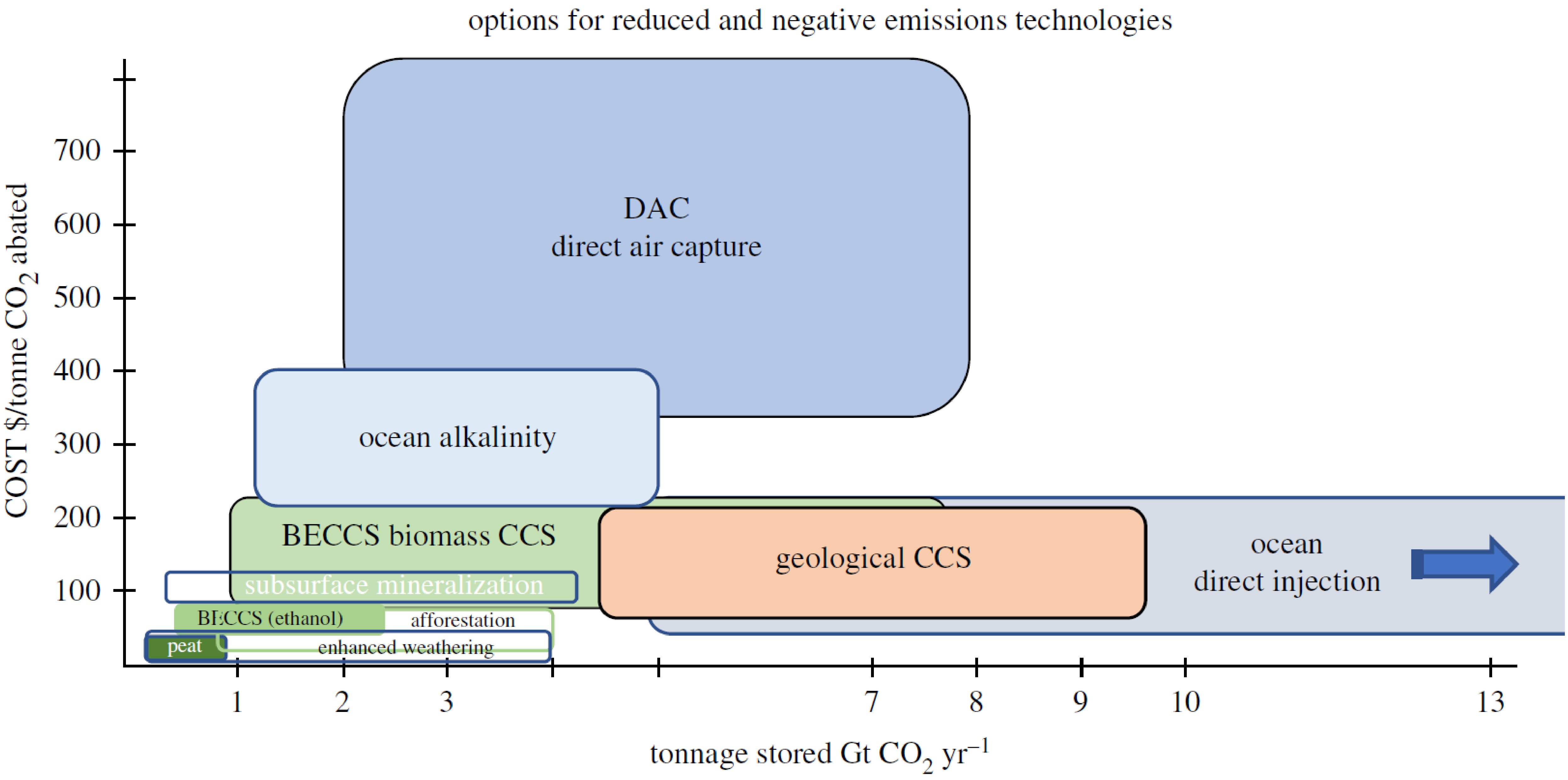
BioEnergy Carbon Capture and Utilization (BECCU)

- E.g. to produce electrofuels (electricity => H_2, H_2+CO_2 =>hydrocarbon fuel)

Figure 7 Afforestation and reforestation, and soil carbon sequestration have the lowest costs among the NETs



Source: Vivid Economics, based on Fuss et al. (2018)


options for reduced and negative emissions technologies
COST $/tonne CO_2 abated
700
600
500
400
300
200
100
DAC
direct air capture
ocean alkalinity
BECCS biomass CCS
subsurface mineralization
BECCS (ethanol)
afforestation
peat
enhanced weathering
geological CCS
ocean
direct injection
1
2
3
7
8
9
10
13
tonnage stored Gt CO_2 yr^{-1}

	Cost	Potential	Storage Safety	Other
BECCS	Moderate	Fairly high	High	
Forestation	Low	**Limited**	**Low**	Accountability
Agricultural methods	Low	**Limited**	**Low**	**Accountability !!**
Biochar	Moderate	Fairly high	Fairly high	Accountability
Direct air capture	**High**	Unlimited	High	
Ocean liming	Fairly high	High	High	Poorly investigated
Enhanced weathering	Moderate	High	High	Poorly investigated

Biggest misconceptions of Bio-CCS: **1. Not needed**.

Incentives still lacking. Inertia of energy infrastructure.

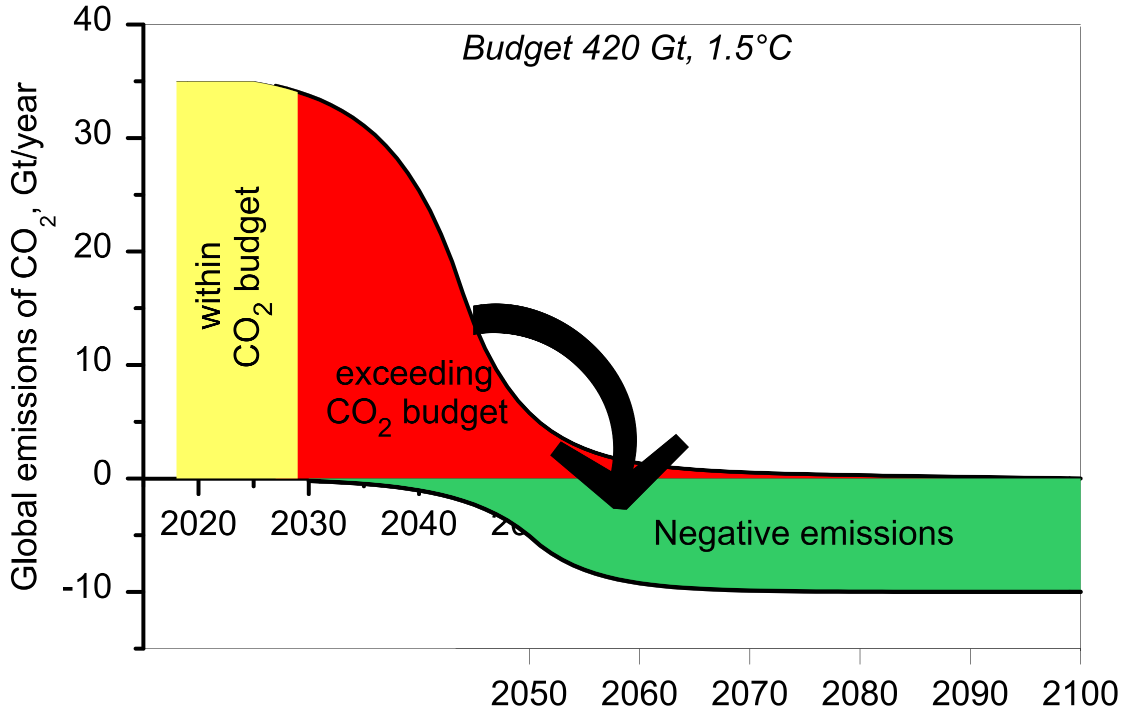
Global CO_2 budget for max +1.5°C spent around 2029

All emissions after 2029 must be removed from the atmosphere.

Emissions cannot be stopped in only 7 years.

Budget will be exceeded very significantly

Enormous negative emissions will be needed



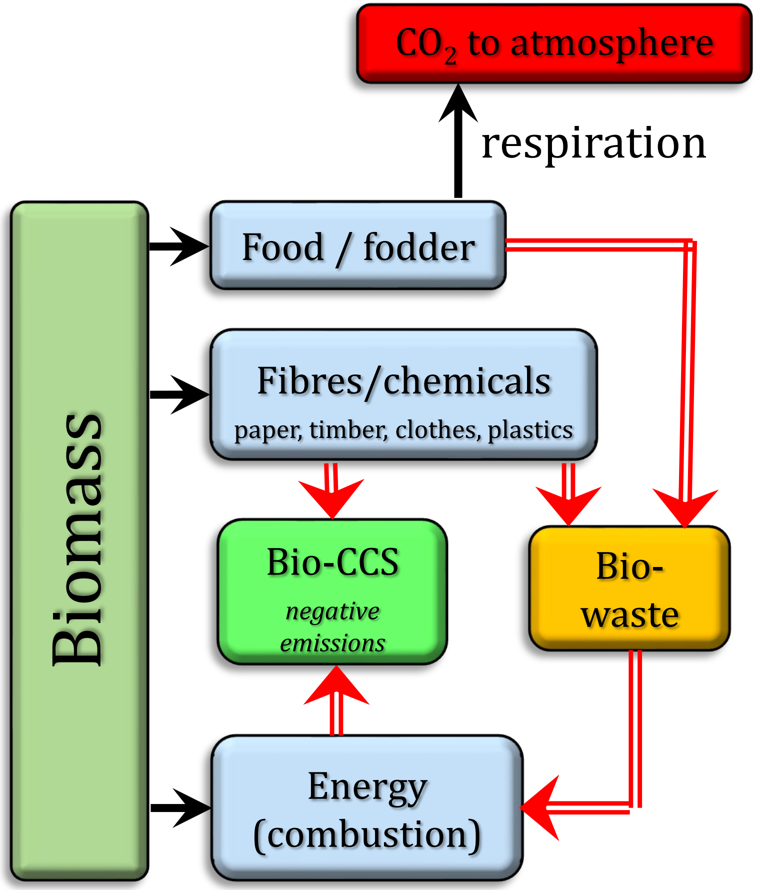
Biggest misconceptions of Bio-CCS: **2. Not enough (”Two more India needed …”)**

Bio-CCS, can/should be combined with other uses of biomass

Total primary production:
220 Gton CO_2/year

Global extraction of biomass corresponds to
22 Gton CO_2/year
(6 lost in respiration)

(fossil emissions are
37 Gton CO_2/year)



But, if we use the biomass to produce transportation fuels, the CO_2 can not be captured.

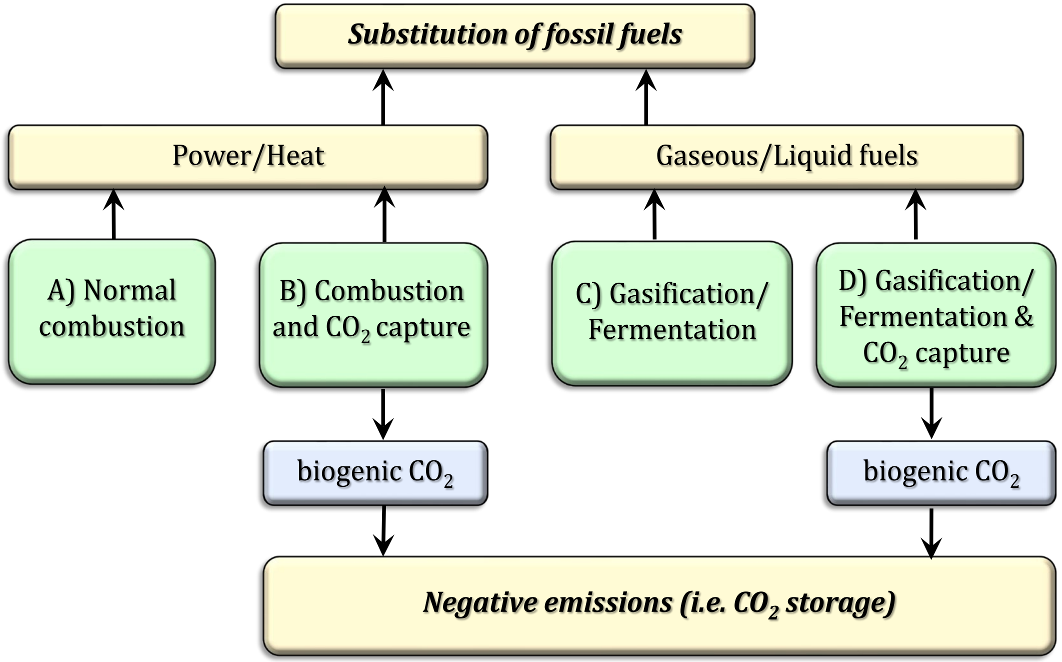
DN DEBATT REPLIKER

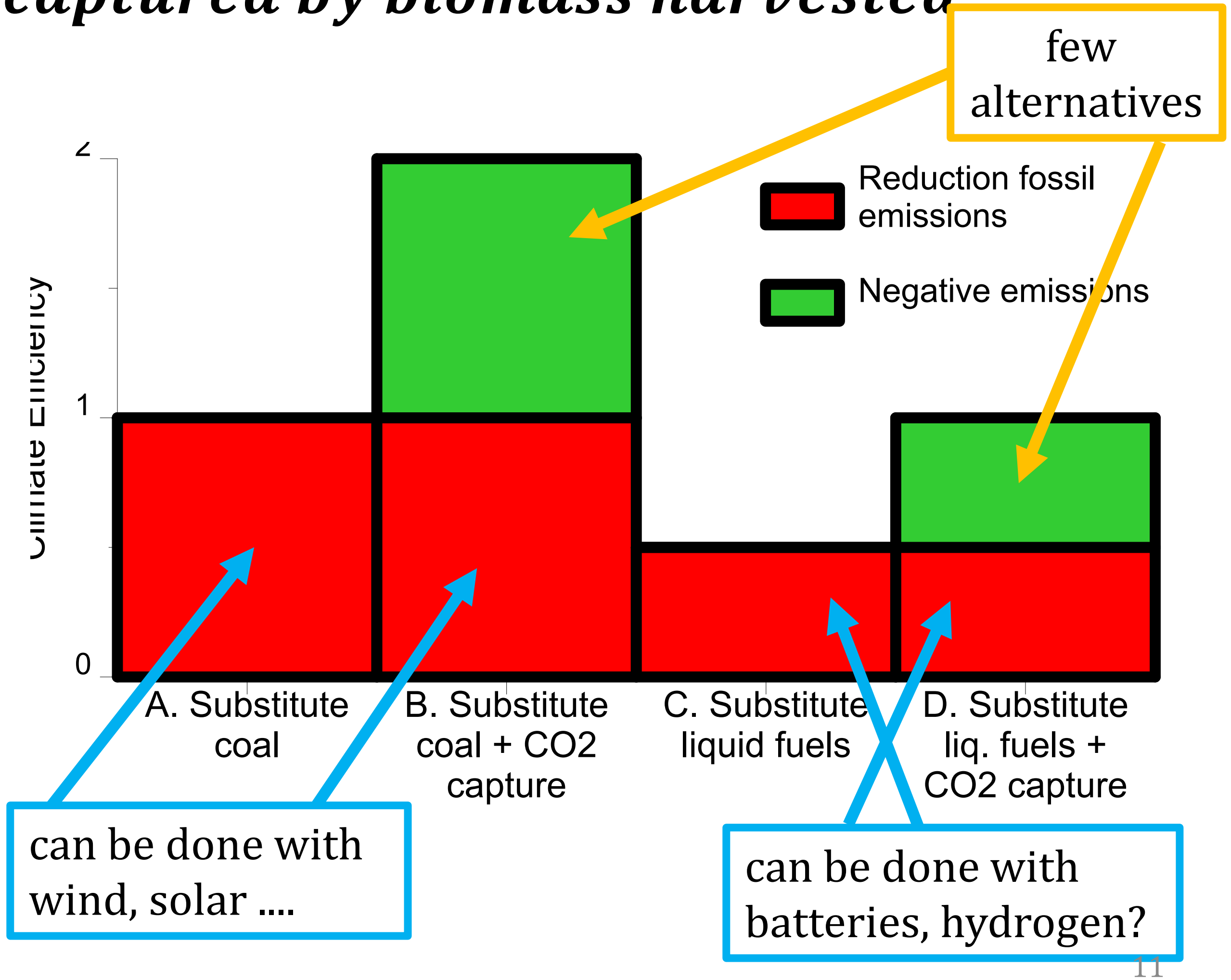
DN Debatt Repliker. ”Ska vi släppa ut två ton grön koldioxid för att ta bort ett ton fossil koldioxid?”

UPPDATERAD 2021-09-28 PUBLICERAD 2021-09-28

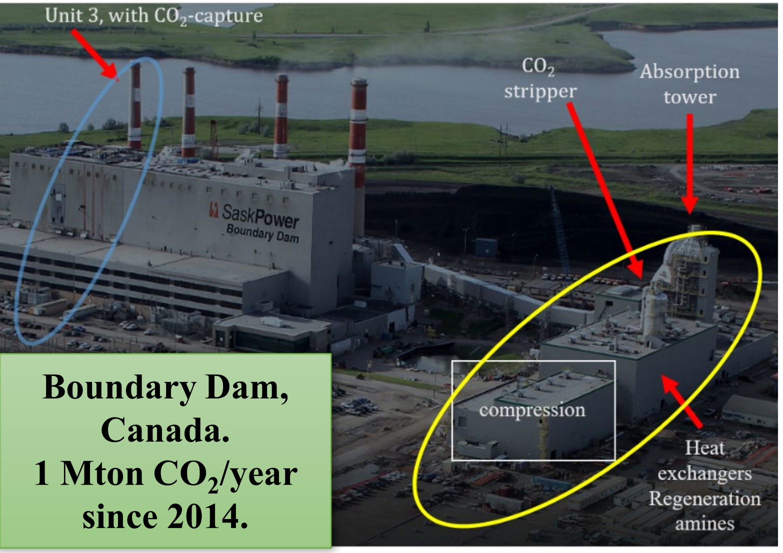
But, ”to be enough”, biomass must be used efficiently, (not unlimited resource)

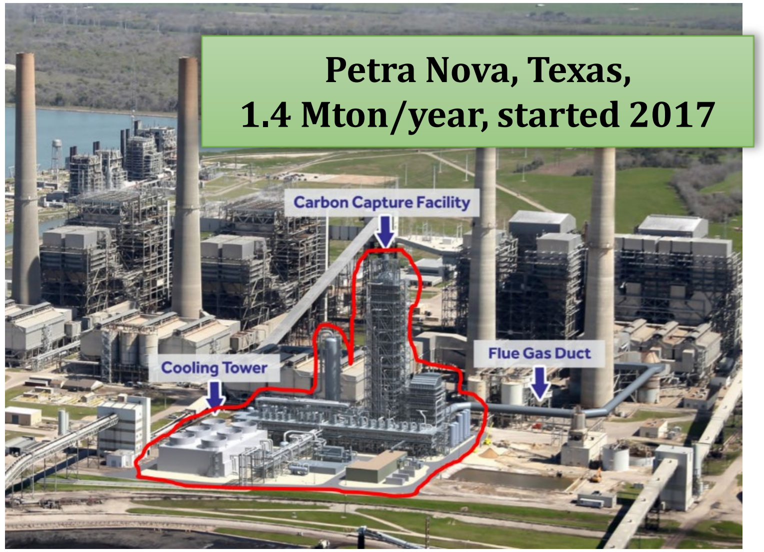
$$Climate\ Efficiency = \frac{reduction\ of\ CO_2\ in\ atmosphere}{CO_2\ captured\ by\ biomass\ harvested}$$





Biggest misconc. …. : **3. Not existing technology / not existing at scale**





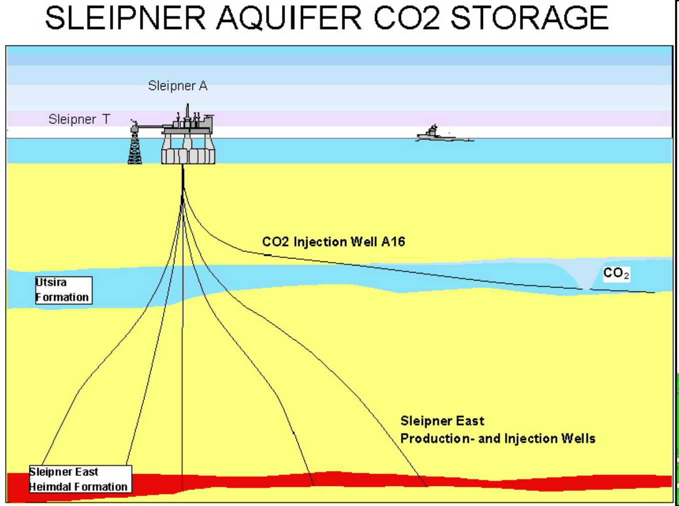
Both capture and storage does exist at scale. (L2-L4,L9)

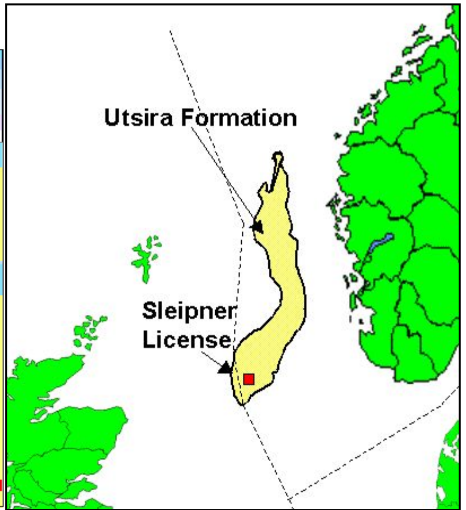
Worldwide:

40 Mton CO_2/year stored

(0.1% of global emissions)

(Present plans: 1 Gt Mt/y, 3%)





Biggest misconceptions of bio-CCS: **4. It's not safe**

This is *not* true for bio-CCS (L9)

But, it is true for the "natural sink"

Forestation/afforestation

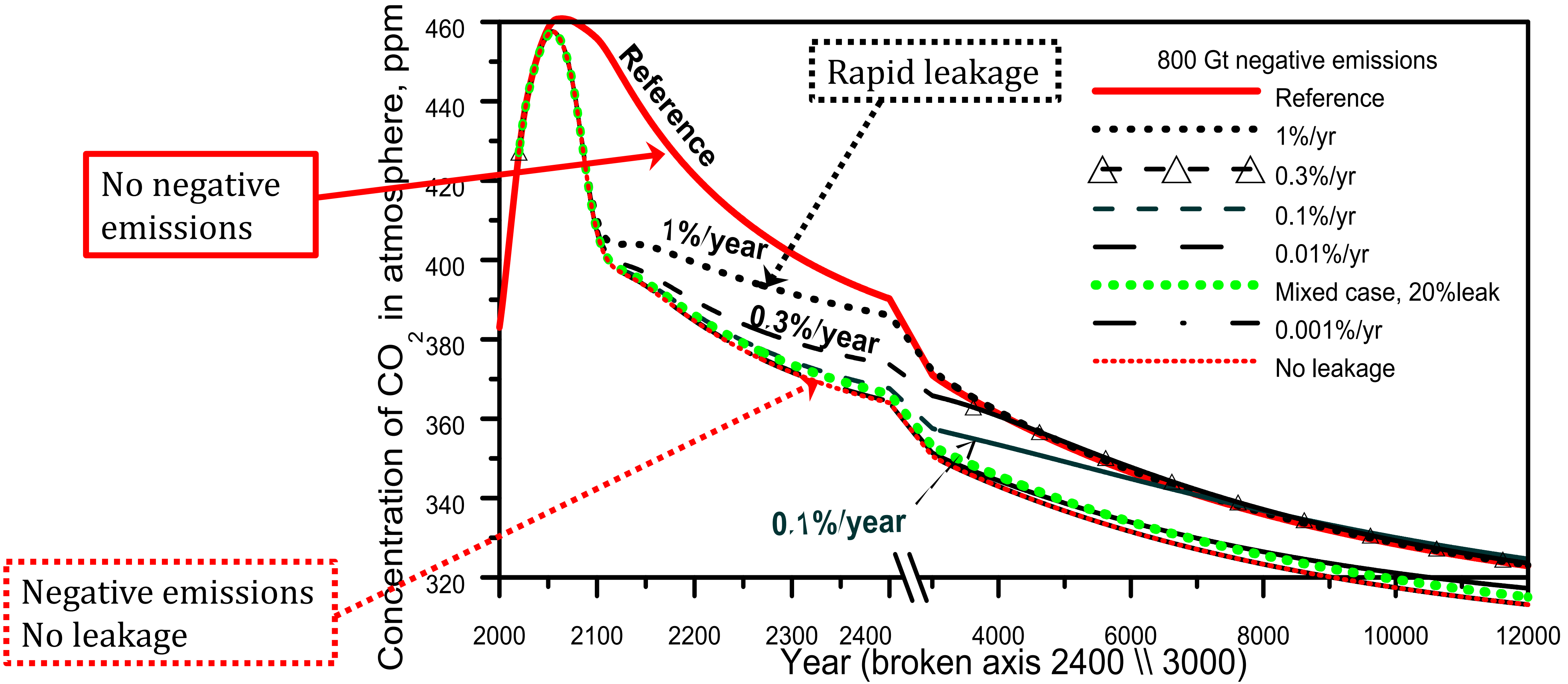
- Fire
- Insects
- Deforestation

Agricultural methods to store carbon

- Changed agricultural methods
- Changed environment

But what is the impact of leakage for the climate?

Atmospheric CO_2 for no negative emissions and negative emissions with and without leakage.



REF: Lyngfelt A, Johansson D, and Lindeberg E. Negative CO_2 Emissions - An Analysis of the Retention Times Required with Respect to Possible Carbon Leakage. *International Journal of Greenhouse Gas Control* **87** (2019) 27–33.

Biggest misconceptions of bio-CCS: **5. Not needed now / not priority...**

To reach the volumes needed, we need to start now!

The later we start, the greater the overshoot of the budget, resulting in much more damage and risks of feed-back loops and reaching tipping points.

Biggest misconceptions of bio-CCS: **6. It's expensive**

Cost of CCS/Bio-CCS ≈ 0.1 €/kg CO_2

Carbon dioxide intensity in global economy: 0.25 kg CO_2/€

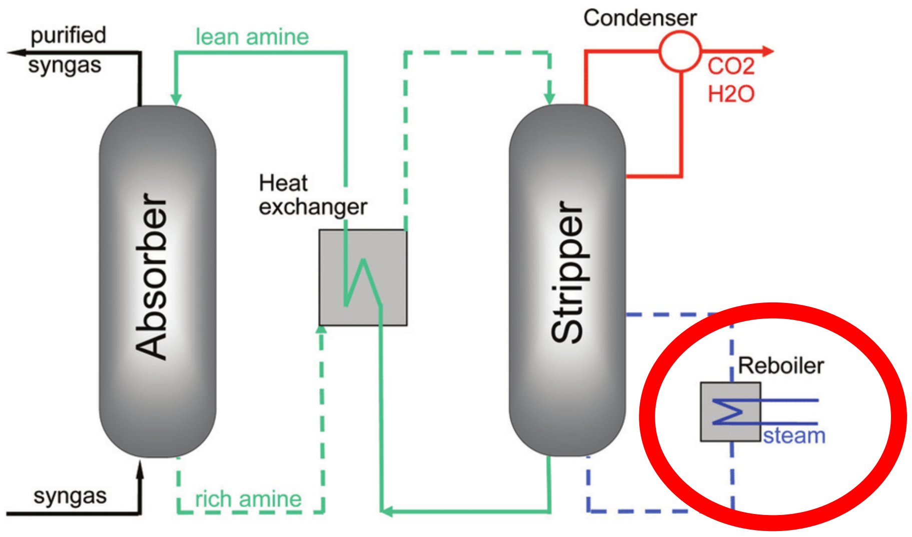
Thus: a CO_2 fee/tax of 0.1 €/kg corresponds to ***2.5% of global economy***

The cost to avoid CO_2 emission is often lower than this.

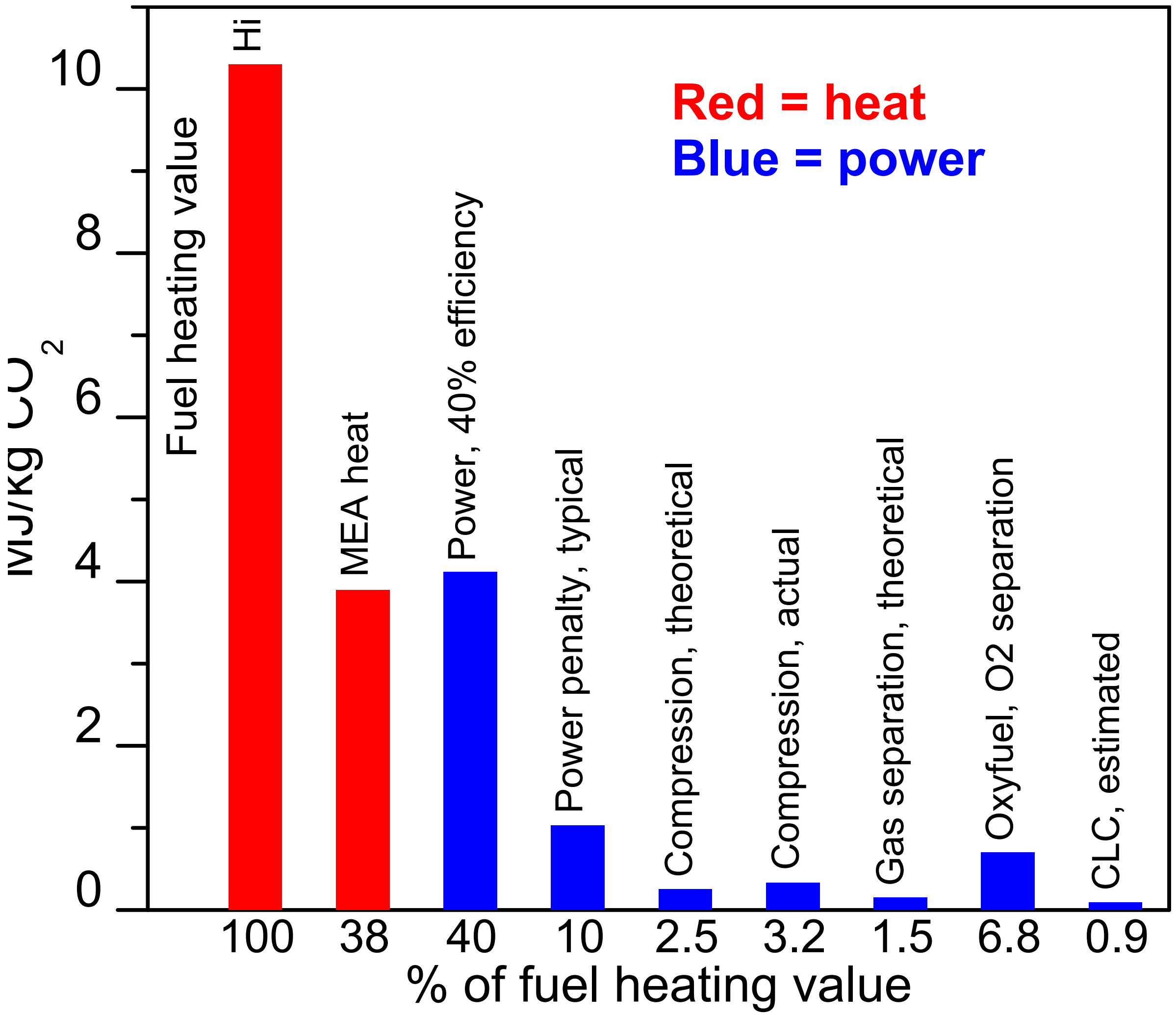
Thus: The cost for the economy would be considerably less than 2.5%.

But, it <u>is</u> true that carbon capture has a high energy penalty (L2-L4)

Absorption of CO2
with monoethanolamine (MEA)



Energy Penalty of CO_2 capture



New technology may significantly reduce energy penalty and cost of Bio-CCS

Chemical-Looping Combustion (CLC)

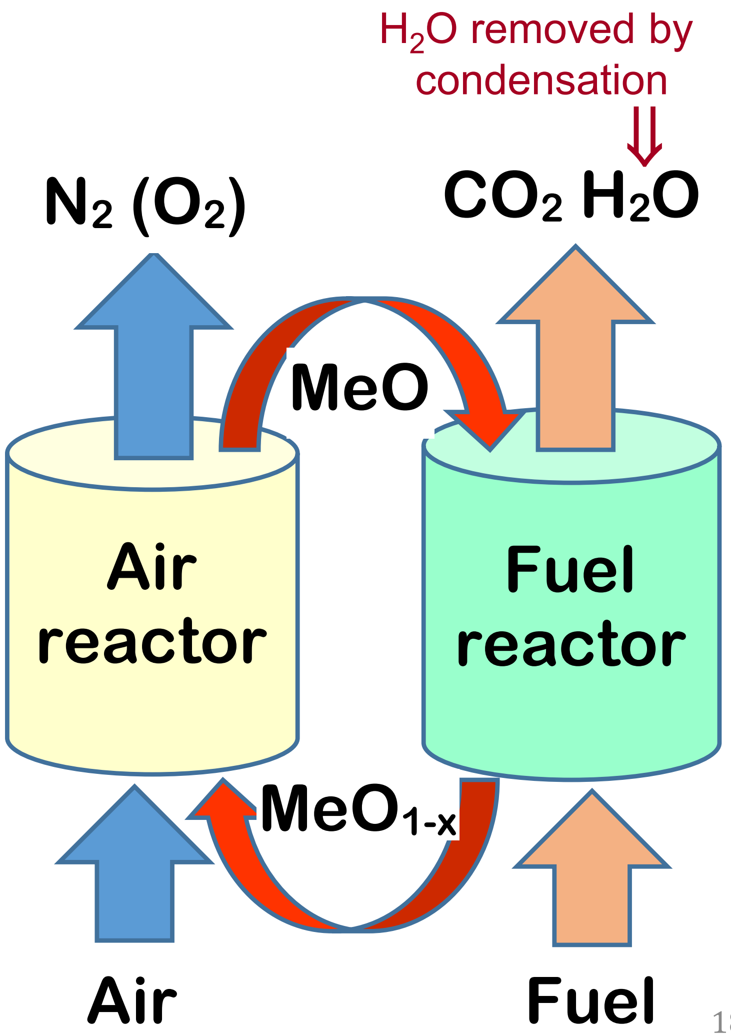
Oxygen is transferred from air to fuel by metal oxide particles

Inherent CO_2 capture:

- fuel and combustion air *never mixed*
- *no active gas separation needed*

Unique potential for reducing costs of CO_2 capture

But does it work in practice?



Yes, it works!!

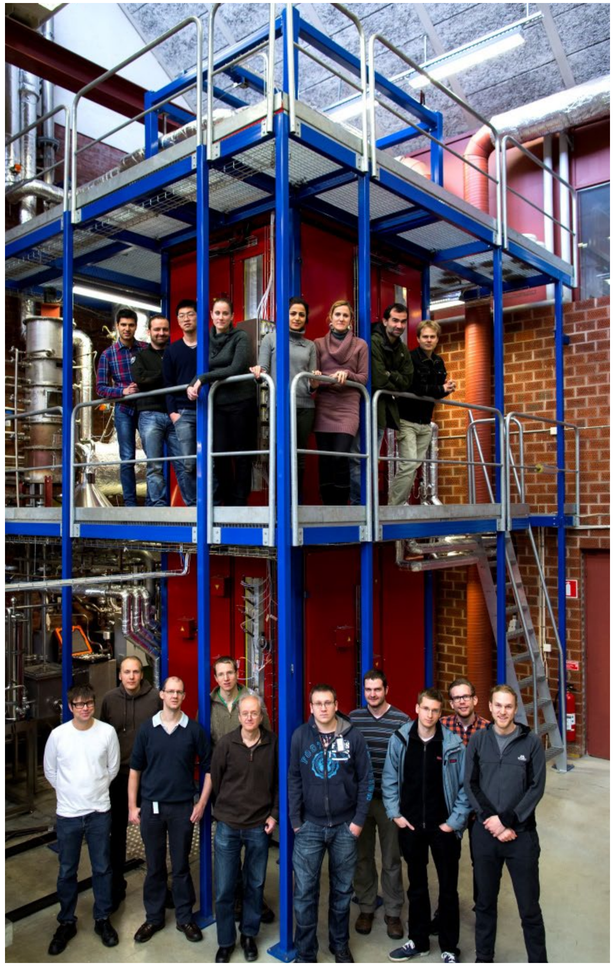
Total chemical-looping operation at Chalmers: 4 200 h in four pilots

Worldwide: 12 000 h in 49 pilots

10 kW gas, 2003

300 W gas, 2004

10 kW solid fuel, 2006



100 kW solid fuel, 2011

What is a fluidized bed?

In small biomass boilers grate firing is used.

For larger boilers fluidized bed is common

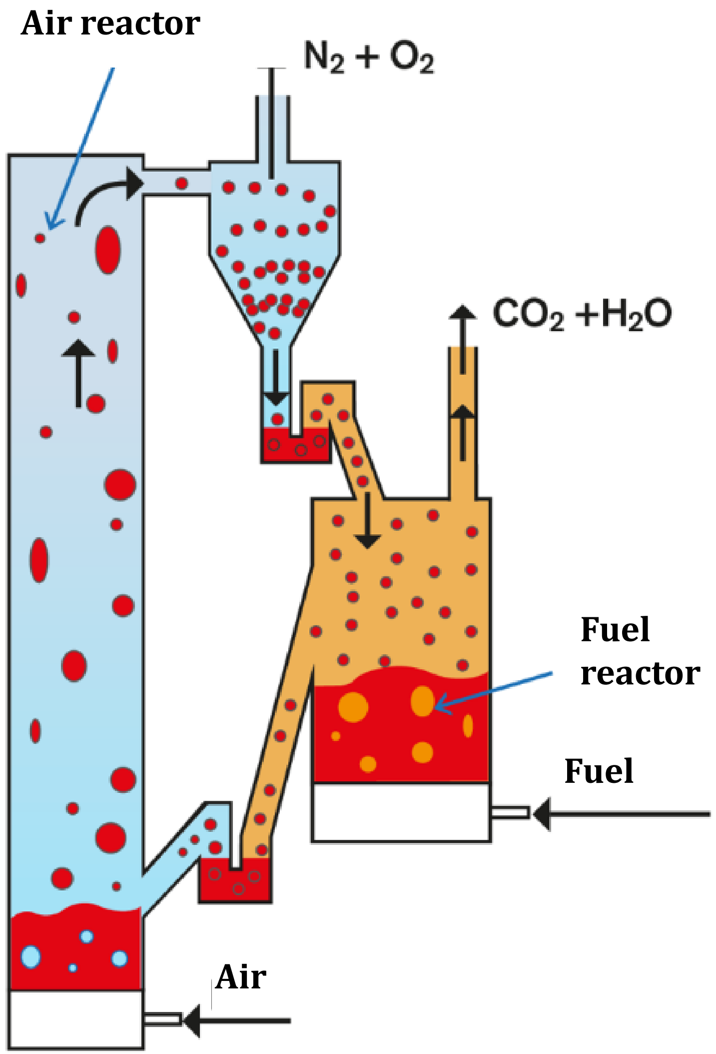
If gas (air) is blown through a bed av particles (e.g. sand) you get a fluidized bed.

↑

Behaves like a liquid

Circulating fluidized-bed boiler for burning biomass

Chemical Looping Combustion



Conventional biomass combustion is similar to Chemical-looping Combustion:

>>>Low added cost for CLC

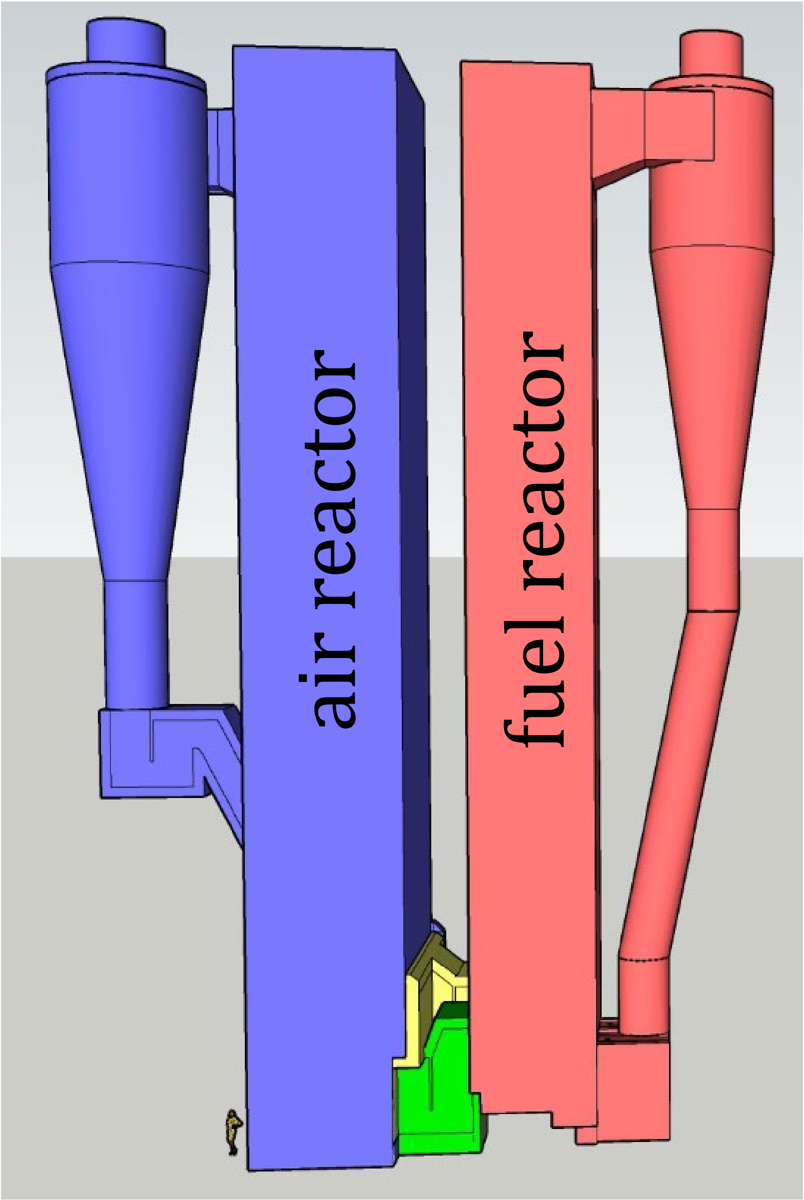
Actual circulation in CFB boilers is 5-50% of what is needed for CLC

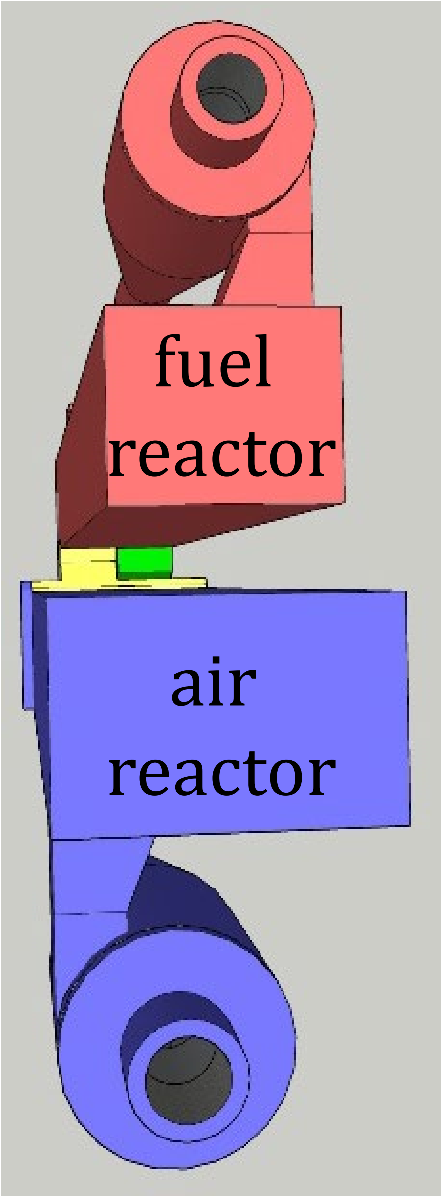
But the upwards flow decreases exponentially, and there is a corresponding downflow along the walls.

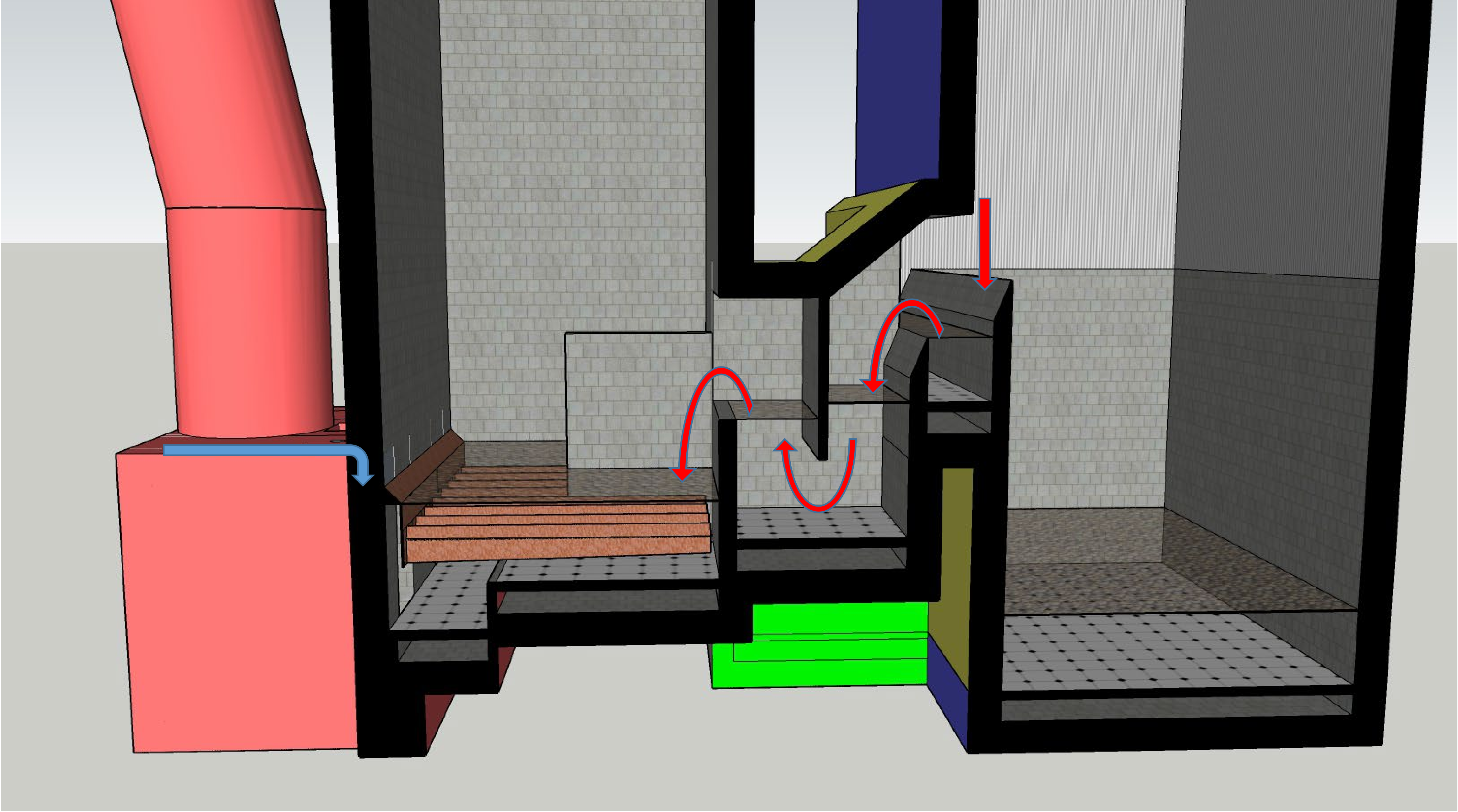
Thus, collection of down-flow along the walls, would be sufficient.

Lyngfelt, A., Pallarés, D., Linderholm, C., Lind, F., Thunman, H., and Leckner, B., Achieving Adequate Circulation in Chemical-Looping Combustion – Design Proposal for a 200 MW_{th} CLC Boiler, *Energy & Fuels (in press) 2022*

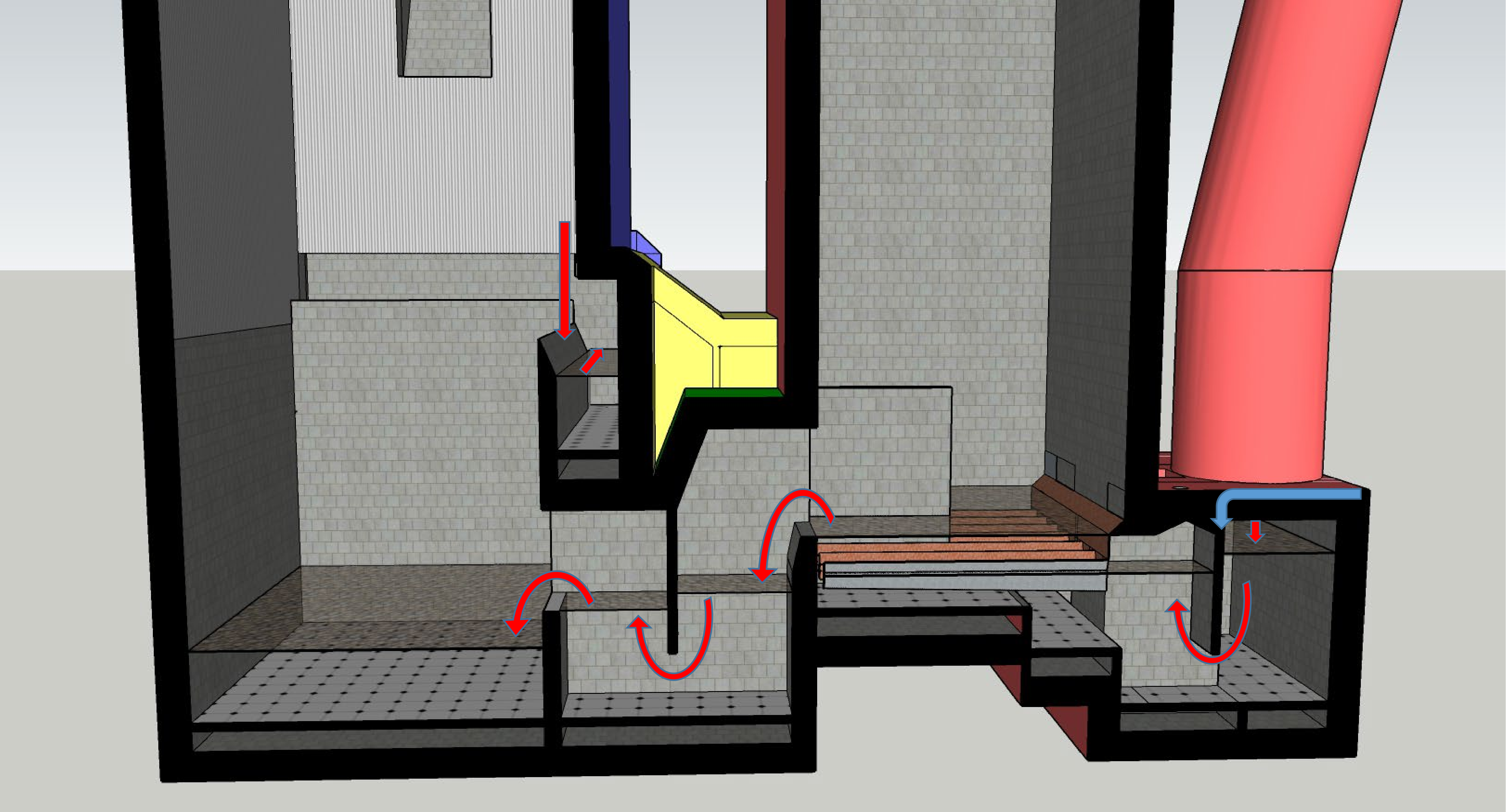
200 MW CLC-CFB boiler, 40 m high



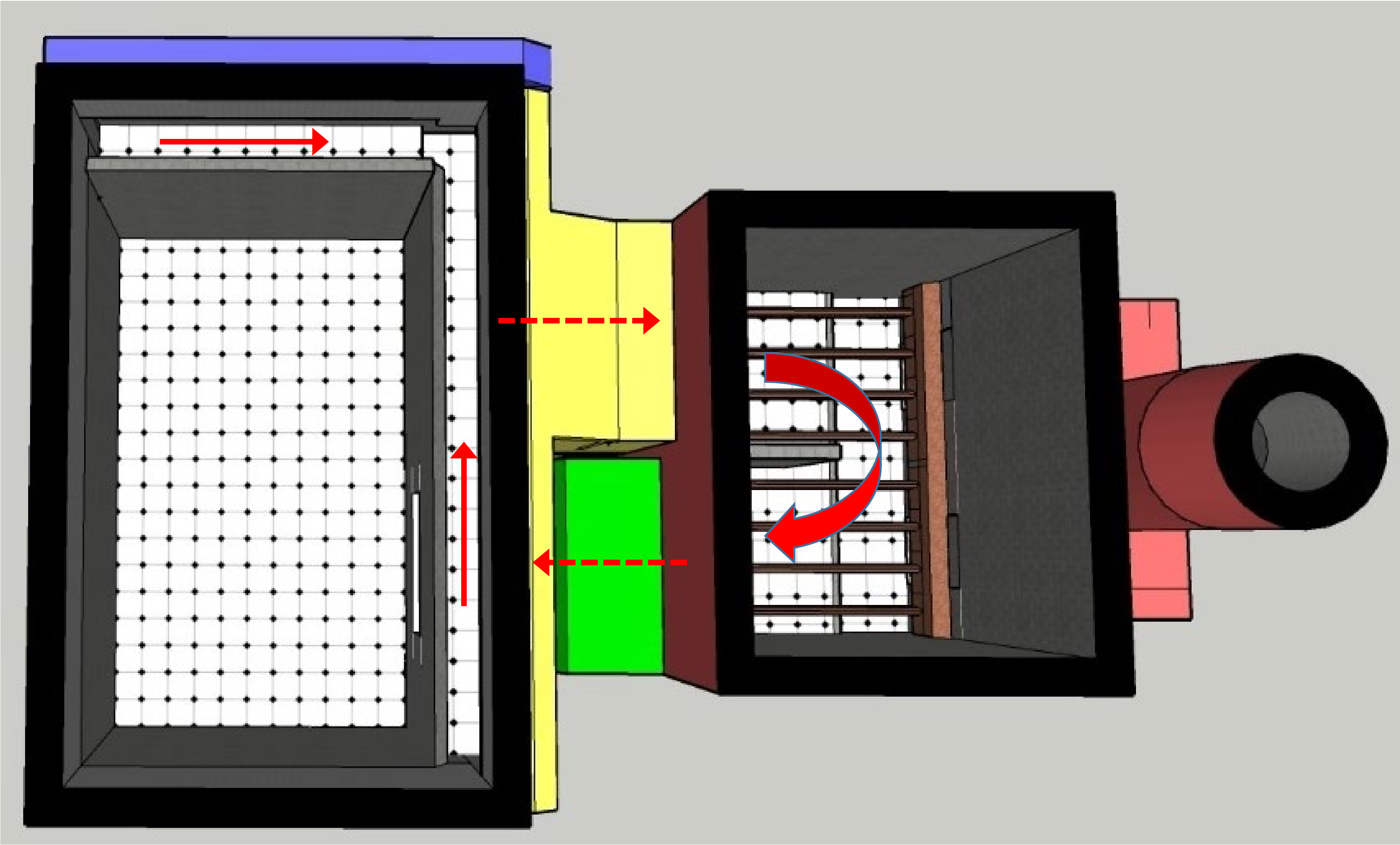




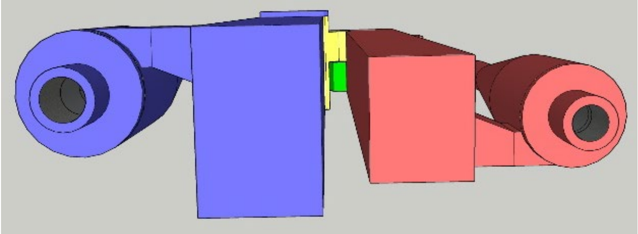
fuel reactor air reactor



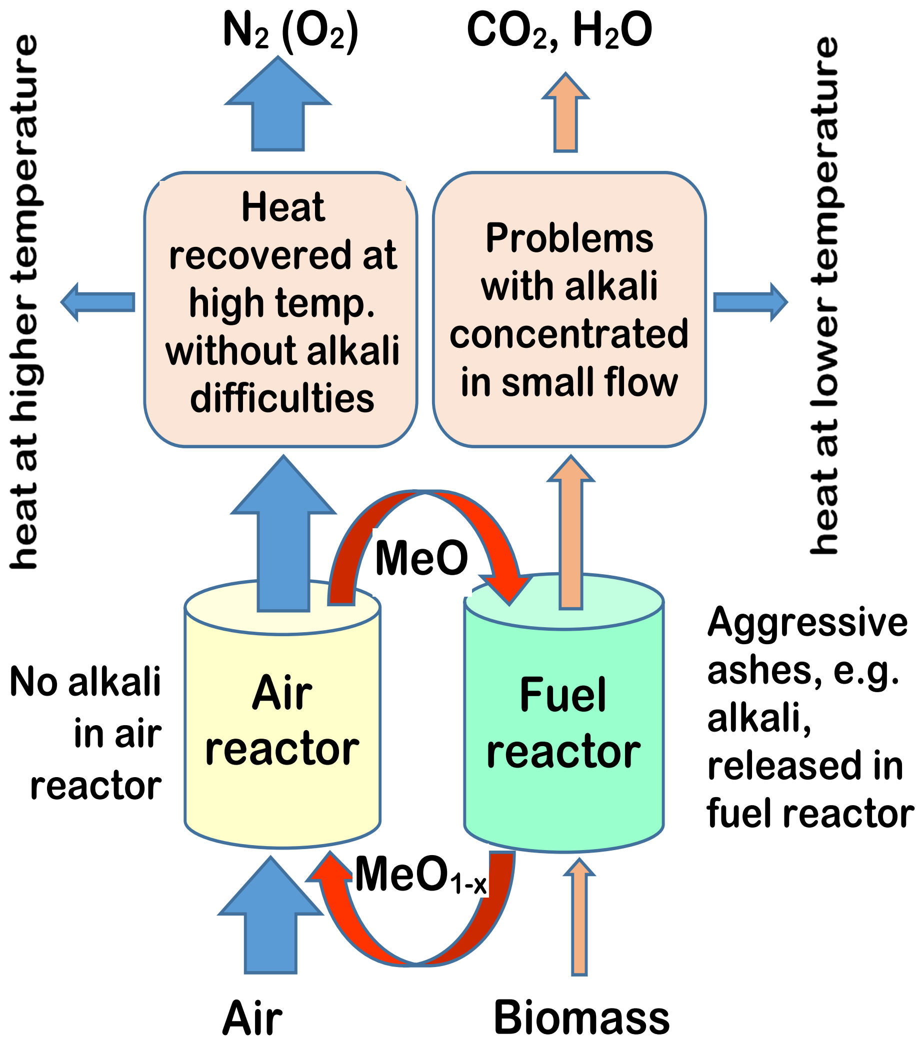
air reactor　　fuel reactor



air reactor



fuel reactor



Alkali in biomass gives low
ash-melting temperature
together with silica (i.e. sand).

With ilmenite oxygen carrier ($FeTiO_3$) the alkali forms non-sticky titanates.

>20,000 h of OCAC (oxygen-carrier aided combustion) in 75 MW CFB with ilmenite

Could range of possible fuels be extended?

NO will be in the concentrated CO_2 flow
Also conditions for reducing NO are very good in the fuel reactor.
Perhaps NO can be eliminated ?

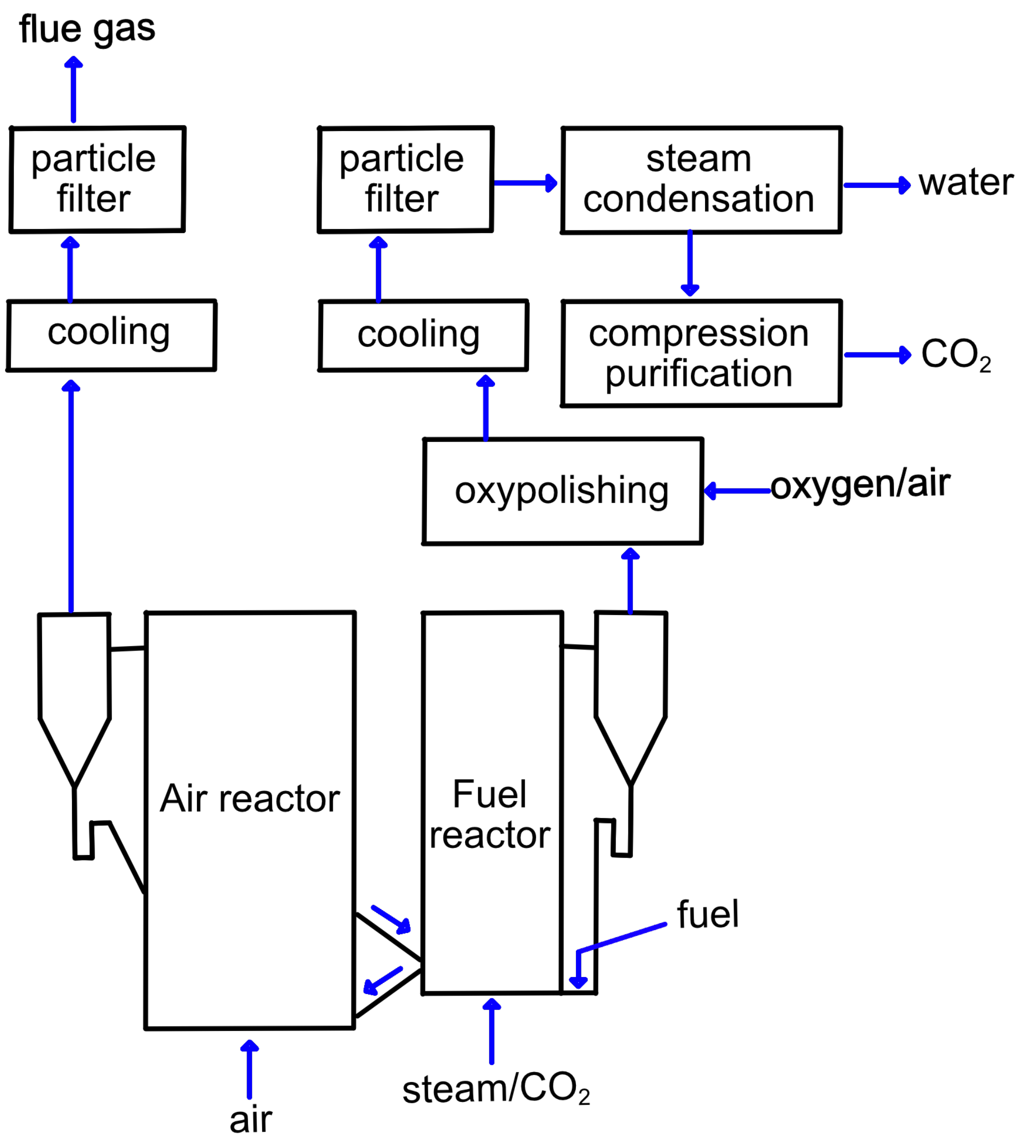
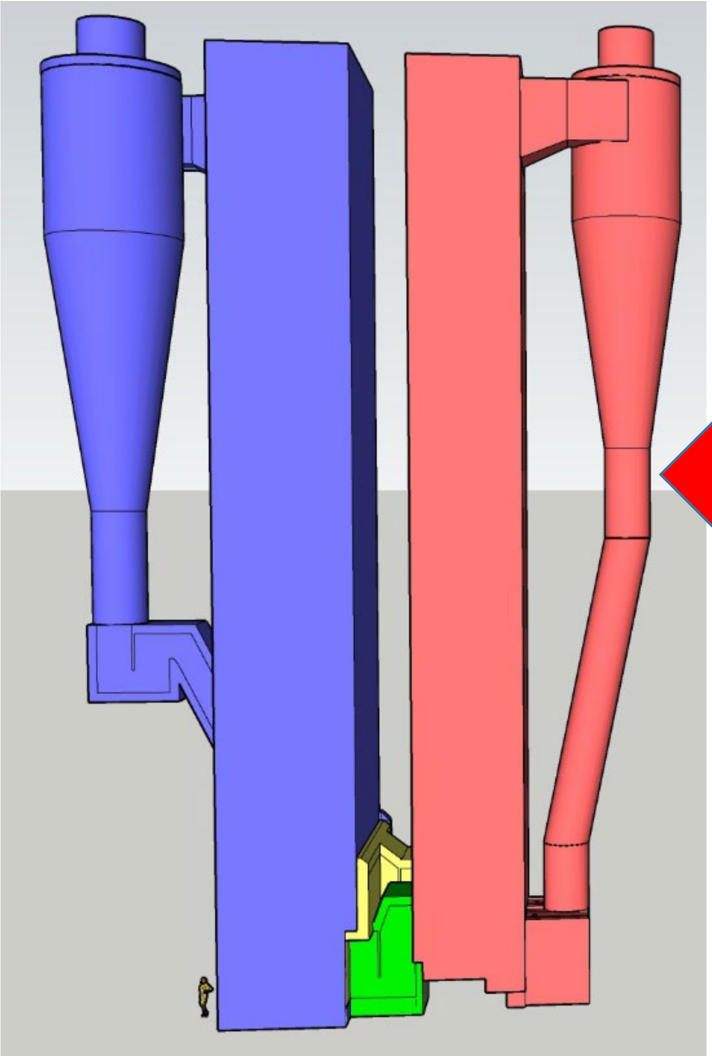
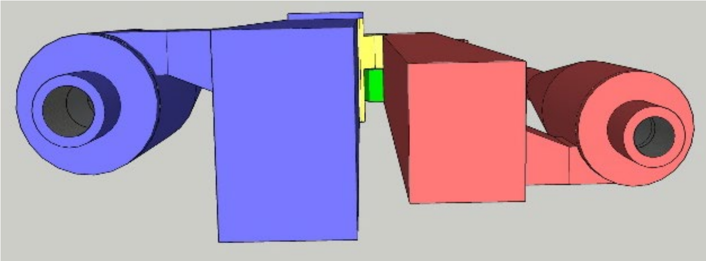


Table 1. Required purity of CO_2.[62,63]

Component	ppm
Water, H_2O	≤30
Oxygen, O_2	≤10
Sulphur oxides, SO_x	≤10
Nitric oxides/nitrogen dioxide, NO_x	≤10
Hydrogen sulphide, H_2S	≤9
Carbon monoxide, CO	≤100
Amine	≤10
Ammonia, NH_3	≤10
Hydrogen, H_2	≤50
Formaldehyde	≤20
Acetaldehyde	≤20
Mercury	≤0.03





Added cost:

1500 m² insulated wall
at
2000 €/m²

>>> 3 M€

or

0.3 M€/year

capture: 0.4 Mt CO_2/year

cost of fuel reactor : **0.75 €/t CO_2**

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

[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

Chemical Looping combustion (CLC)

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

Highly concentrated CO_2 stream can be obtained at small added cost

Expected cost: 20-25 €/ton CO_2, or 25-50% of competing technologies

Works with biomass

Eliminate/reduce emissions of NO_x

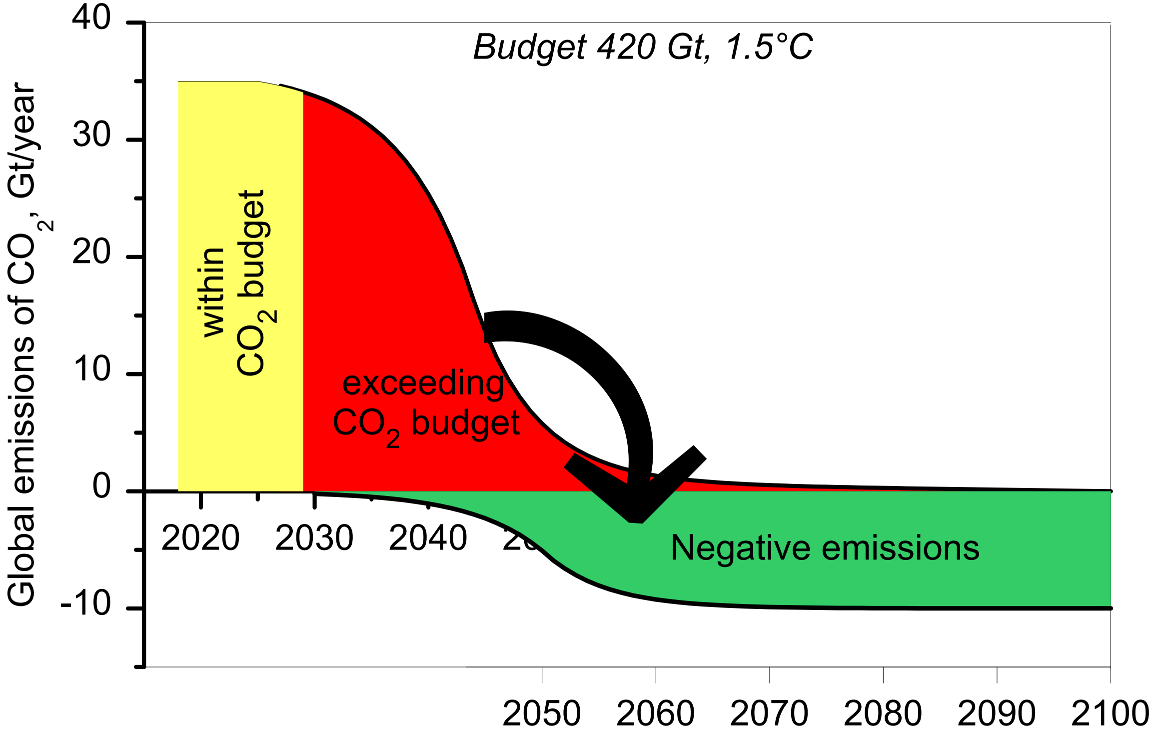
Eliminate/reduce problems with alkali ash components

Presently no market – poor interest from industry to engage in development

Not a misconception about bio-CCS:

7. Handing over a gigantic climate debt, the challenge to clean up the atmosphere, to our children and grandchildren is a moral hazard or moral collapse.

Unfortunately TRUE!



What is the key problem with this gigantic climate debt?

Not lack of potential for negative emissions
Not that we will be too poor to afford it

It is the *challenge in sharing* the gigantic climate debt,
perhaps 100.000 €/capita,
between nations and within nations

Who will be willing to pay? Who can be made to pay?

Try to imagine finance ministers giving negative emissions priority in budget over health care, education, defence etc.

Will we hand over **a problem** to our children **that is insoluble**, i.e. how to share the climate debt?

The problem involves sharing the burden between nations with

- *widely different historic emissions*,
- different motivation,
- different political systems and
- *different opportunities* for achieving negative emissions.

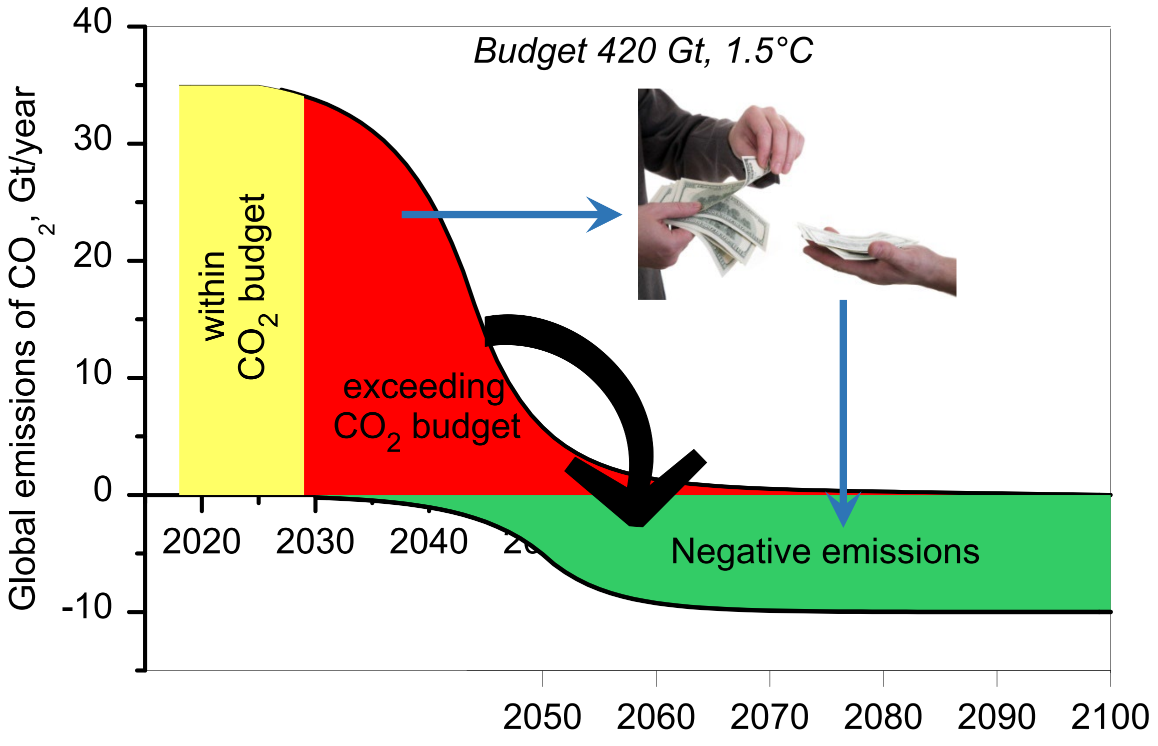
Can negative emissions - with *little tangible and immediate climate benefits for voters* - can be prioritized *in competition with public expenditures like healthcare and education ?*

A possible solution:

"A CO_2 Emitter Liability"

making emitters responsible for removing emitted CO_2 from atmosphere.

Note the need to pay for future negative emissions



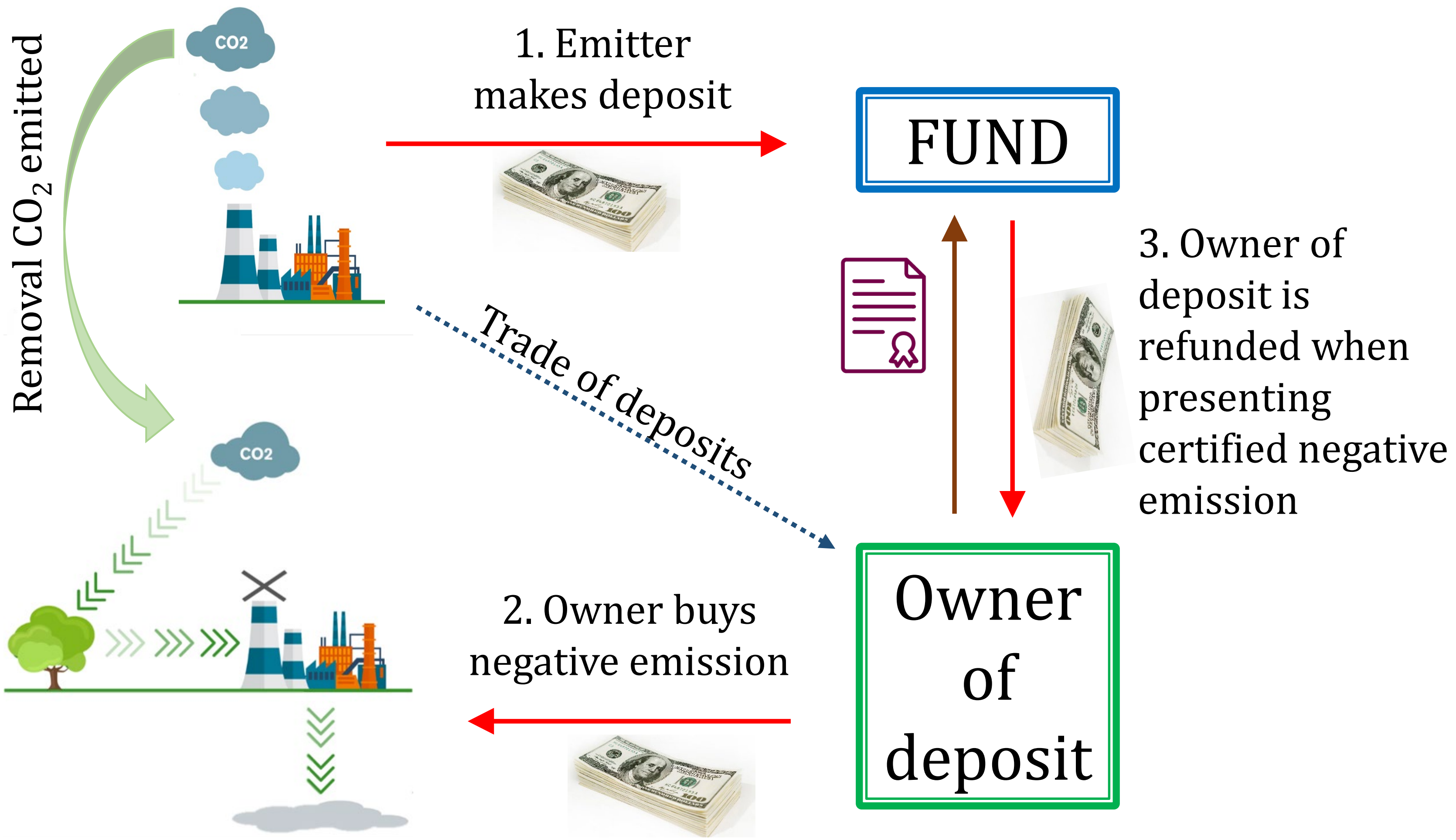
REF: Lyngfelt, A., and Fridahl, M., CO_2 Emitter Liability using Atmospheric CO_2 Removal Deposits (ACORDs) for Financing of Future Negative Emissions, *2nd International Conference on Negative CO2 Emissions*, June 14-17, 2022, Göteborg, Sweden

Such CO_2 recovery a liability:

- would be **fair, comprehensible and rational**,
- would provide a strong incentive for emissions reductions.
- should be introduced **as soon as possible**, to minimize temperature overshoot and associated damage and minimize risks for the triggering of climate system tipping points.
- would need a design that considers that a majority of the negative emissions will be made long after actual the emissions.
- could be operationalized through a **deposit and refund scheme**.

Thus, emitters make financial deposits. Deposits can be refunded, presenting proof of certified negative emissions.

Atmospheric CO_2 Removal Deposits (ACORDs)



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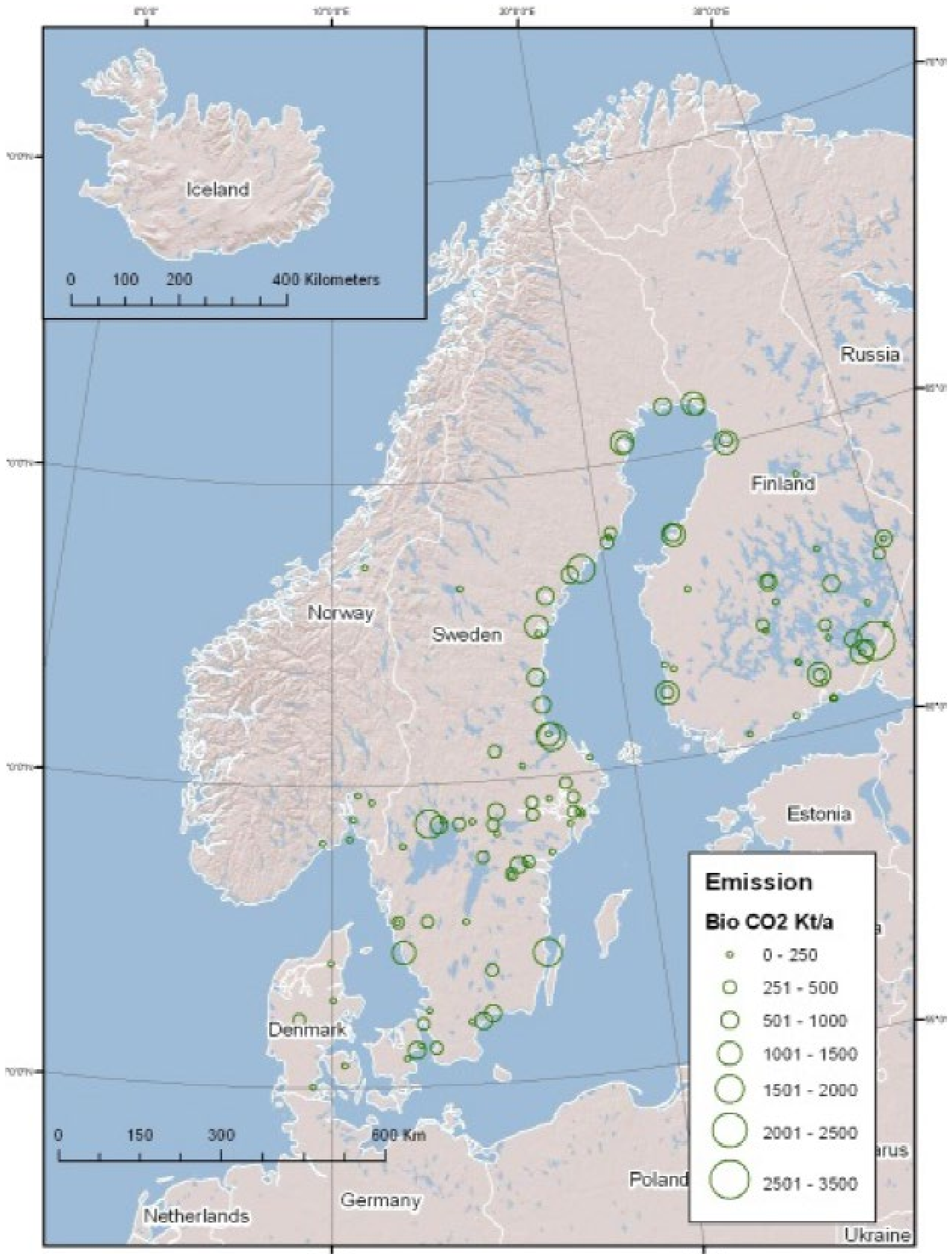
Large potential for negative CO_2 emissions in Nordic countries

Sweden:
>30 Mt/year biogenic CO_2 emissions from point sources >100.000 ton/year

(Total Swedish fossil CO_2 emissions 40 Mt/year)

Sweden exceeded it's rightful share of the 1.5°C budget 30 years ago.



Negative emissions and Bio-CCS

- It's needed.
- Biomass: It could be enough:
  - if we decrease fossil fuel emissions rapidly
  - if we can prevent the harvested carbon from returning to the atmosphere.
  - if we are careful with use of biogenic transportation fuels.
- Technology is known, and used in large scale. (*i.e.* CCS)
- Storage is safe. (Bio-CCS) Later leakage not necessarily a problem (Nature-based)
- ”Not needed now”. – It's very much needed!
- Bio-CCS is not cheap, but the cost is reasonable.
  - Novel technology (chemical-looping) has potential for significant cost reduction.
- It is a moral collapse to hand over the insoluble question of how to share responsibility for, and costs of, gigantic negative emissions between nations
- Financing of negative emissions could be solved by introducing a CO_2 emitter liability, making the emittors pay for future negative CO_2 emission.
- This can be accomplished using Atmospheric CO_2 Removal Deposits (ACORDS)

Thank you !

Lecture assignment (L6)

<u>300 word text</u>

Discuss briefly the various options for negative emissions in term of costs, storage safety, accountability, and potential.

Does storage of CO_2 make sense if the CO_2 stored leaks? Discuss the effects of leakage of stored CO_2.

Where is the difficulty in incentivizing negative CO_2 emissions, as compared to emission reductions.?