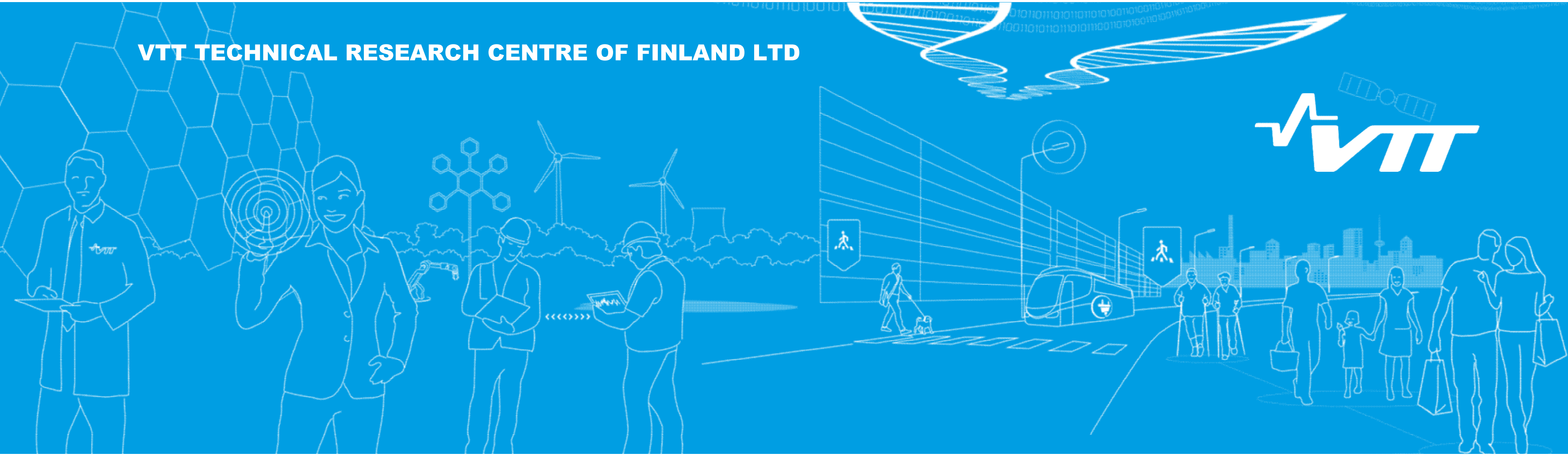

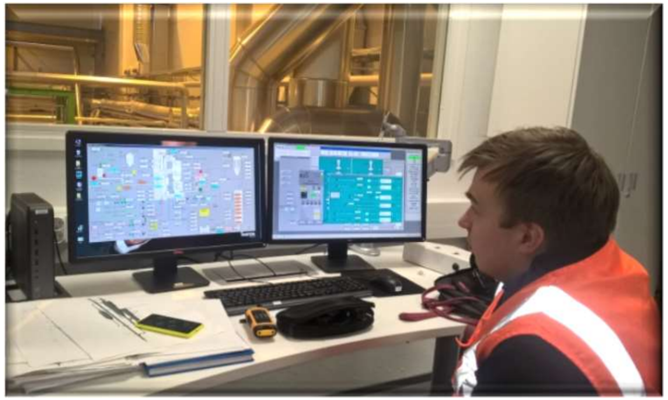

Capturing carbon with chemical looping combustion of biomass

Nordic Baltic Bioenergy Conference
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Content

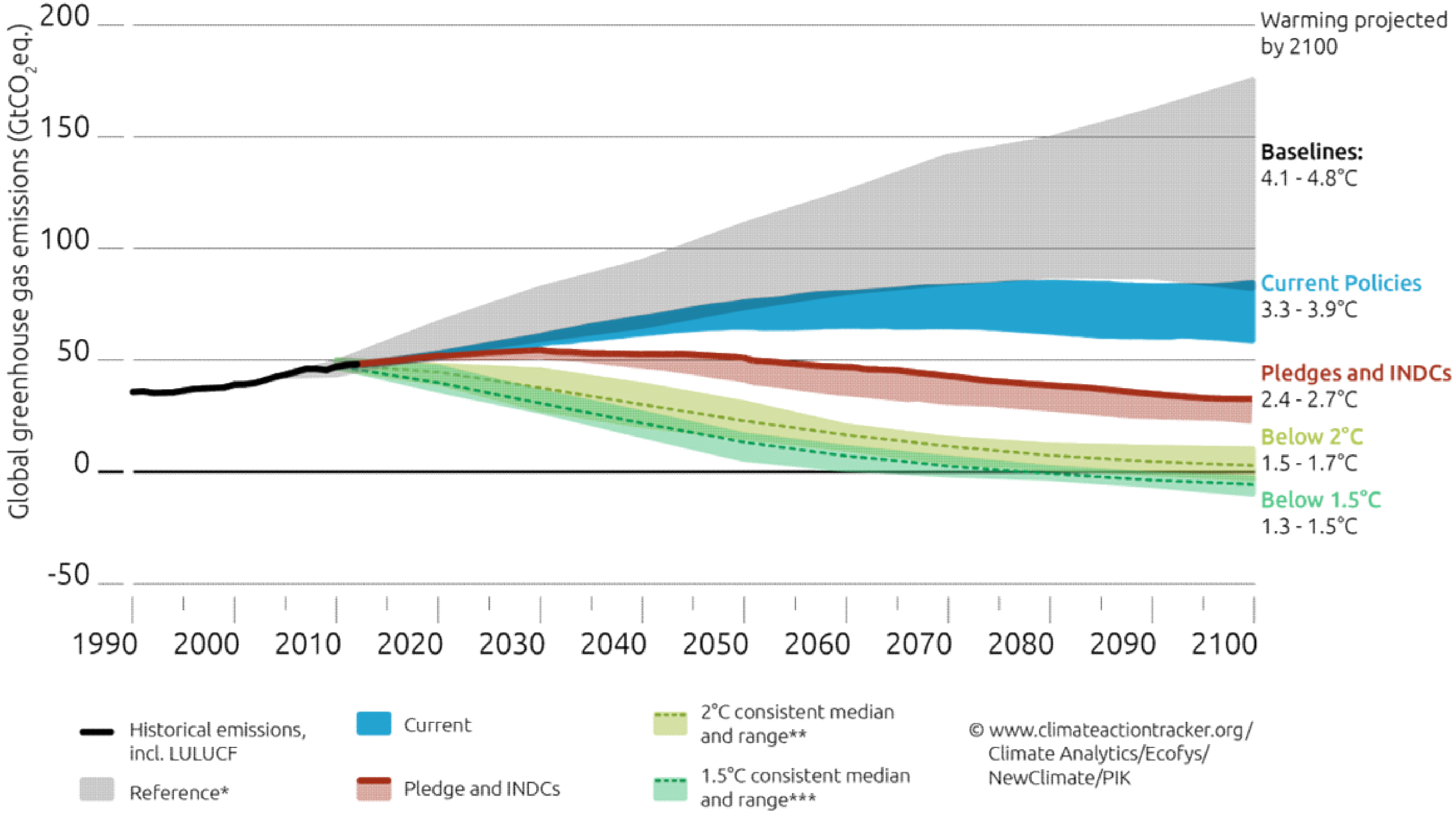
- Background and motivation
- What is chemical looping combustion (CLC)?
- What are negative CO_2 emissions?
- Piloting of bio-CLC
- Techno-economical assessment, preliminary results
- Summary

After the Paris agreement the target is "CO_2 - neutral" society

- CO_2 removal technologies such as BECCS (Bio-Energy Carbon Capture and Storage) are becoming essential for achieving the 2 °C target [1]
- CCS and bioenergy as the two most valuable technologies for achieving climate policy objectives – more important than energy efficiency improvements, nuclear, solar power and wind power – motivated by their combined ability to produce very significant negative emissions via BECCS [2]

1. Climate Change 2014: Mitigation of Climate Change, Intergovernmental Panel on Climate Change, 2014.
2. Kriegler E., Weyant J., Blanford G., Krey V., Clarke L., Edmonds J., Fawcett A., Luderer G., Riahi K., Richels R., Rose S., Tavoni M., van Vuuren D, (2014), The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies, Climate Change 123, pp. 353-367.

Negative GHG-emissions at end this century required to go below 2ºC

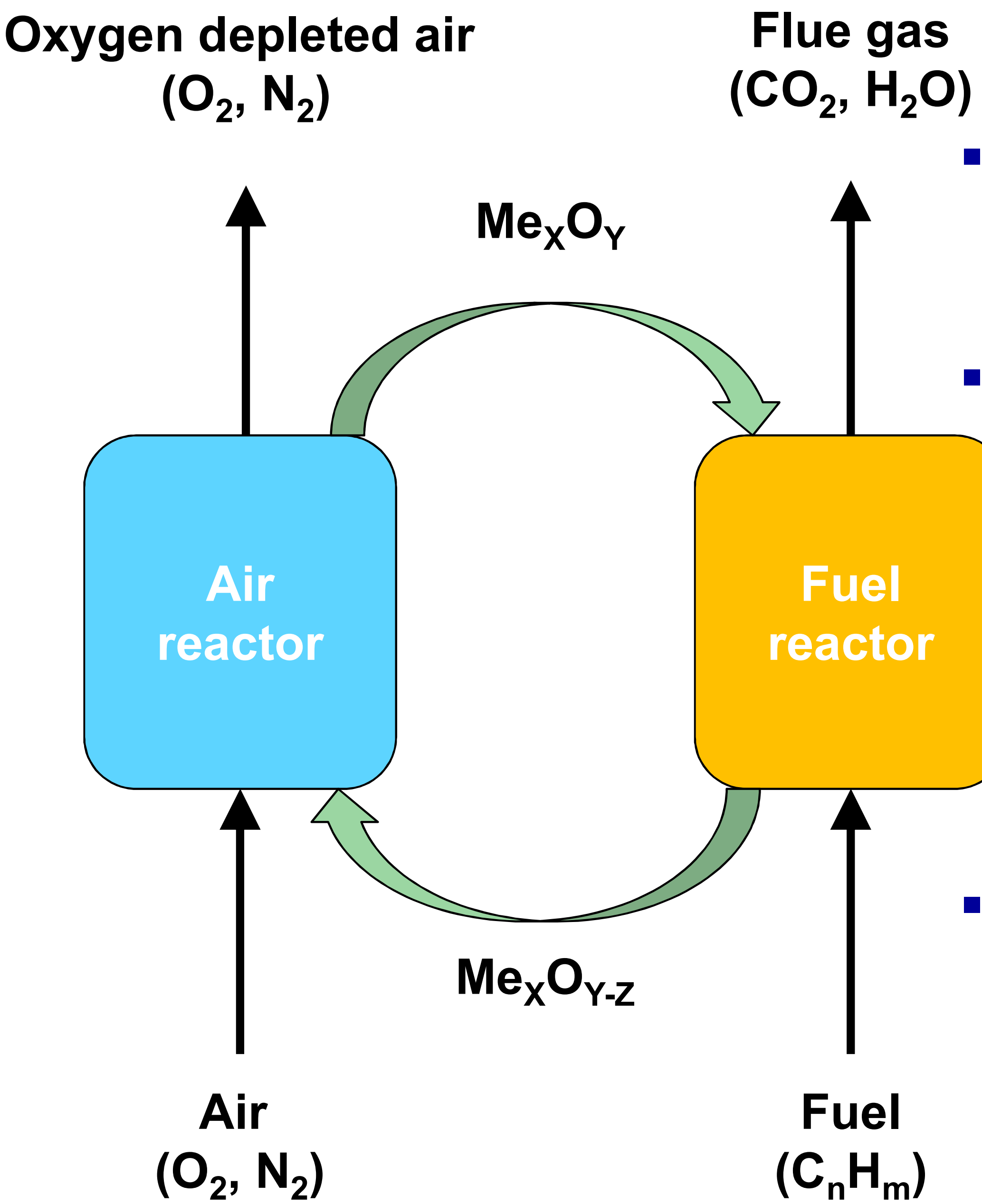


* 5%-95% percentile of AR5 WGIII scenarios in concentration category 7, containing 64% of the baseline scenarios assessed by the IPCC

** Greater than 66% chance of staying within 2°C in 2100. Median and 10th to 90th percentile range. Pathway range excludes delayed action scenarios and any that deviate more than 5% from historic emissions in 2010.

*** Greater than or equal to 50% chance of staying below 1.5°C in 2100. Median and 10th to 90th percentile range. Pathway range excludes delayed action scenarios and any that deviate more than 5% from historic emissions in 2010.

Chemical Looping Combustion – principle



- Oxygen carrier (OC):
  - transfers oxygen from air to fuel reactor
  - active part is metal (e.g. Fe, Cu, Mn, Ni, ...)
- Oxygen can be released
  - by heterogeneous combustion reaction between gaseous fuel and OC
  - by *in situ* gasification of solid fuel followed by heterogeneous combustion reaction (*i*G-CLC)
  - by chemical looping oxygen uncoupling (CLOU) where O_2 is released due to effect of O_2 partial pressure and temperature
- The total amount of released heat is the same as for normal combustion
  - Oxidation reaction in air reactor is highly exothermic
  - Reduction reaction is often endothermic

Background and motivation

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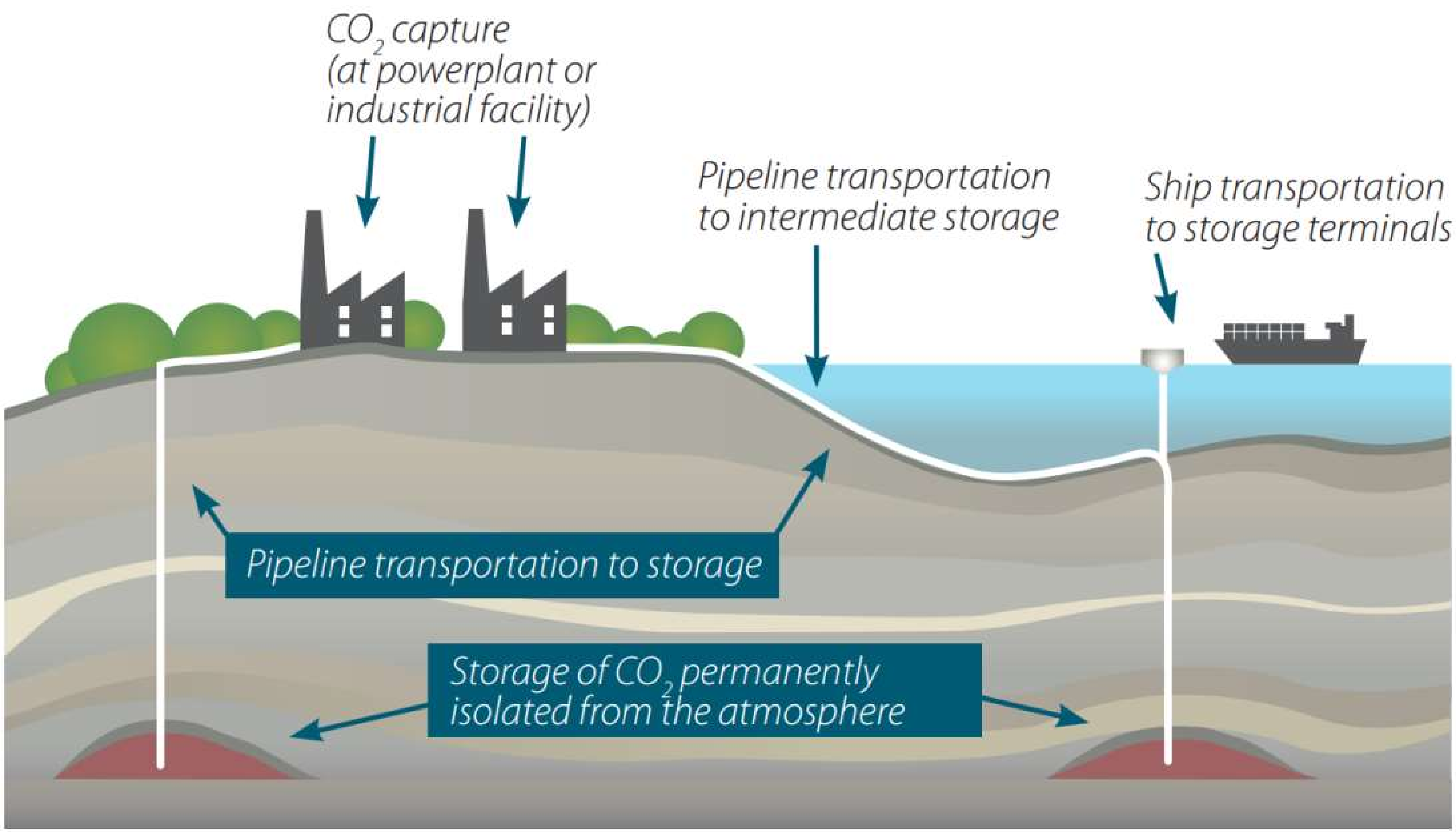
Piloting of bio-CLC

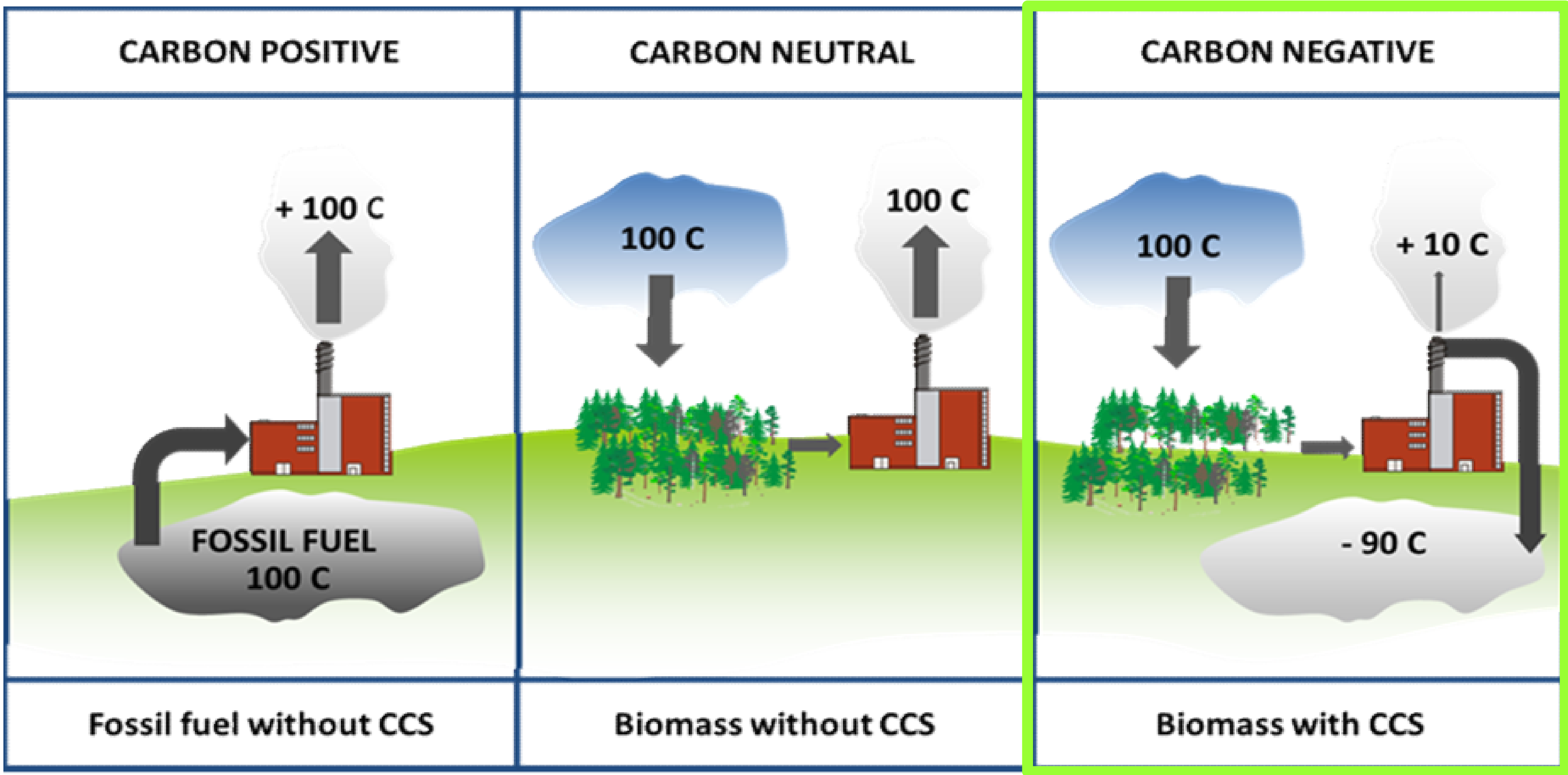
Techno-economical assessment

Summary

Carbon Capture and Storage - CCS



Carbon balance



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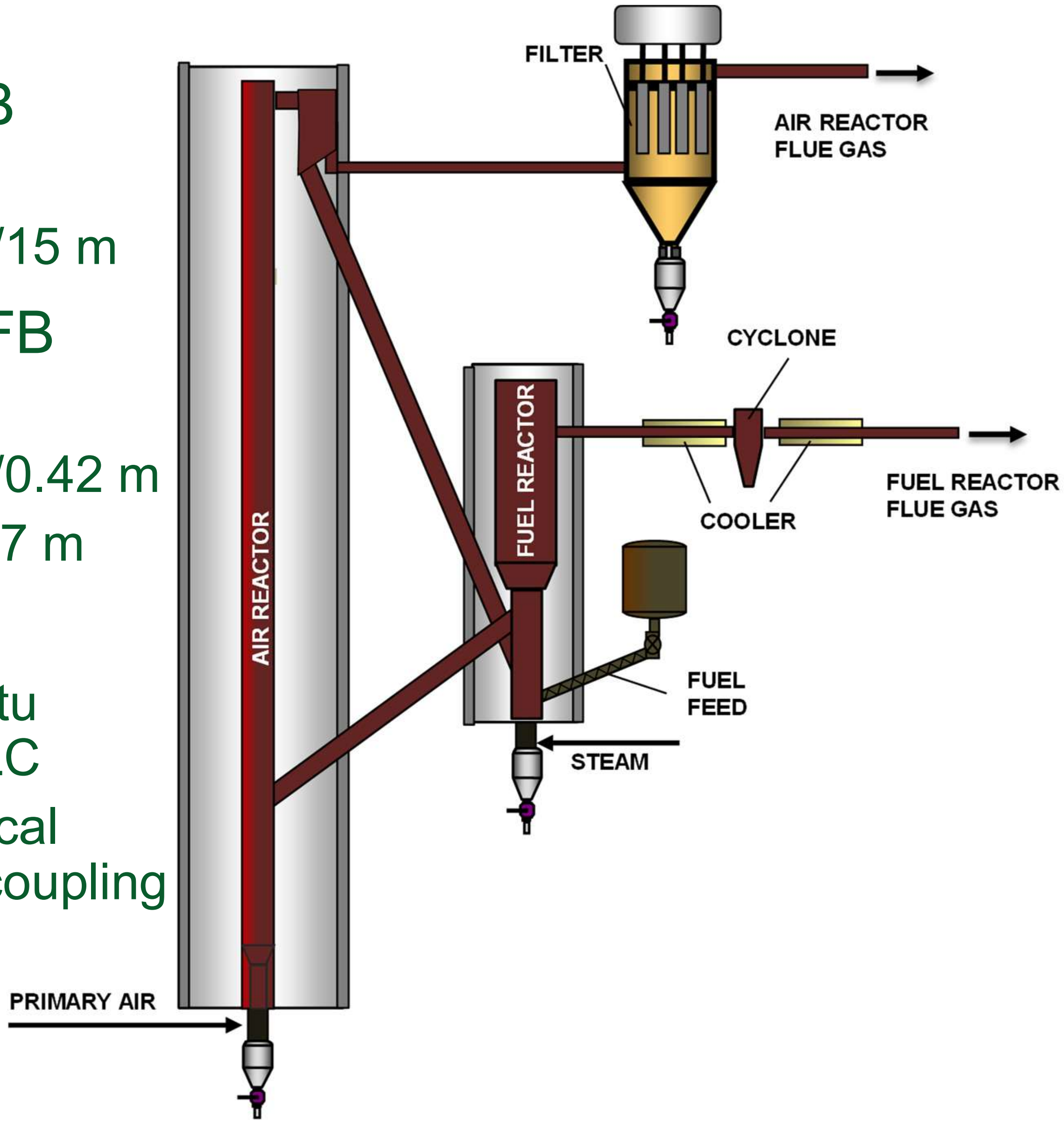
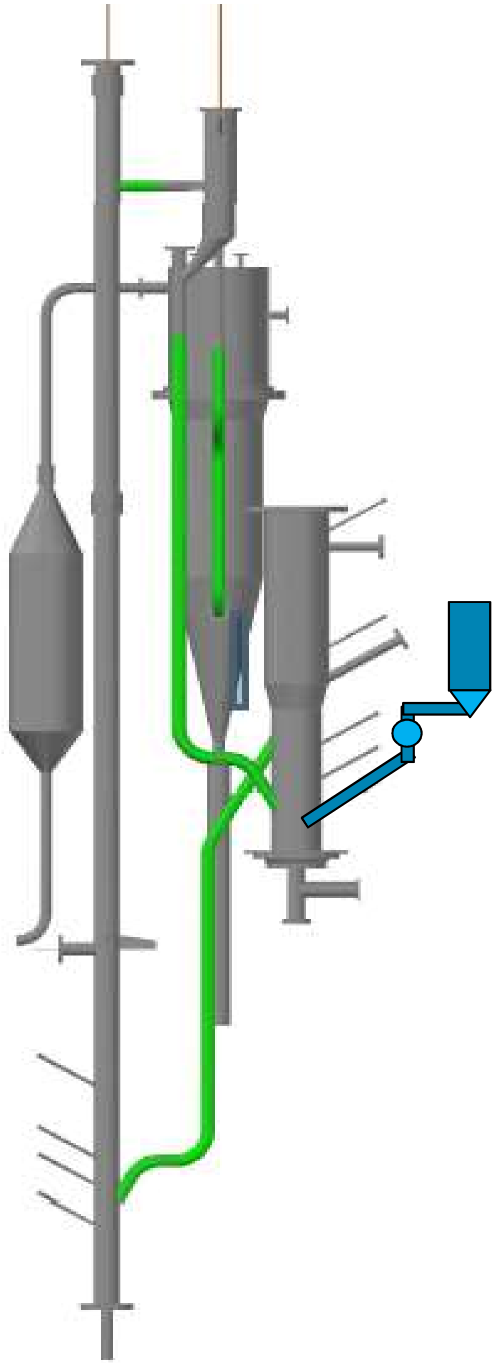
Dual fluidized bed CLC process development unit

- Air reactor - CFB
  - Height 8 m
  - Diameter 0.10/15 m
- Fuel reactor - BFB
  - Height 2.5 m
  - Diameter 0.32/0.42 m
  - Bed height ~0.7 m
- Fuel power
  - 10-20 kW in-situ gasification CLC
  - ~50 kW chemical looping O_2 uncoupling





Fuels and oxygen carrier

		VAPO white pellets	Arbaflame black pellets
Moisture	m-% a.r.	6.0	4.9
Ash	m-% a.r.	0.5	0.5
Volatiles	m-% a.r.	78.4	75.2
Fixed C	m-% a.r.	15.1	19.4
C	m-% a.r.	47.6	50.7
H	m-% a.r.	5.6	5.8
N	m-% a.r.	0.1	<0.1
S	m-% a.r.	<0.01	<0.01
O	m-% a.r.	40.2	38.1
LHV	MJ/kg a.r.	17.67	19.29

a.r. = as received

Ilmenite (natural ore) oxygen carrier

- supplied by Titania A/S, Norway
- very pure (>95 m-%) ilmenite $TiFeO_3$
- Narrow PSD, D_{50} = 270 µm, D_{10} = 190 µm and D_{90} = 390 µm
- bulk density of the fresh ilmenite 2600 kg/m^3

Test matrix and key performance indicators

High O2 demand

But good C-capture

			Fuel reactor			Air reactor		Key indicators	
Test #	Fuel type	Duration min	Fuel kW	H2O m/s	Bed ºC	Air m/s	Bed ºC	Oxygen demand %	Carbon capture eff. %
1	VAPO white pellet	15	14	0.23	840	5.2	864	34	96
2		10	14	0.12	852	5.2	865	41	93
3		15	14	0.17	848	7.3	847	32	95
4	Arba-flame black pellet	20	15	0.23	845	5.2	869	32	94
5		10	15	0.12	863	5.2	875	38	92
6		25	22	0.17	848	6.0	878	34	88
7		20	19	0.17	852	7.4	868	30	83
8		40	9	0.12	860	7.4	862	29	86
9		15	19	0.12	851	6.5	872	31	87

- The main challenge encountered during the tests was to maintain a high enough bed temperature in the fuel reactor.
- The desired temperature level above 900ºC, needed for optimal performance of the ilmenite oxygen carrier, was not achieved in any test.
  - As the DFB-PDU was originally constructed for gasification applications, its design is not optimal for chemical looping combustion.

Conclusions from the pilot tests

- Promising results for using chemical looping combustion for biomass combustion with reduced risk of high temperature corrosion enabling the option to use higher steam values in bio-CLC than in conventional biomass combustion applications, improving the power generation efficiency.
  - This increase in efficiency could partially compensate for the efficiency loss due to the CO_2 compression or liquefaction needed for further transportation of CO_2 for final storage or use in chemical processes.
  - Although these results indicate a clear benefit of bio-CLC over conventional biomass combustion, this phenomenon needs to be studied in more detail for verification.

- Although the oxygen demand remained relatively high due to incomplete fuel conversion in the fuel reactor, the problem was mainly due to the PDU being originally designed for gasification.
  - Improvements planned (and use of CLOU materials as OC may help)
  - The problems are not expected to be an issue in a large scale application of bio-CLC.

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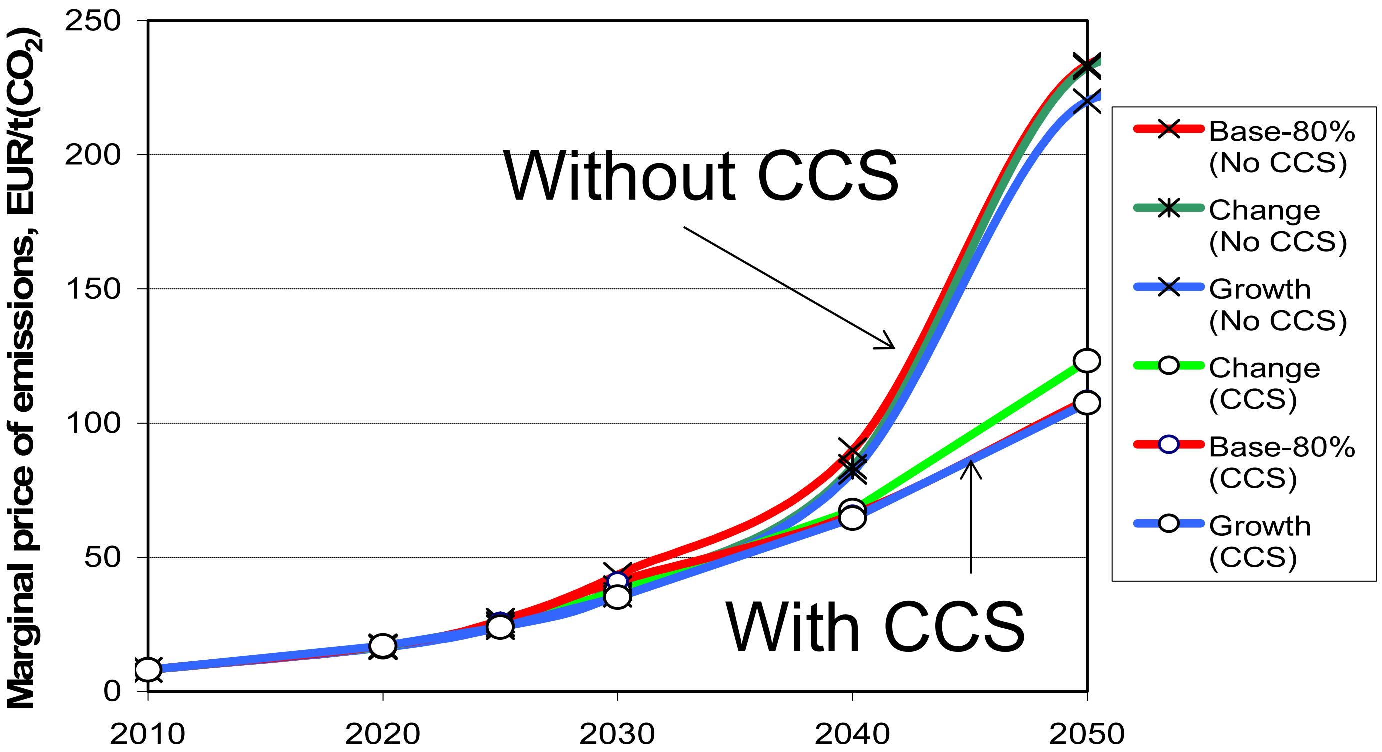
To study the role of CCS the CCSP scenarios were run with and without CCS

- In Base-80% scenario existing industrial and other economical structures result in higher CO_2 emissions
- In Growth scenario, CCS competes with rapidly developing other clean technologies
- In Change scenario only the bio-CCS is allowed. In addition the share of nuclear is the lowest.

CO_2 price doubles in those cases CCS is excluded



Cost of carbon capture

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
Coal grinding	0.2	0.2	0.1
Lower air ratio	-0.5	-0.5	-0.5
Total	20	15.9-25.8	3.9

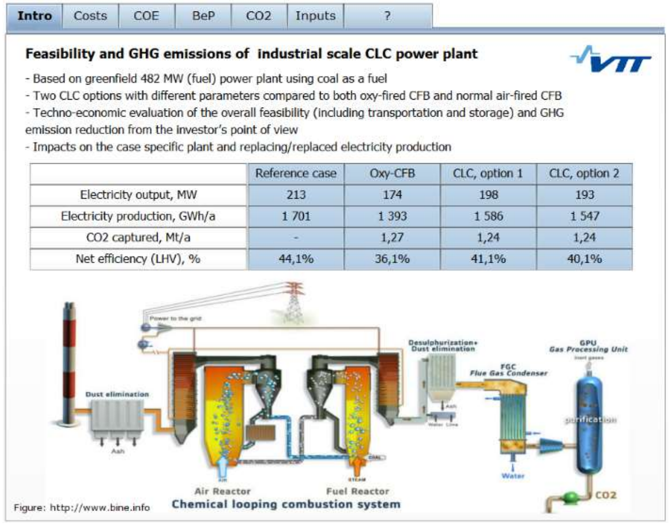
When applying OTSC steam cycle 10-15% efficiency improvement potential (~3.5-5.5 %-p.)

Taken from: Lyngfelt, A.; Leckner, B., "A 1000MWth boiler for chemical-looping combustion of solid fuels-Discussion of design and costs", Applied Energy, 2014, In press.

Techno-Economic Assessments of CLC concepts

Several case studies conducted:

- Prefeasibility-type-of assessments
- Profitability of CLC plant investment and operation in different market conditions
- CHP and condensing plants at commercial scale (up to 500 MW_{fuel})
- Comparison to oxy- and air-fired CFB
- Biomass, coal, natural gas, co-firing


Intro | Costs | COE | BeP | CO2 | Inputs | ?

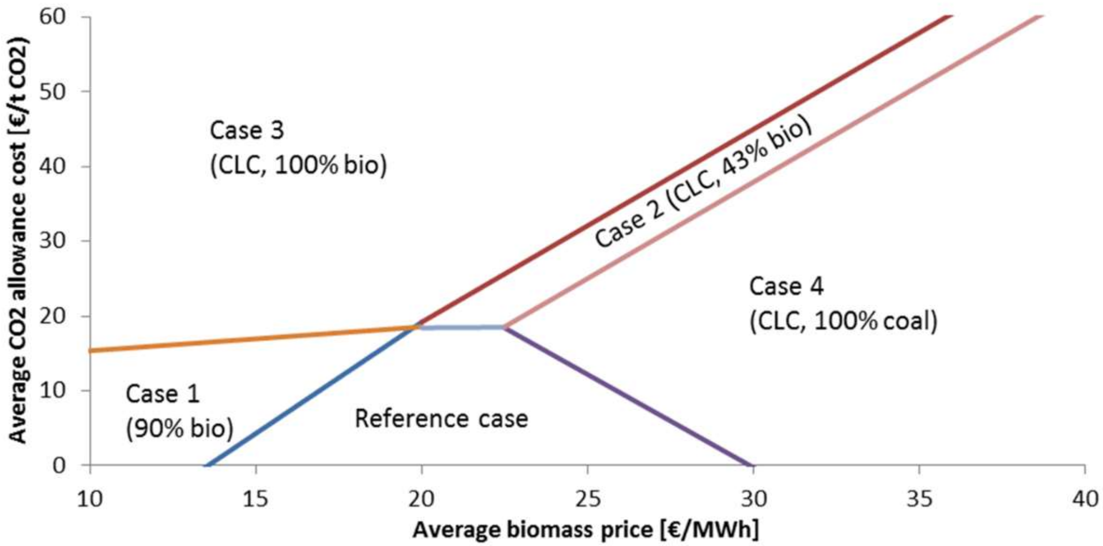
Feasibility and GHG emissions of industrial scale CLC power plant

- Based on greenfield 482 MW (fuel) power plant using coal as a fuel
- Two CLC options with different parameters compared to both oxy-fired CFB and normal air-fired CFB
- Techno-economic evaluation of the overall feasibility (including transportation and storage) and GHG emission reduction from the investor's point of view
- Impacts on the case specific plant and replacing/replaced electricity production

	Reference case	Oxy-CFB	CLC, option 1	CLC, option 2
Electricity output, MW	213	174	198	193
Electricity production, GWh/a	1 701	1 393	1 586	1 547
CO2 captured, Mt/a	-	1,27	1,24	1,24
Net efficiency (LHV), %	44,1%	36,1%	41,1%	40,1%

See TEA example on-line: [Techno-economic toolkit]

- Costs of captured CO_2 as low as 20 €/t



http://ccspfinalreport.fi/tools/clc.html

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Summary

- Negative GHG-emissions at end this century required to go below 2ºC
- Bio-CCS only industrial scale carbon negative technology that can be deployed today
- Chemical looping combustion is a novel technology enabling CCS with lower energy penalty compared to other CCS technologies
- Promising experimental results of bio-CLC with reduced risk of high temperature corrosion enabling the option to use higher steam values in bio-CLC than in conventional biomass combustion applications, improving the power generation efficiency.
- Techno-economical assessments show superior performance of CLC/bio-CLC

➢ Next step: demonstration in industrial scale

Acknowledgements

- This work was carried out in
  1. The Carbon Capture and Storage Program (CCSP) research program coordinated by CLIC Innovation Oy with funding from Tekes - the Finnish Funding Agency for Innovation
  2. The Nordic Flagship Project No: 77732 “Negative CO_2 emissions in the Nordic energy system” (2015-2019) funded by Nordic Energy Research

Thank you!
Questions?

Back-up slides

Corrosion risk in air reactor flue gas path

- The CO_2 concentration in the air reactor flue gas was <0.2 vol-% (dry) indicating insignificant combustion reactions.
- No indications of accumulation of alkaline components to the surface of oxygen carrier particles were found according to XRF analyses
- No alkaline containing aerosols found from the gas flow sampled before the filter (at ~450°C)
- Chlorine concentrations were under the detection limit in all samples.

➢ It can be concluded that concentrations of vaporized alkali chlorides components in air reactor flue gas are much lower than in conventional biomass combustion applications.

  ➢ This reduces the risk of high temperature corrosion of super heater tubes enabling the option to use higher steam values (temperature, pressure) improving the power generation efficiency.

- Although these results indicate a clear benefit of bio-CLC over conventional biomass combustion, this phenomenon needs to be studied in more detail for verification.

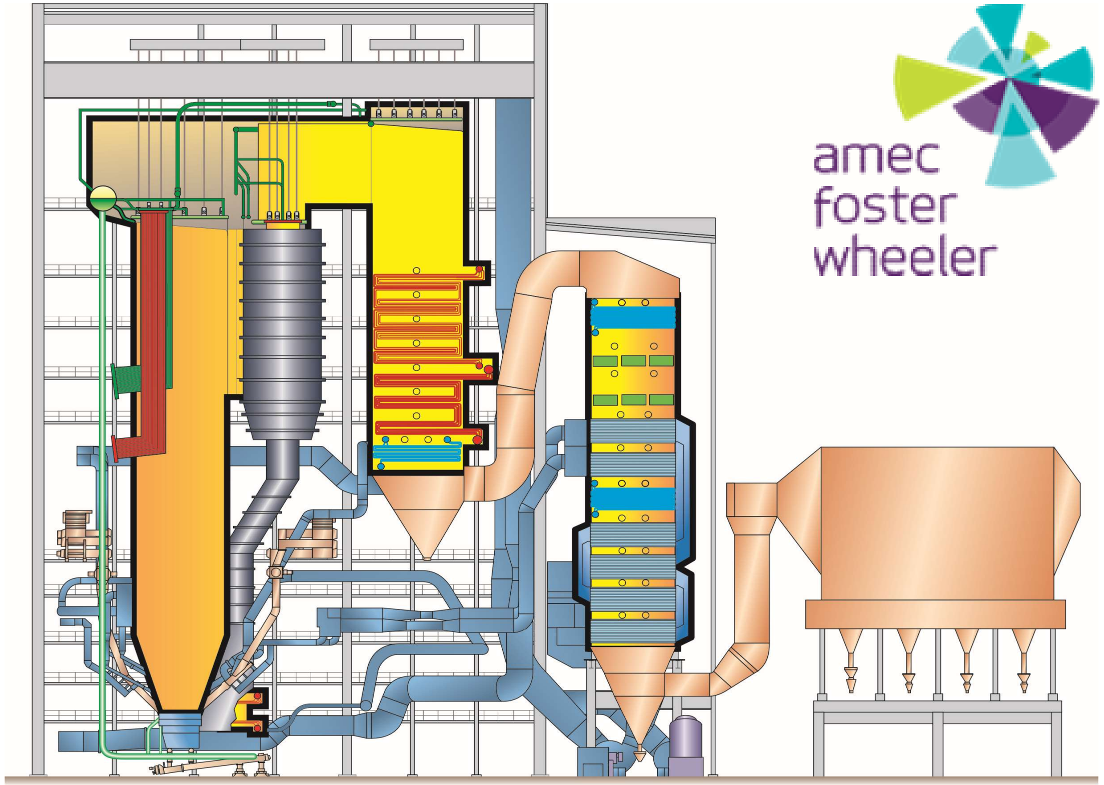
Bio-CLC

- *Bio-CLC could be profitable also without CCS.*
  - It is expected that high-temperature corrosion problems can be significantly reduced in Bio-CLC as compared to conventional biomass combustion.
  - This is because heat will be extracted mainly in the exothermic air reactor, in which there will be no alkali compounds present and very little fly ash.
  - This should allow the use of improved steam data compared to conventional biomass combustion and improved efficiency for power generation.
  - ➢ Hence implementation of Bio-CLC could in fact be economically feasible already before there is an infrastructure for CO_2 transport and storage available.
- *Bio-CLC could be demonstrated in large scale at lower economic risk.*
  - A demonstration plant could be designed so that it would be possible to operate it also as an ordinary CFB boiler.
  - This means that after the demonstration period, the unit could be operated in CFB mode if its performance in CLC mode is unsatisfactory.
  - ➢ This would reduce the economic risk of such a venture greatly, if there is need for a utility on the demonstration site.

World's Largest CFB Firing 100 % Biomass

Polaniec, Poland, 569 t/h, 447 MW_{th}

- Customer: GDF Suez Energia Polska
- Plant start-up: Q4, 2012
- Fuels: Wood biomass + max 20 % high-alkaline agro biomass
- Design features:
  - CFB furnace 24 m x 7.6 m x 43 m
  - Three steam-cooled separators
  - Step grid
  - Additive feeding systems
  - INTREX SH 3 & RH 2



Electrical output, gross/net	**MW_e**	**205/190**
Net efficiency, LHV/HHV	**%**	**36.5/31.4**
Steam flow rate, SH/RH	**kg/s**	**158/135**
Steam pressure, SH/RH	**bar, g**	**126/19**
Steam temperature, SH/RH	**°C**	**535/535**

Emission		Guarantee	Measured[1]
NO_x	mg/m^3n	150	140
SO_2	mg/m^3n	150	3
CO	mg/m^3n	50	< 5
Dust	mg/m^3n	20	4

1) F. van Dijen, H. Gennart, "The New 200MWe Wood-Fired CFBC at Polaniec/Poland"