Flagship Project Negative CO_2

–

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

Anders Lyngfelt

Magnus Rydén

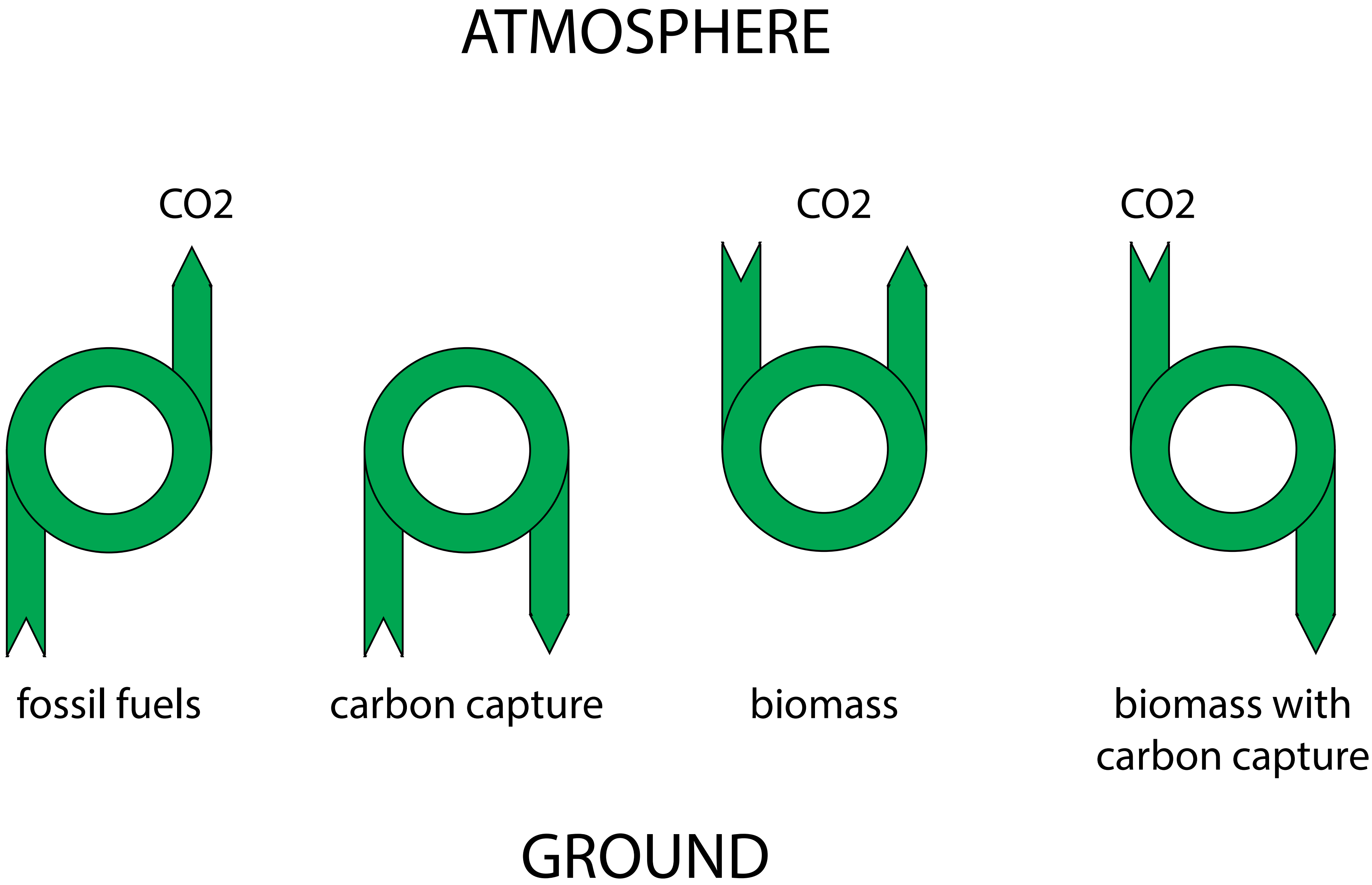
Start-up meeting,
September 25, 2015
Nordic Energy Research,
Oslo

Part 1. Introduction and Background (Anders)

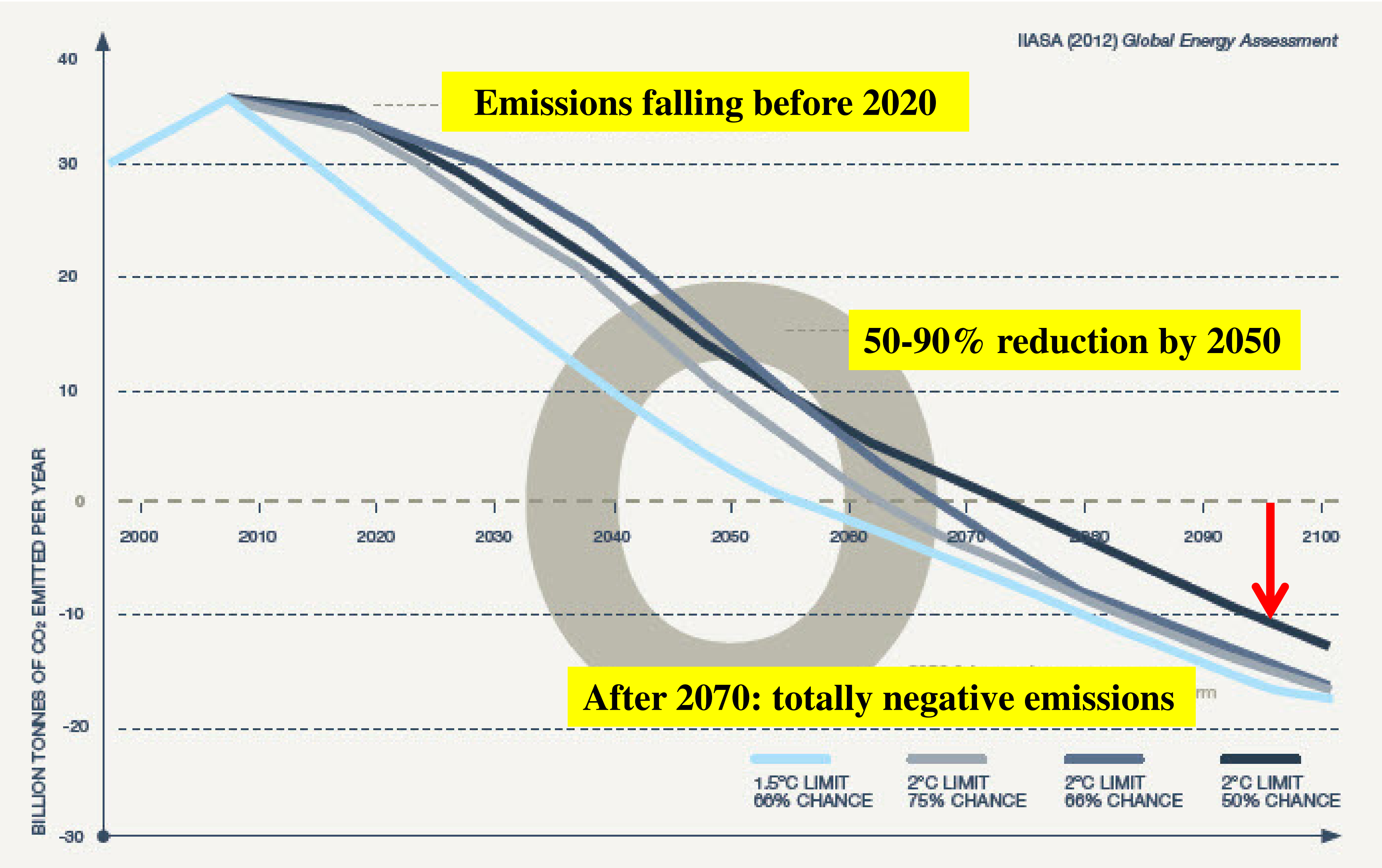
- Why BECCS ?
  - The need for BioEnergy Carbon Capture and Storage
- Why CLC?
  - What’s special with Chemical-Looping Combustion ?
- Why Nordic Countries ?
- Are the costs reasonable ?

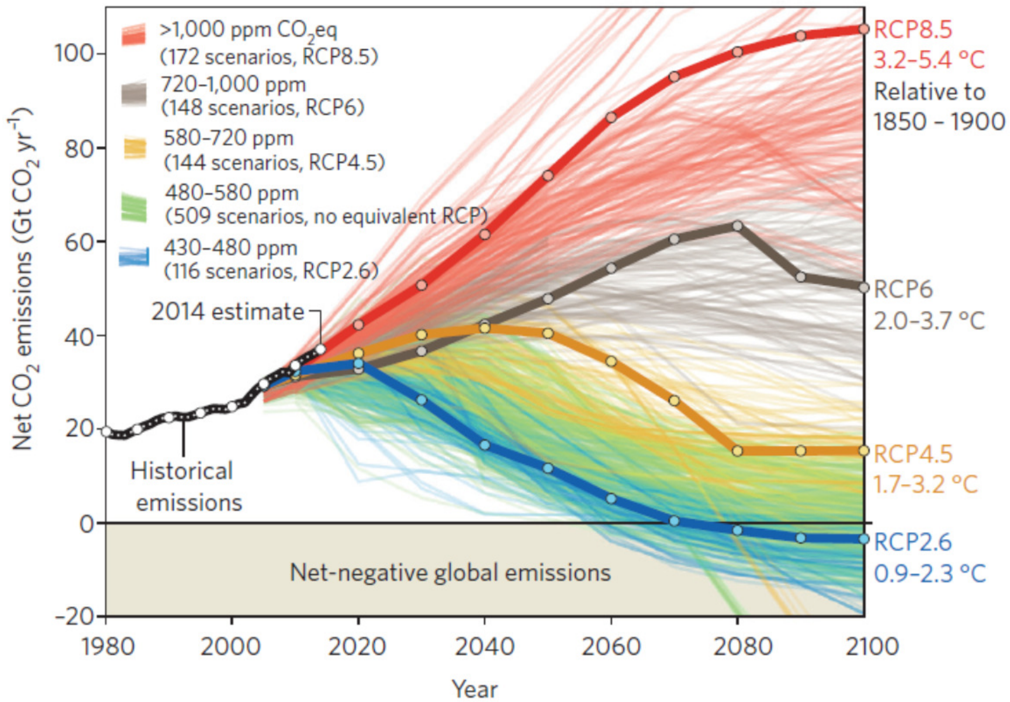
Part 2. Project Description (Magnus)

BECCS (Bioenergy Carbon Capture & Storage)



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.





IPCC report: Models reaching the 2°C target needs (101 of 116):

- **Totally negative emissions beyond 2060-2080, <20 GtCO_2/yr**
- **Negative emissions of 2-10 Gt CO_2/yr already in 2050**

Compare: Biomass 10% of energy supply 2012 (IEA), => 5-6 GtCO_2/yr

From: Fuss et al., Nature Climate Change, 4 (2014) 850-853

CCS status

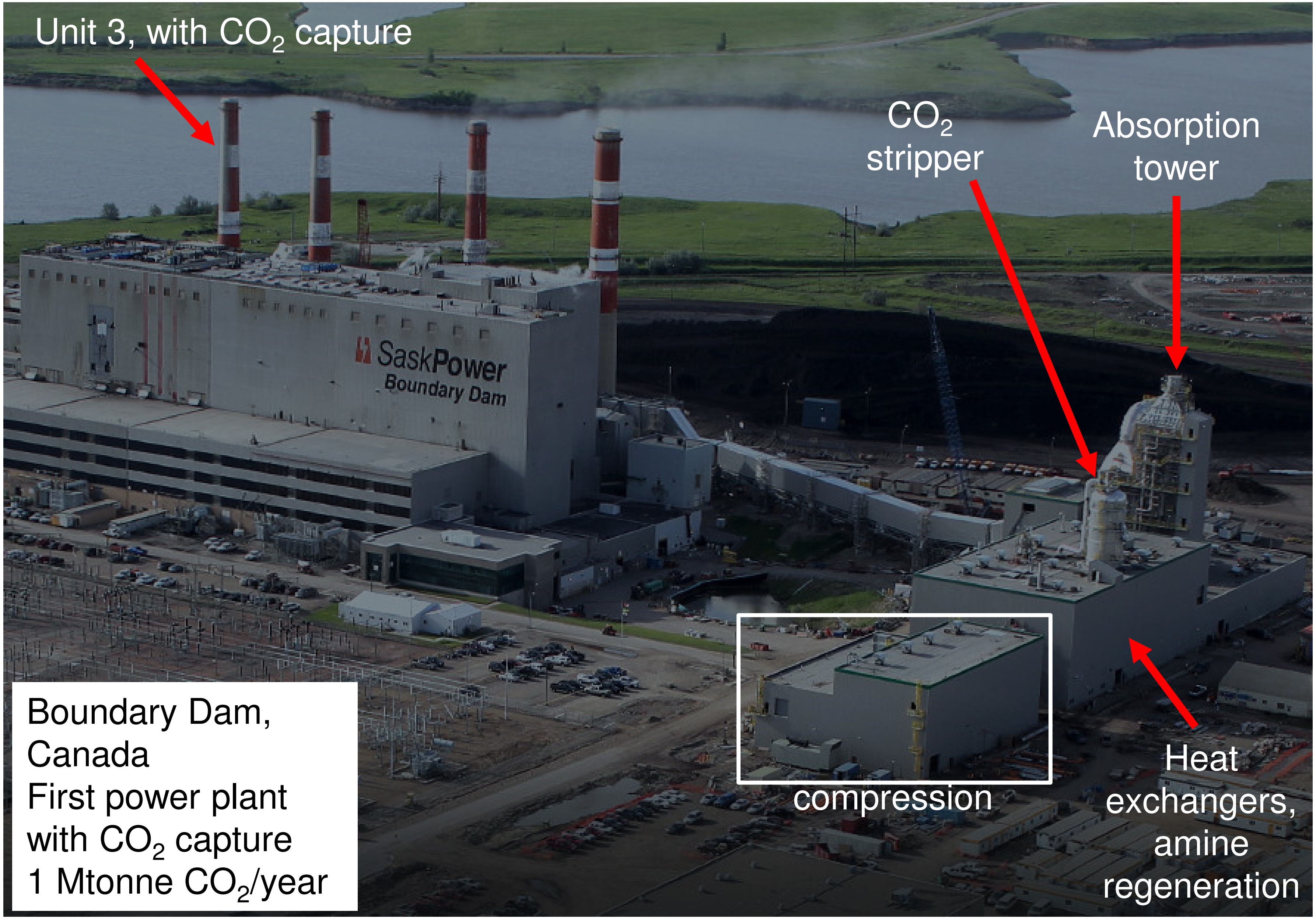
Three main technologies[1], all having

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

- **First commercial large post-oxidation in operation 1 year (Boundary Dam, Canada)**
- **Large-scale precombustion being built (Kemper, US) 2016**
- **Oxyfuel, planned, not decided (White Rose, UK) 2020 ?**

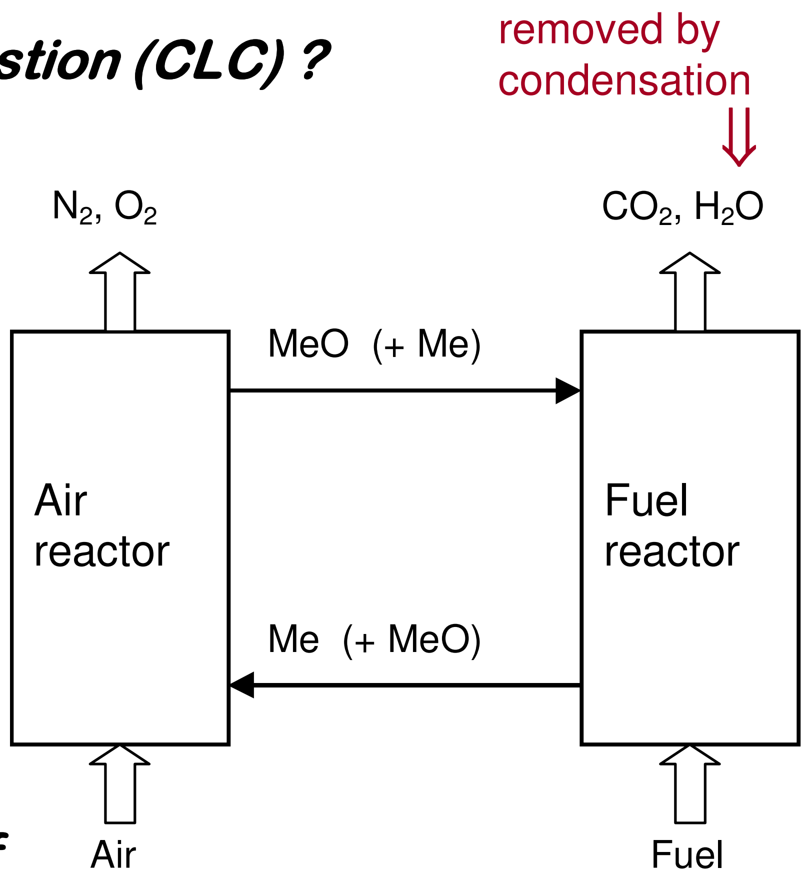
[1] post-, pre- and oxycombustion

Anders Lyngfelt, Chalmers University of Technology



Why chemical-looping combustion (CLC) ?

Oxygen is transferred from air to fuel by metal oxide particles



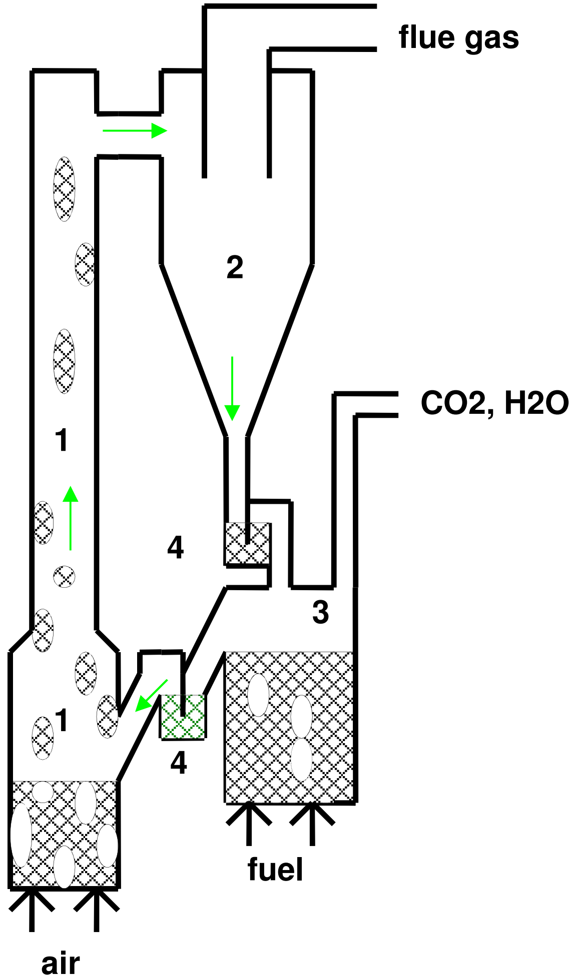
Inherent CO_2 capture:

- **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 ?**

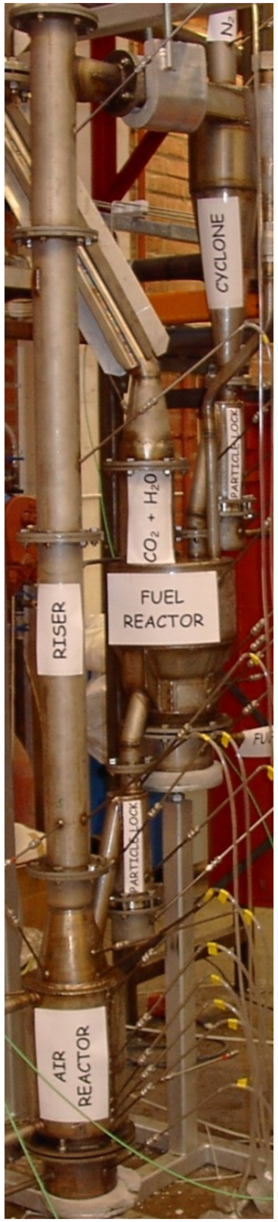
Chalmers' 10 kW gas-CLC, 2003

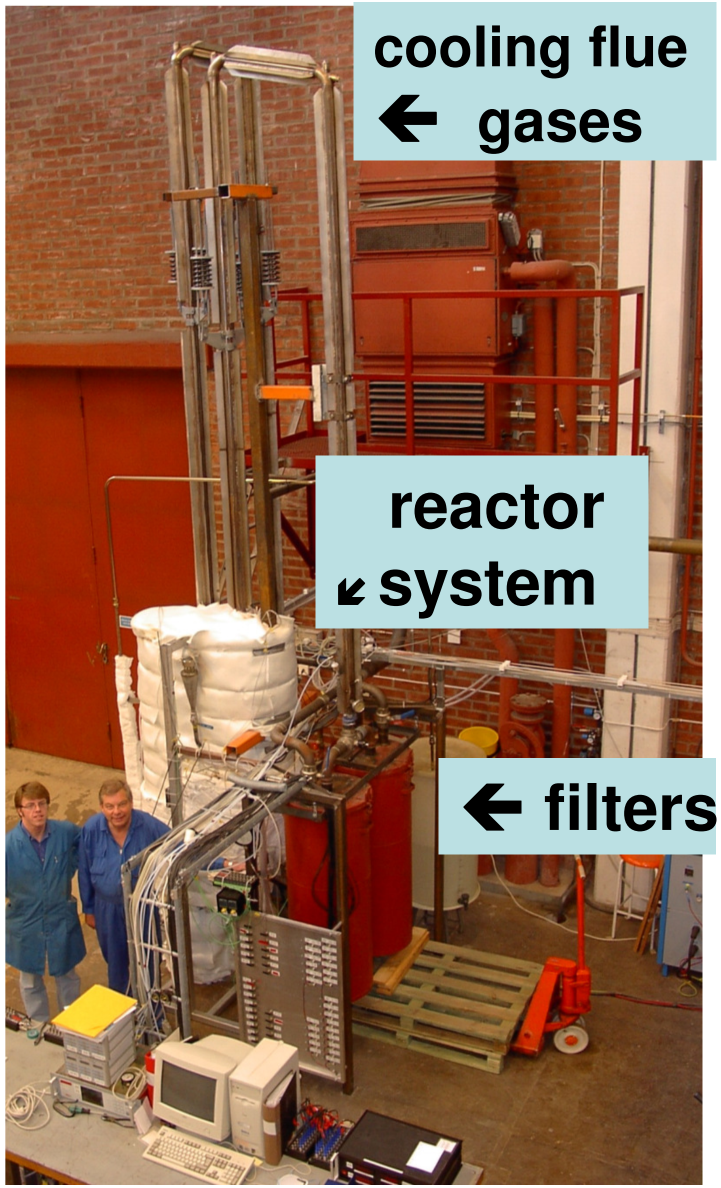


1 air reactor, 2 cyclone

3 fuel reactor, 4 loop seals

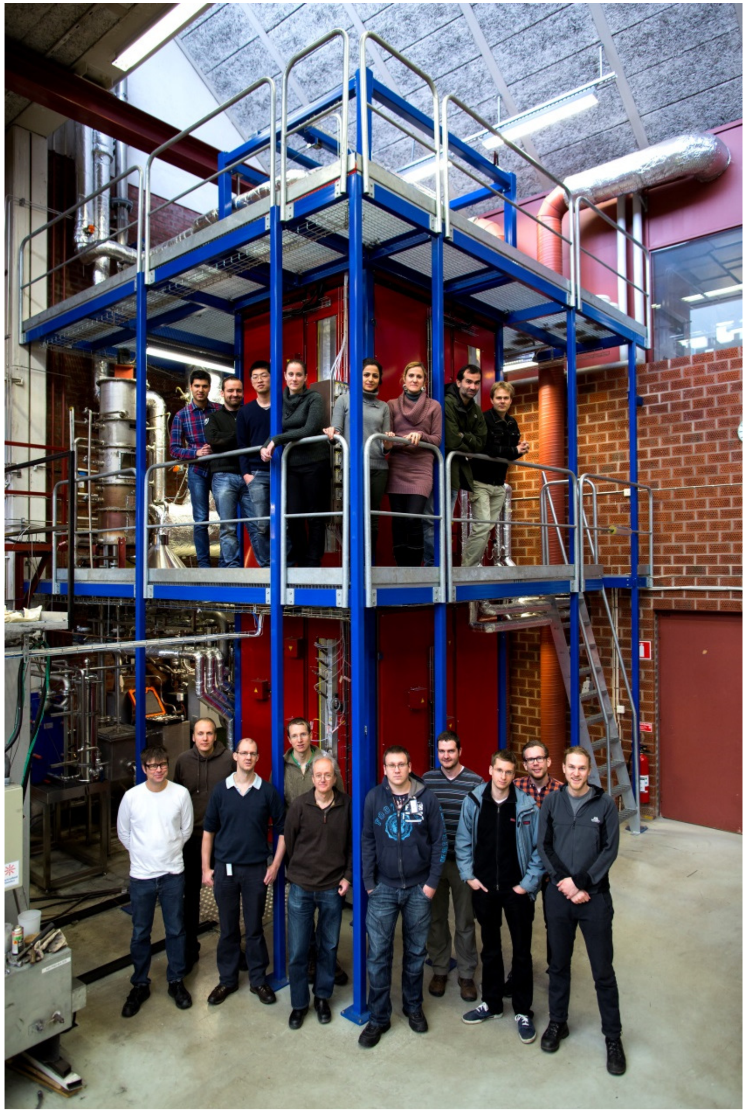
without insulation

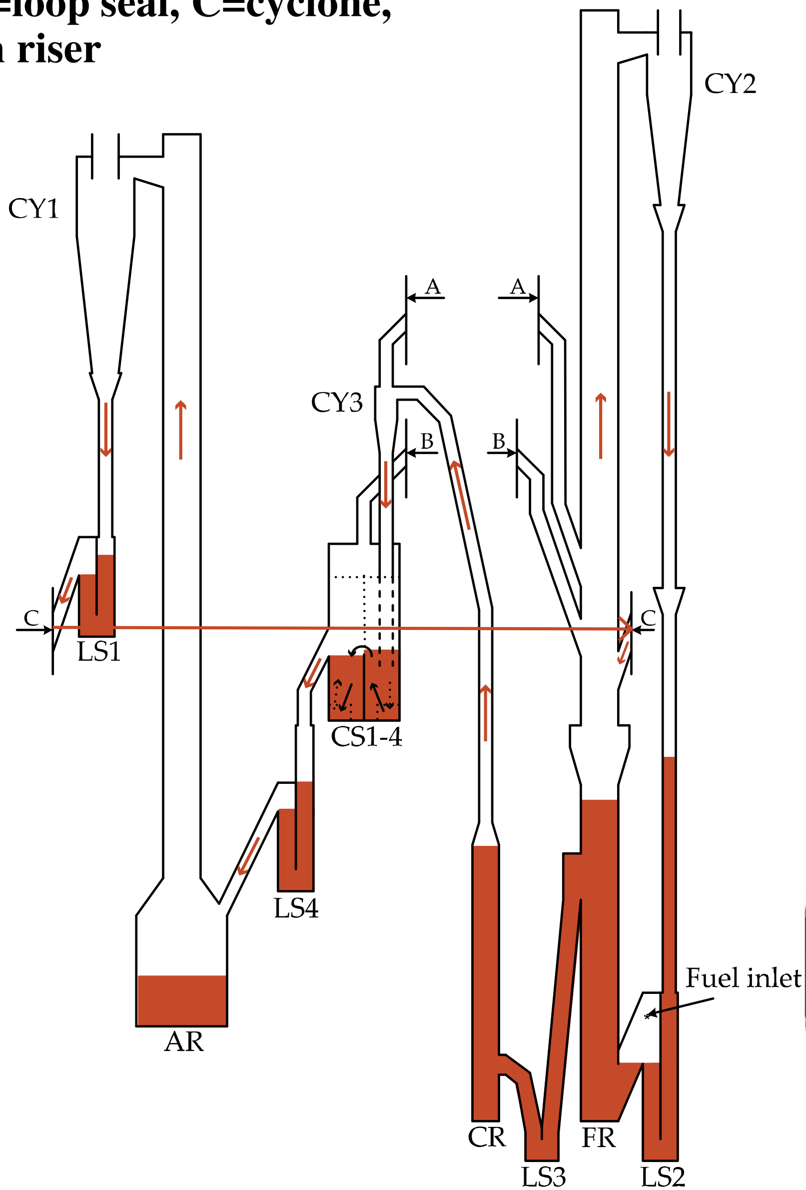


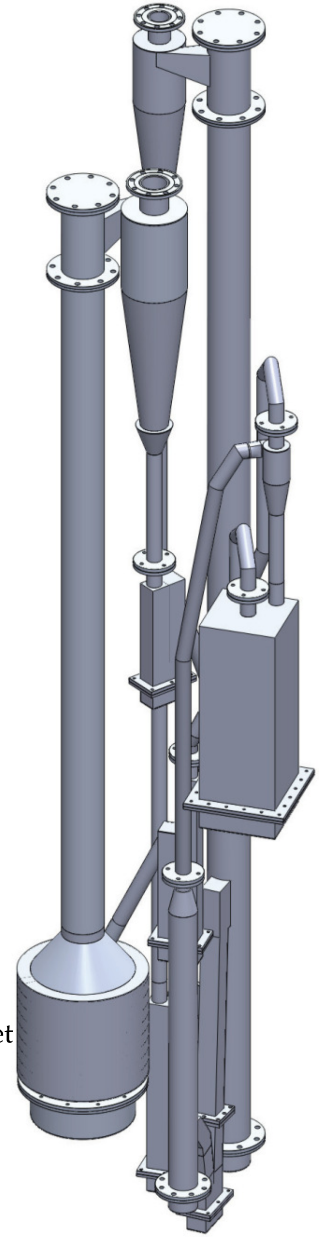


Chalmers’ 100 kW CLC for solid fuel, 2011

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







Where are we ?

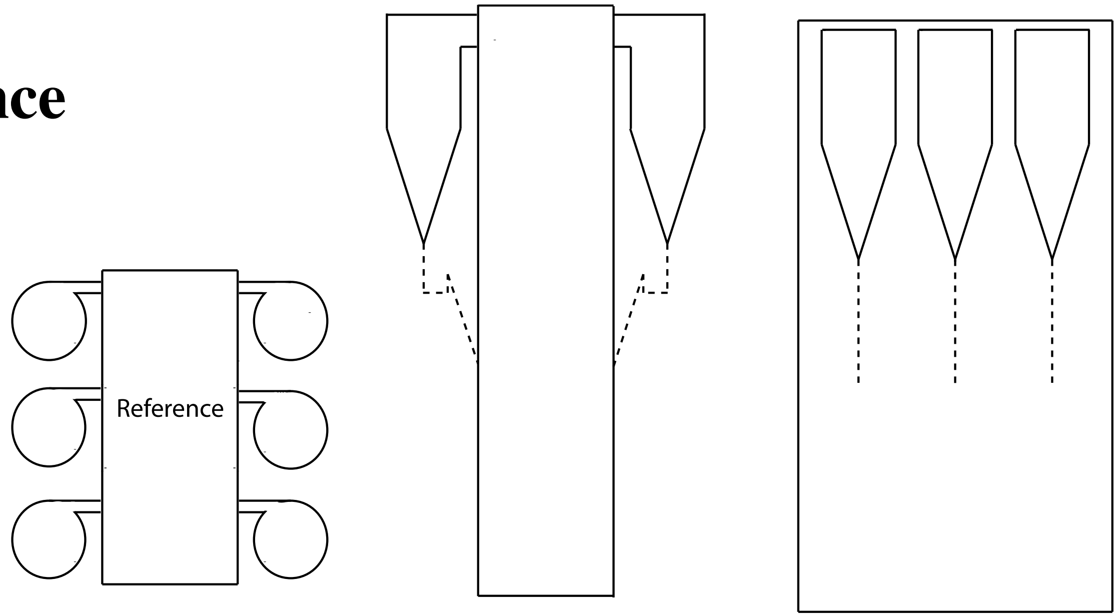
- **CLC operation worldwide**
  - 24 pilots : 0.3 kW – 3 MW
  - >7500 h with >70 oxygen carriers
    - 4400 h at Chalmers with >50 oxygen carriers
- **CLC with solid fuels**
  - Low cost oxygen carriers can be used
  - Incomplete conversion/capture
    - Some oxy-polishing needed, estimate: 5-15%
    - Up to 98% CO_2 capture attained
  - 400 h operation at Chalmers (10 kW and 100 kW)

1000 MW_{th} reference CFB:

Depth 11 m

Height 48 m

Width 25.5



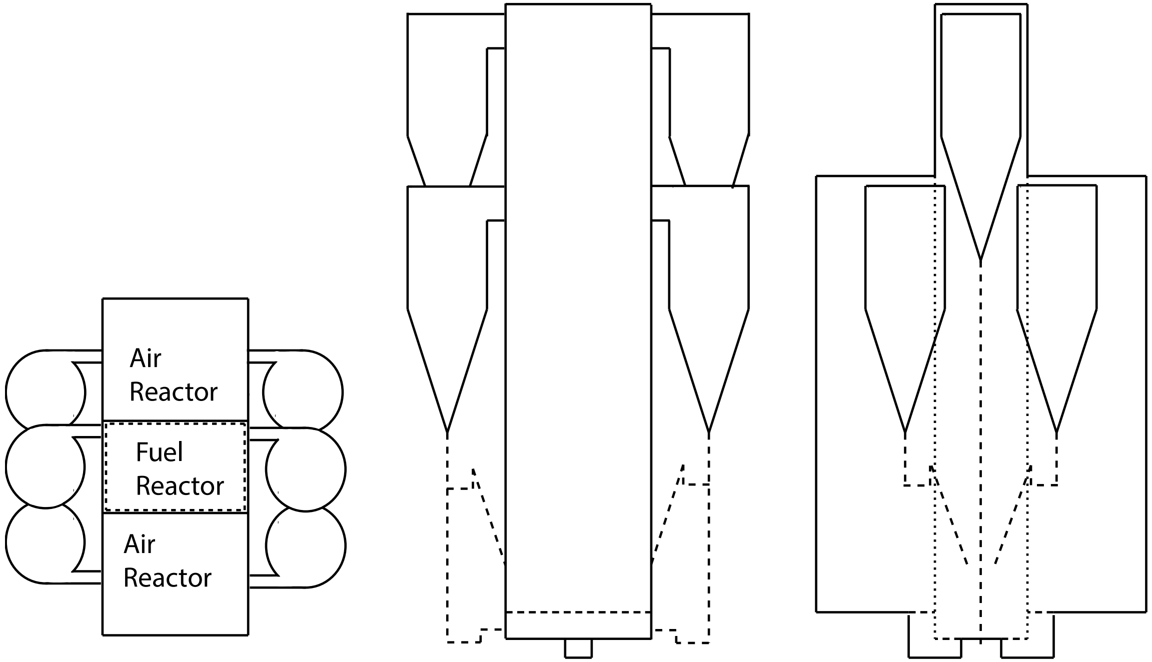
1000 MW_{th} CLC:

Depth 11 m

Height 48 m

Width 25

- fuel reactor:
  - 11×7 m



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)*

Detailed cost analysis of CLC, based on difference with CFB

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

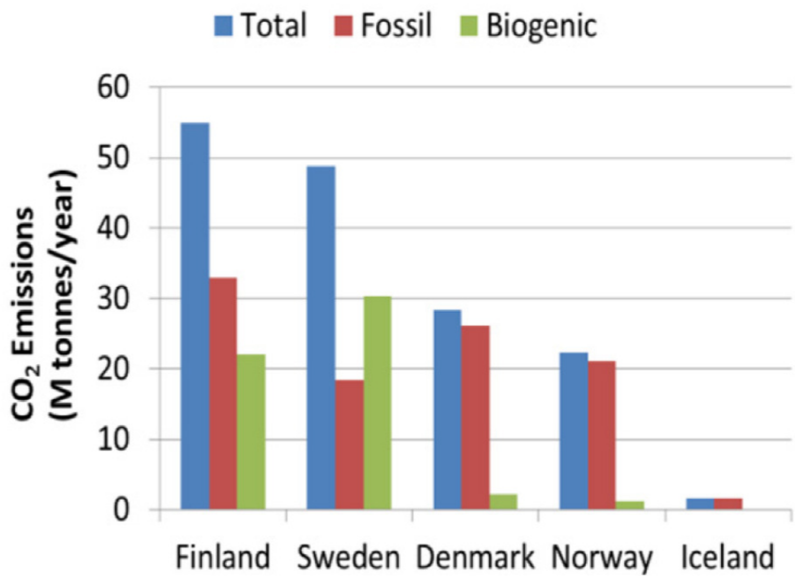
From:
Lyngfelt, A., and Leckner, B., A 1000 MWth Boiler for Chemical-Looping Combustion of Solid Fuels - Discussion of Design and Costs, *Applied Energy* in press *(available on-line)*

Estimated cost of CLC, less than half of competing technologies

Should be suitable for biomass.

- larger biomass boilers normally use CFB technology

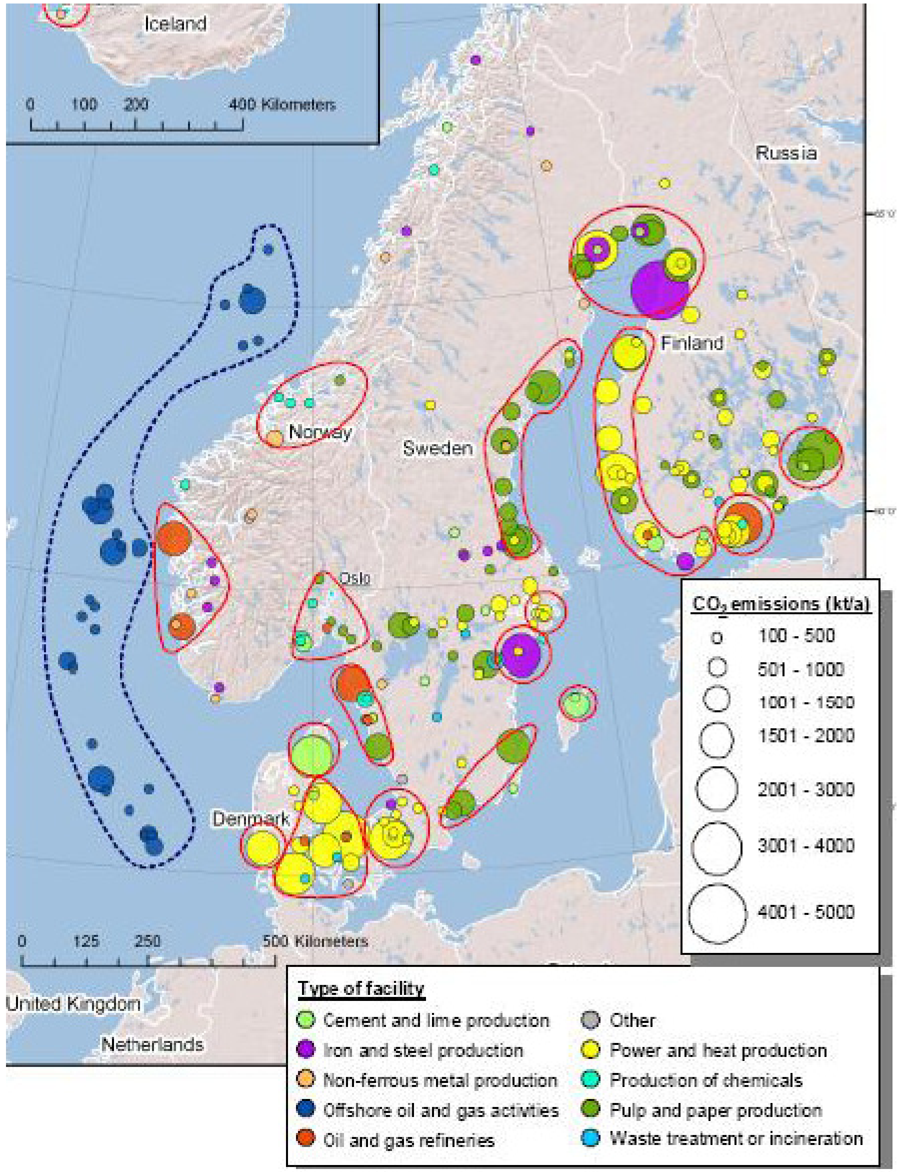
CO_2 capture and storage in Nordic countries



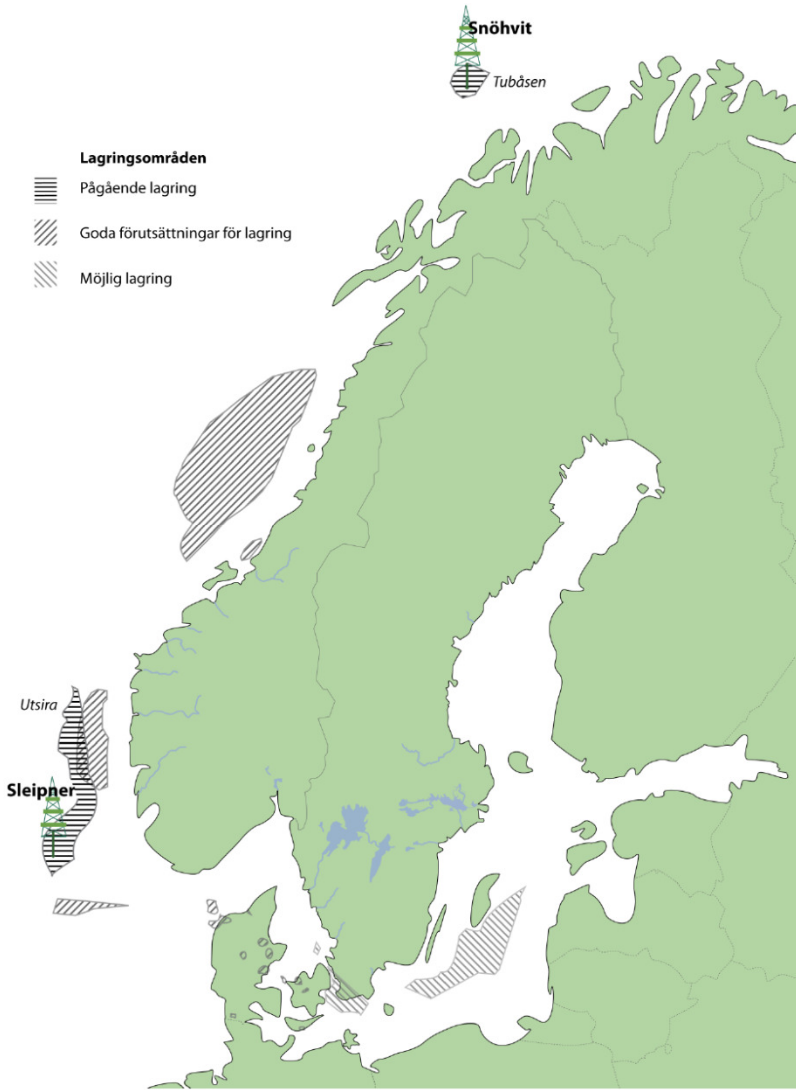
CO_2 emissions, sources >100 000 tons/year

>50 Mt/year biogenic

total Nordic fossil CO2 emissions 200 Mt/year



potential storage locations



CO_2 biofuel point sources

Baltic Sea: storage <15 000 Mt, uncertain

Nordic countries and BECCS

- 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”
- Moral: we are rich, if we cannot afford it who can ?

What is a reasonable cost ?

carbon intensity ≈ 1 kg CO_2/€   (EU half of that)

=>

”avoidance cost” much less than 1 €/kg CO_2

Thus, avoidance cost < 0.1 €/kg CO_2

leads to cost <10% of GDP

Avoidance costs <0.1 preferred !!!

CCS costs in relation to other mitigation costs

	€/kg CO_2
<u>Avoidance costs CCS:</u>	
CO_2 storage	>0.002
CO_2 transport	>0.002
CO_2 capture & storage	0.05
Östersjöprojektet	0.03-0.07
CLC with solid fuels (?)	0.02
<u>INCENTIVES:</u>	
<u>example fuel cost:</u>	
petrol, 11:50 kr/L	0.50
coal, 600 kr/ton	0.02
Swedish CO_2 tax	0.125
Example ”Swedish climate Programme” (*cost!*) [1]	0.34
Example ”CO_2 free vehicle fleet” (3-fold rise in petrol price) [2]	1.2

[1] Riksrevisionen, *(The Swedish National Audit Office) Biodrivmedel för bättre klimat, RiR 2011:10.*

[2] Konjunkturinstitutet, *(National Institute of Economic Research, NIER, Sweden) Miljö, ekonomi och politik 2013*.

Conclusions

- **BECCS will be needed in large scale to meet climate targets**
- **CCS has reasonable costs**
- **Nordic countries are very suitable for developing BECCS**
- **CLC has unique potential for dramatically reduced cost of CO_2 capture**

Questions ?

>270 publications on chemical-looping on:
http://www.entek.chalmers.se/lyngfelt/co2/co2publ.htm

Oslo 2015-09-25
Presentation of Nordic Energy Research Flagship Project:

Negative CO_2

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

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Project aims

Primary objectives

- Take Bio-CLC to the next level of development, enabling up-scaling to semi-commercial scale (10-100 MW_{th}).
- Provide a realistic plan for how a semi-commercial demonstration plant can be funded, built and operated in the Nordic countries.

Secondary objectives

- Answer specific research questions and improve knowledge in areas related to work package activities, as will be outlined below.
- Build a strong and dedicated research alliance, devoted to the development and realization of Bio-CLC and BECCS in the Nordic countries.

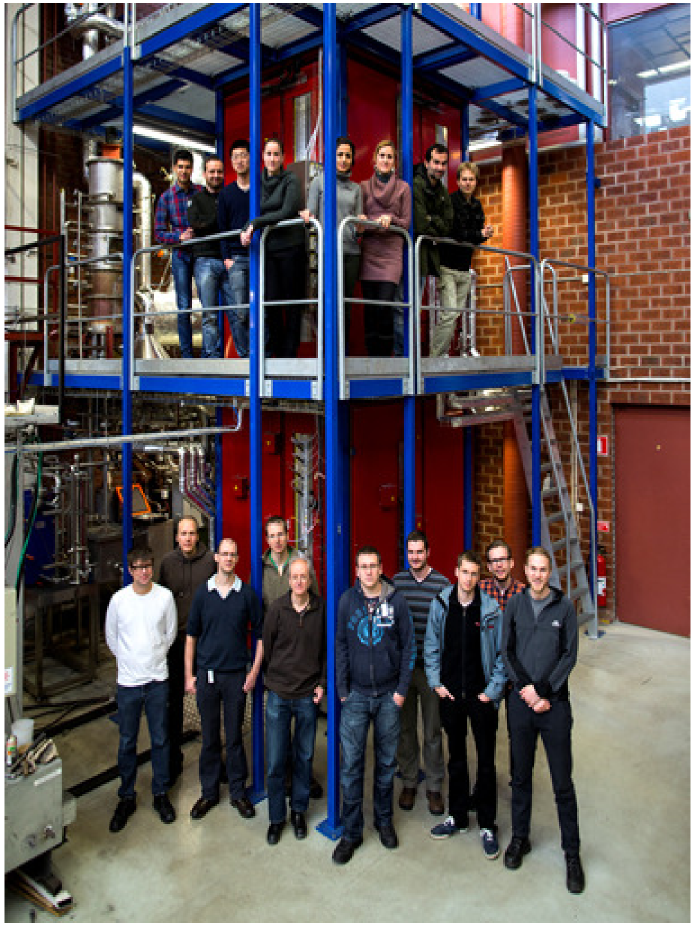
Project Partners

	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

Chalmers University of Technology

CHALMERS

- Key persons:
  - Prof. Anders Lyngfelt
  - Assoc. Prof. Magnus Rydén
  - Prof. Klas Andersson
- Key competences
  - Chemical-looping combustion and oxygen carriers (>250 publications, >14 examined PhD, >40% of global pilot plant operation experience).
  - Fluidization, combustion and gasification of biomass, flue-gas cleaning, SO_x NO_x chemistry.
- Main activities
  - Management and coordination, leader of WP1.
  - Leader of WP4 on flue gas cleaning.
  - Bio-CLC experiments in 100 kW pilot unit.
  - Demonstration at semi-commercial scale.
  - Procurement of oxygen carrier materials (with support of Sibelco Nordic AB).

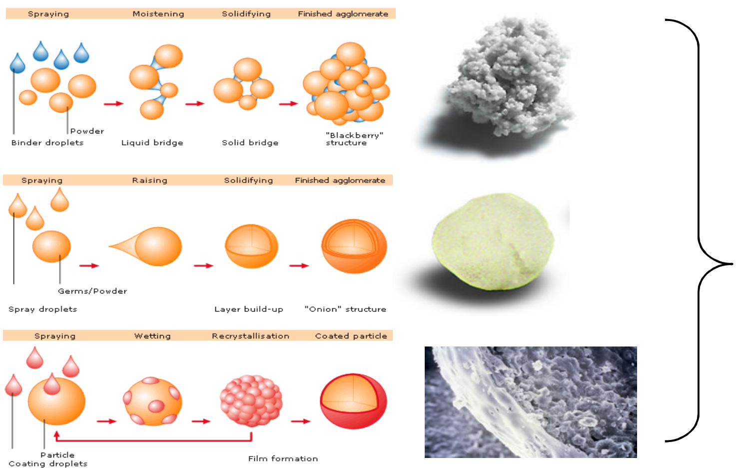


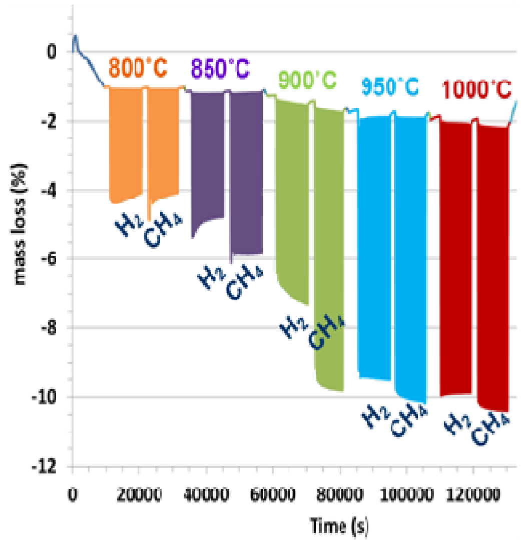
The Bellona Foundation

- Key persons:
  - Mr. Hallstein Havåg
  - Mrs. Sirin Engen
  - Mr. Keith Whiriskey
  - Mrs. Marika Andersen
- Key competences
  - First environmental non-governmental organization to engage with CCS and to champion the need for negative CO_2 emissions to meet climate targets.
  - Communication and policy making for bioenergy and CCS.
- Main activities
  - Leader of WP8 on dissemination.
  - Communication activities i.e. presentations, leaflets, branding, web portal, audio visual material, social media engagement, representation to stakeholders, relevant networks, events, round-table discussions, panels along with specialist and generalist publications.
  - Designated key contributions to implementation, upscaling and energy system analysis.

SINTEF Materials and Chemistry

- Key persons:
  - Dr. Yngve Larring
  - Dr. Mehdi Pishahang
  - Dr. Tommy Mokkelbost
- Key competences
  - Material chemistry in general.
  - Formulation, optimization and characterization for energy related technologies.
  - Material production on small to semi-industrial scale.
- Main activities
  - Leader of WP3 on oxygen carrier materials.
  - Procurement, development and evaluation of oxygen-carrier materials.
  - Material characterization and analysis.



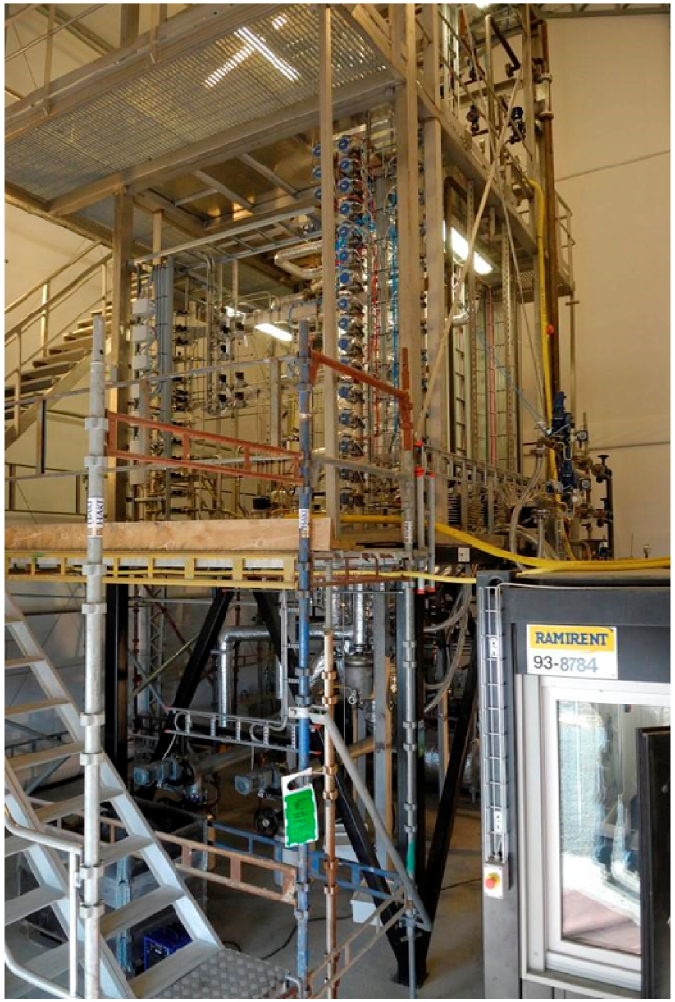


SINTEF Energy Research

- Key persons:
  - Mr. Øyvind Langørgen
  - Dr. Inge Saanum
  - Dr. Jørn Bakken

- Key competences
  - Combustion, CCS processes, oxy-fuel and hydrogen combustion, chemical looping combustion, bioenergy, simulation and technical assessment of thermal process systems.

- Main activities
  - Leader of WP2 on pilot plant operation.
  - Bio-CLC experiments in 150 kW pilot unit.
  - Development of flue gas treatment based on experience from oxy-fuel combustion.
  - Process analysis and upscaling, having a central position in the European Benchmarking Task Force on CCS.



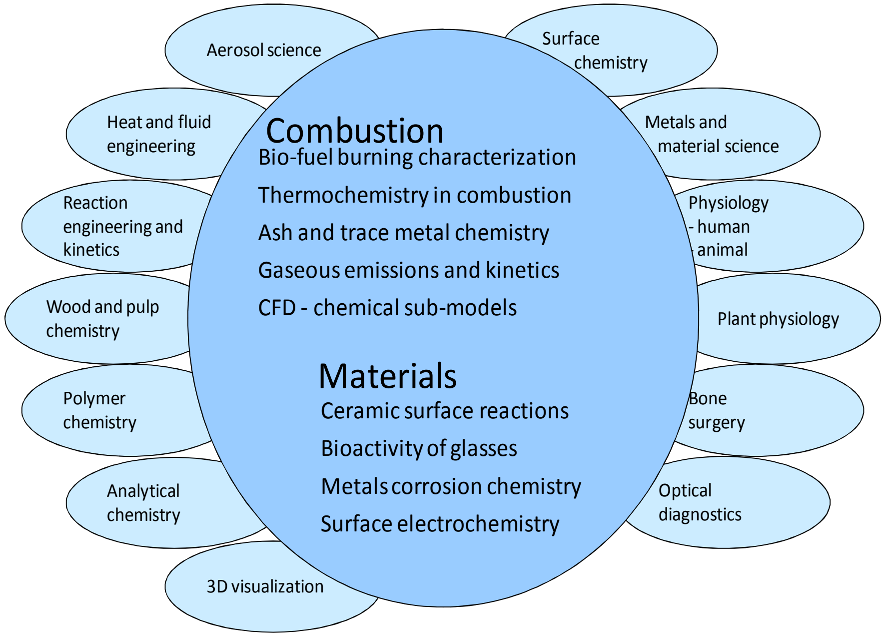
VTT Technical Research Centre of Finland Ltd

- Key persons:
  - Dr. Sebastian Teir
  - Mr. Toni Pikkarainen
  - Mr. Tomi J Lindroos
  - Mr. Juha Lagerbom
- Key competences
  - Fluidized bed process expertise (pyrolysis, gasification, combustion, oxy-fuel combustion, experimental & modeling).
  - Energy system modeling & scenario analyses.
  - Material technology.
- Main activities
  - Leader of WP6 and WP7, i.e. upscaling, implementation and energy system analysis.
  - Techno-economic evaluation of bio-CLC.
  - Role of Bio-CLC in a low-carbon future Nordic energy system.
  - Bio-CLC technology testing & development at VTT's new BioRuukki piloting center.
  - Chemical endurance of oxygen carriers.

Åbo Akademi University

Åbo Akademi

- Key persons:
  - Dr. Maria Zevenhoven
  - Prof. Anders Brink
- Key competences
  - Combustion and material chemistry.
  - Fuel and ash characterization.
  - Biomass conversion.
- Main activities
  - Leader of WP5 on ash chemistry and corrosion.
  - Interactions between oxygen carrier materials and biomass ash.
  - Corrosion tests of reactor materials
  - Measurements of release of ash forming elements.



Advisory Board

Organization	Country
Alstom Power AB	Sweden
Andritz Oy	Finland
Foster Wheeler Energia	Finland
Elkem AS	Norway
Sibelco Nordic AB	Sweden
Titania A/S	Norway
E.ON Sverige AB	Sweden
Fortum Oyj	Finland
Göteborgs Energi	Sweden
AKZO Nobel	Sweden

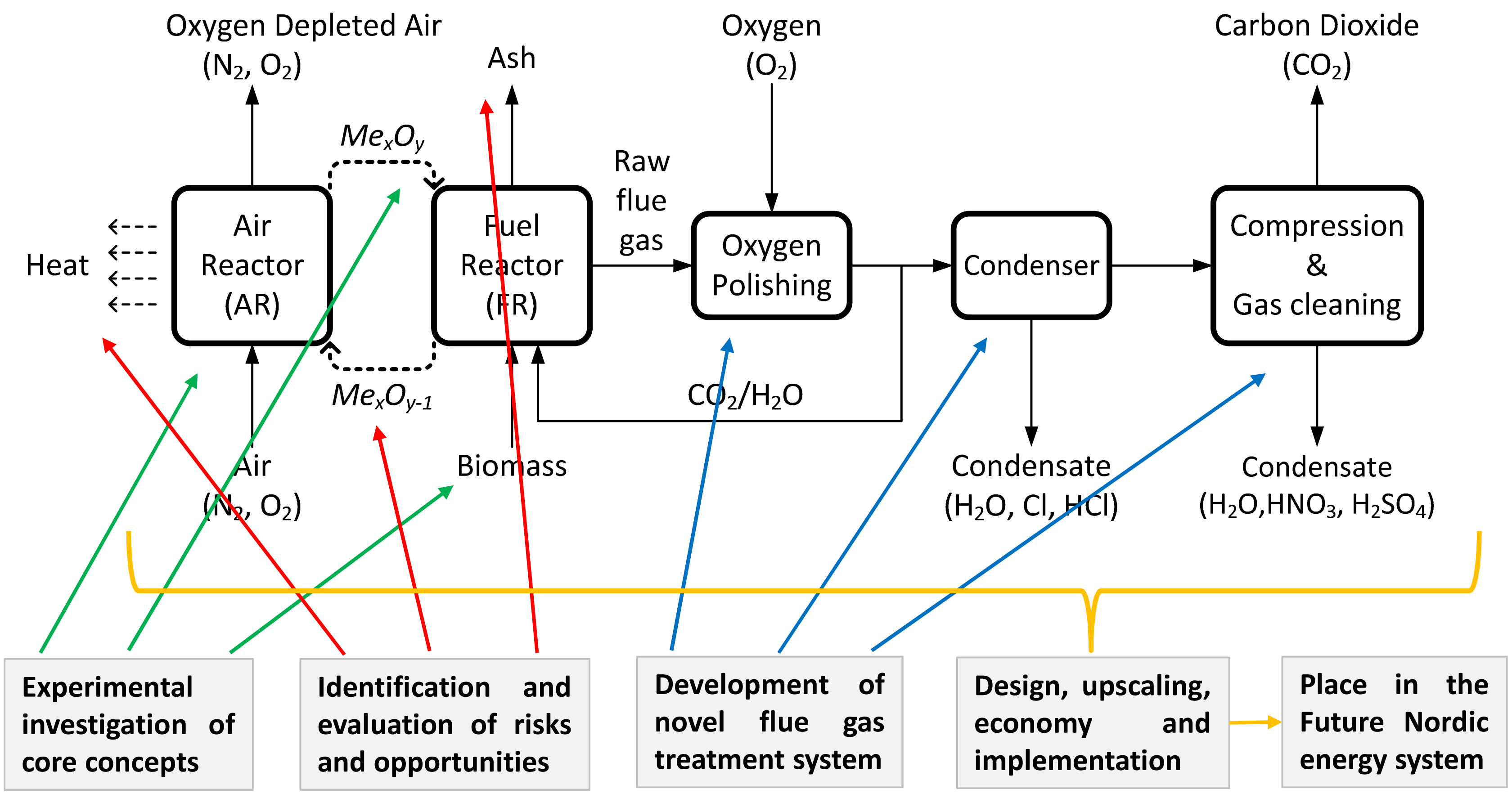
Manufacturers of circulating fluidized bed boilers, equipment for biomass utilization and energy infrastructure in general. Especially Alstom and Andritz have also shown great interest in chemical-looping combustion.

Providers of industrial materials suitable as oxygen carriers for chemical-looping combustion. Covers the range from raw ores to advanced synthetic particles.

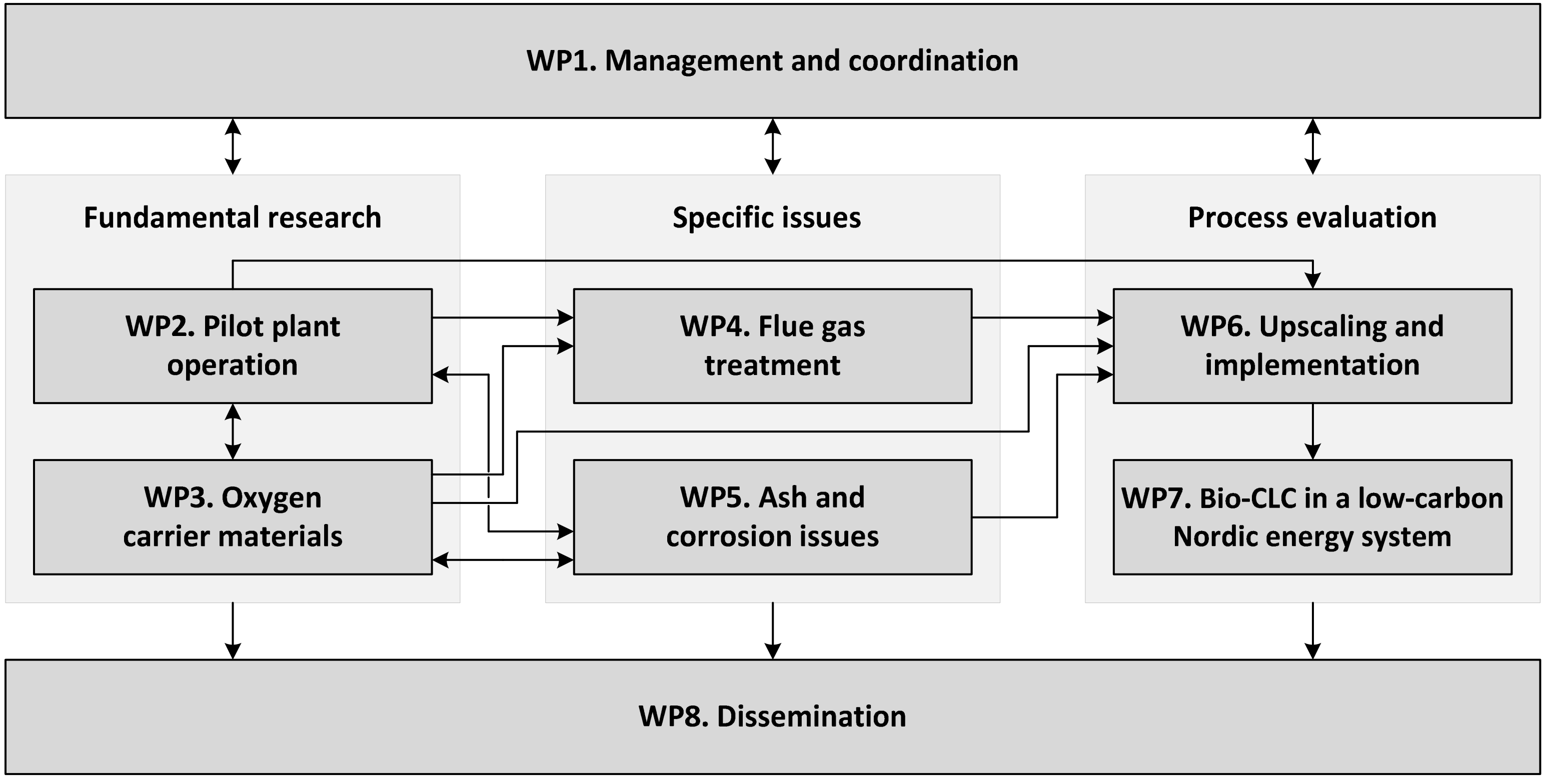
Providers of power and heat and potential end-users. E.ON and Fortum operates numerous fluidized bed boilers. Göteborgs Energi operates a unique fluidized bed facility in the GoBiGas 30 MW_{CH4} biomass gasifier.

Supplier of specialty chemicals. Has interest in novel flue-gas cleaning concepts for carbon capture applications

Research questions



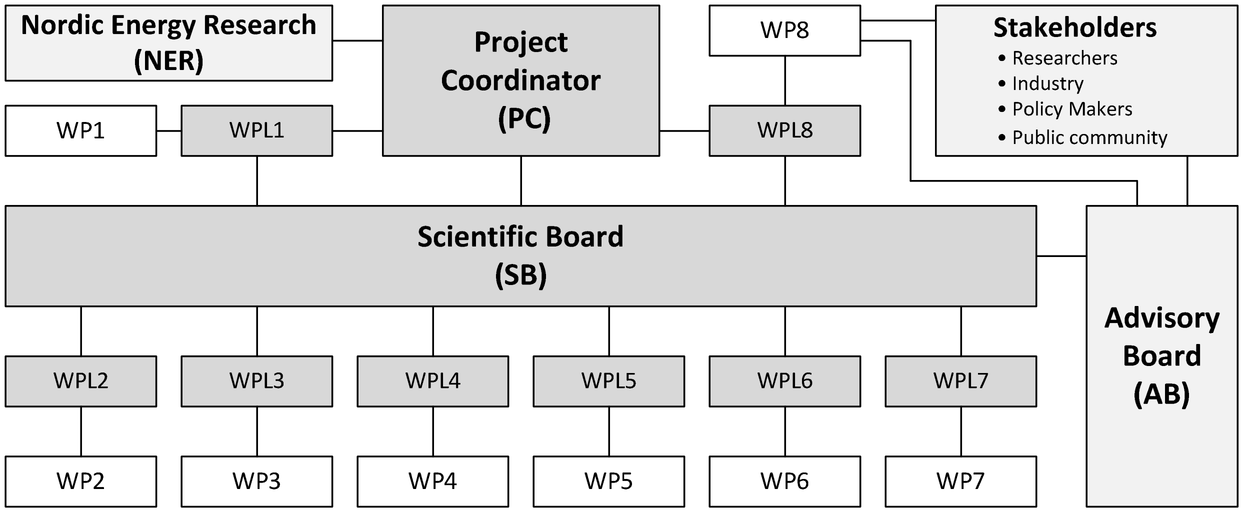
Project Plan



WP1 - Management and coordination

Involved partners: Chalmers, SINTEF ER, SINTEF MC, VTT, Åbo Akademi, Bellona
Work Package Leader: Anders Lyngfelt, Chalmers

- Establishment of Scientific Board, Advisory Board and Consortium Agreement.
- Organization of meetings, day to day management and coordination of work packages.
- Facilitate Nordic network-building.

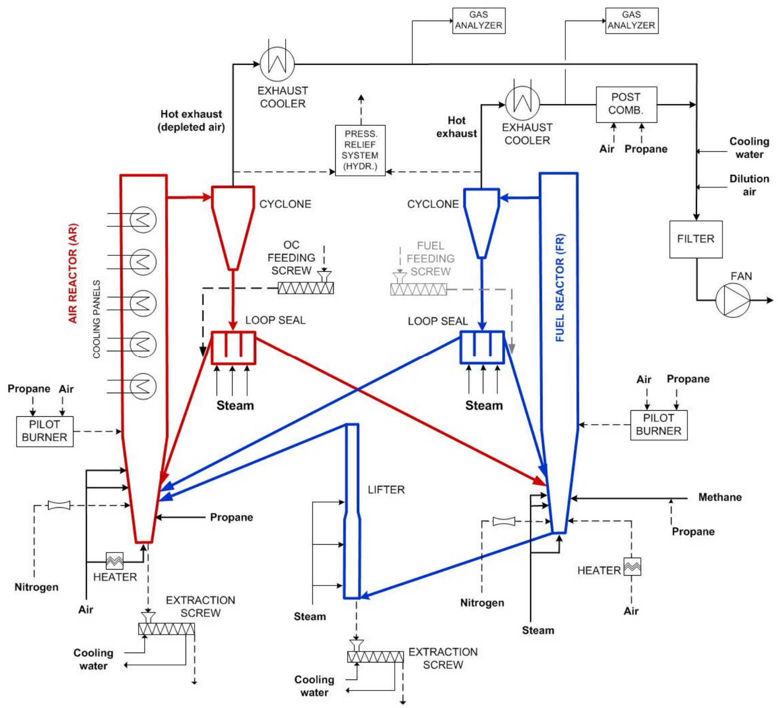


WP2 - Pilot plant operation

Involved partners: SINTEF ER, VTT, Chalmers, Sibelco
Work Package Leader: Øyvind Langørgen, SINTEF ER

WP2 involves practical experiment in three unique pilot units (150 kW at SINTEF ER, 100 kW at Chalmers, 50 kW at VTT).

- Study effect of reactor design, choice of oxygen carrier, process parameters and fuel properties.
- Start with ilmenite oxygen carrier, later campaigns with materials from WP3.
- Main output will be gas conversion, char burnout and attrition behavior of oxygen carrier.
- Vital activity for the development of technical and economic models and process scale-up.

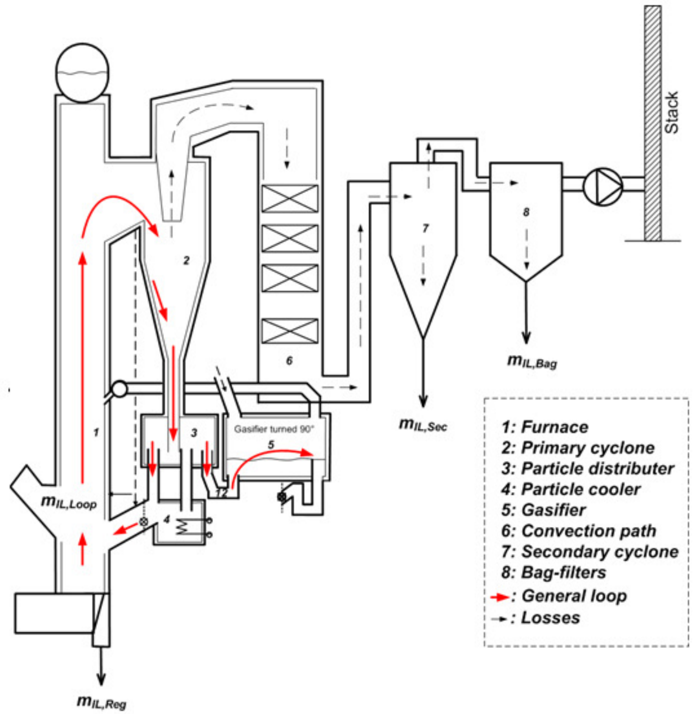


WP2 - Pilot plant operation (continued)

Involved partners: SINTEF ER, VTT, Chalmers, Sibelco
Work Package Leader: Øyvind Langørgen, SINTEF ER

Also included in WP2 is demonstration in semi-commercial CFB research boiler at Chalmers.

- Demonstration of the concept at conditions relevant for industrial applications with respect to factors such as gas velocities, attrition of bed material, ash and solids handling etc.
- Demonstration of large-scale handling and logistics of oxygen carrier particles (>10 tonnes).

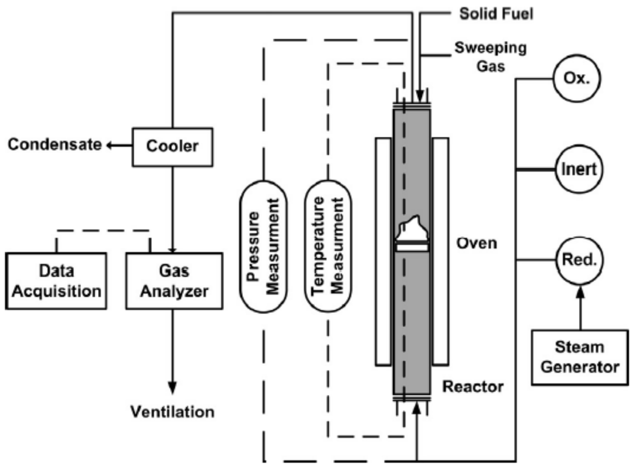


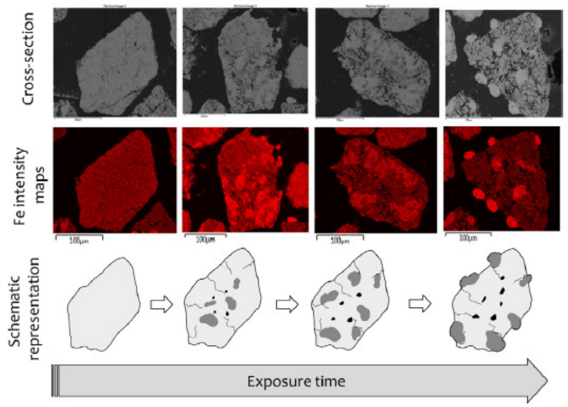
WP3 - Oxygen carrier materials

Involved partners: SINTEF MC, Chalmers, VTT, Sibelco
Work Package Leader: Yngve Larring, SINTEF MC

WP2 involves selection, examination and characterization of oxygen carrier materials for Bio-CLC in laboratory scale experiments.

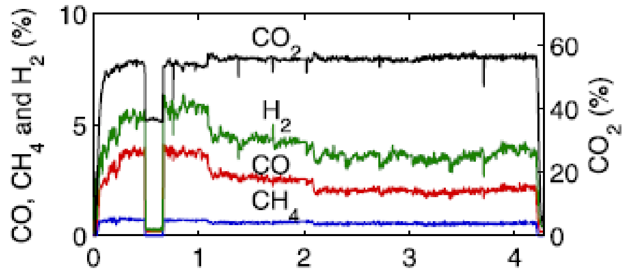
- Impact of using biomass as fuel in CLC currently not well understood. Compared to coal biomass has higher volatiles content, more reactive char residue, less sulphur and different ash composition.
- A range of methods will be used (TGA, DTA, XRD, SEM/EDX, redox experiments in batch fluidized bed, artificial aging, attrition testing).
- Goal is to identify suitable, available and affordable materials and verify their properties.
- Closely integrated with WP2 and WP5.

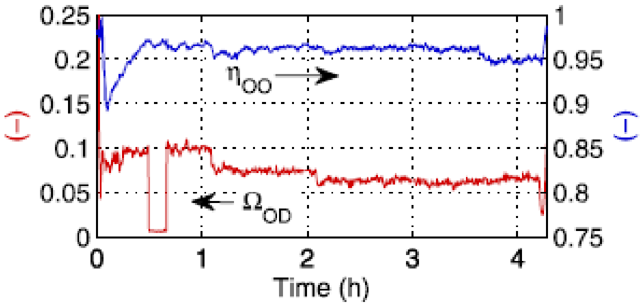


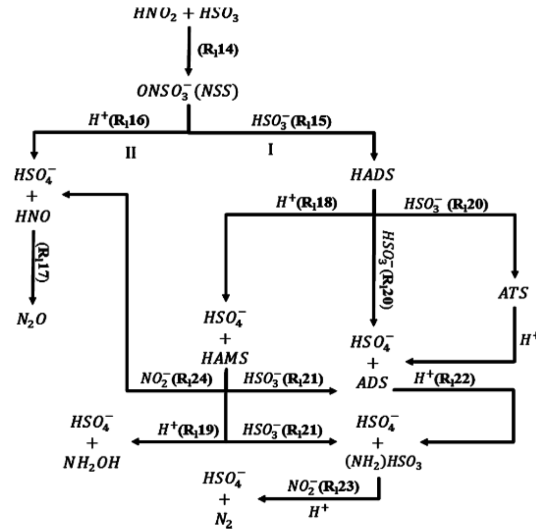


WP4 - Flue gas treatment

Involved partners: Chalmers, SINTEF ER
Work Package Leader: Klas Andersson, Chalmers







This work package involves the development and design of an efficient flue gas treatment system for Bio-CLC capable of converting raw flue gas to compressed CO_2.

- Some combustibles will remain in the flue gas leaving the fuel reactor. Hence an oxy-combustion step is needed to reach full conversion to CO_2 and H_2O.
- Oxy-polishing reactor will be integrated with Chalmers 100 kW pilot, will be tested and evaluated in WP2.
- No N_2-dilution of the flue gas, CO_2 storage requires low temperature and compression. At these conditions both NO_x and SO_x can potentially be captured in the form of acids in the liquid condensate.
- Novel concept that will be examined in a combined modelling and experimental approach.

WP5 - Ash and corrosion issues

Involved partners: Åbo Akademi, VTT, Chalmers
Work Package Leader: Maria Zevenhoven, Åbo Akademi

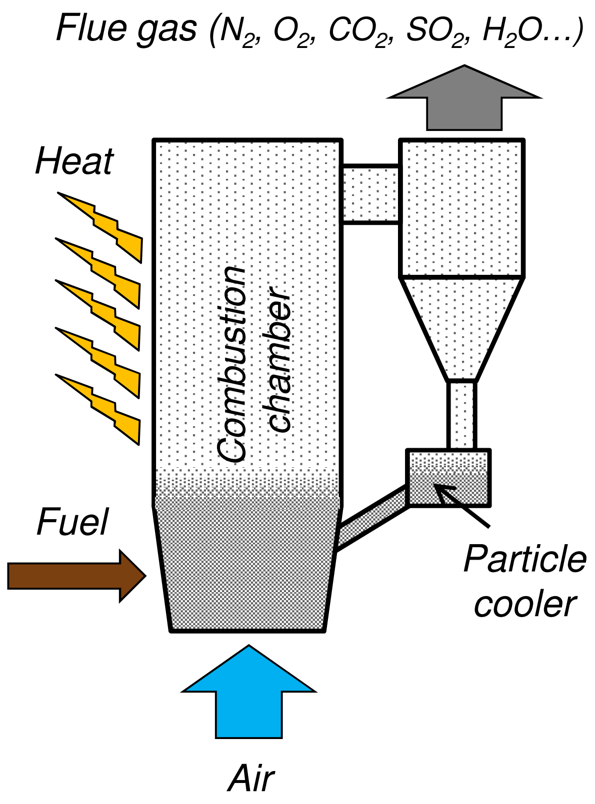
Ash handling and associated corrosion issues is a critical aspect in all biomass applications. Bio-CLC will provide both opportunities and challenges in this area. WP5 involves the following activities:

- Chemical interaction between oxygen carriers and biomass ash, especially at reducing conditions.
- A range of methods will be used (TGA, DTA, XRD, SEM/EDX).
- Ash removal, possibly by separation of ash and oxygen carrier.
- Corrosion behavior by laboratory scale corrosion tests.
- Experiments will be coordinated with WP2 and WP3. Ash chemistry in the fuel reactor will be studied experimentally during the operation of VTT's pilot plant. These studies will focus on alkali release.

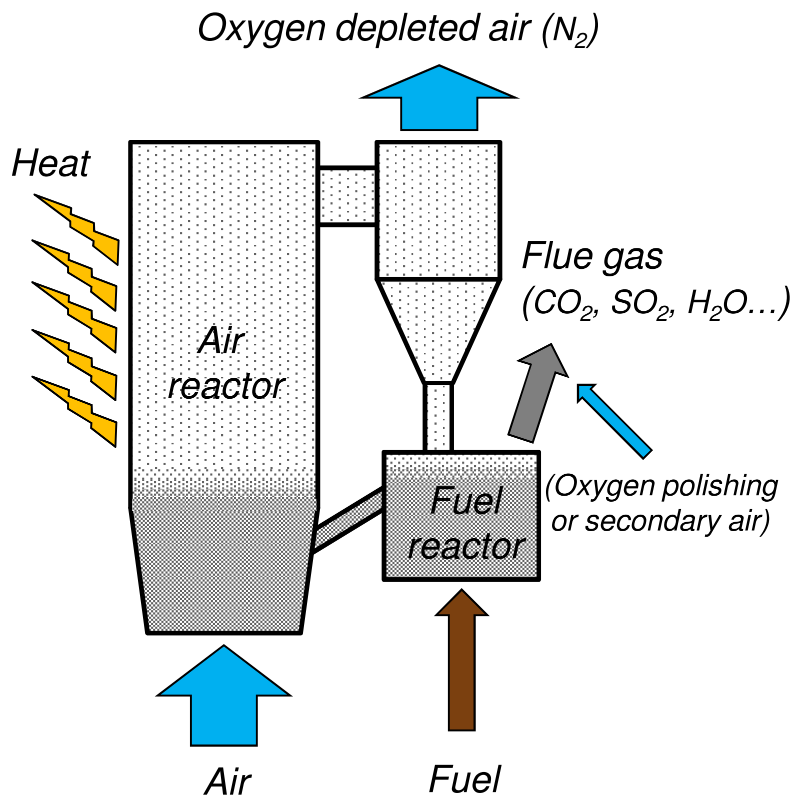
WP5 - Ash and corrosion issues (continued)

Opportunity: Heat is extracted in absence of ash. This could potentially reduce corrosion greatly and allow the use of better steam data compared to conventional combustion.

Circulating Fluidized Bed Boiler



Chemical-Looping Combustion

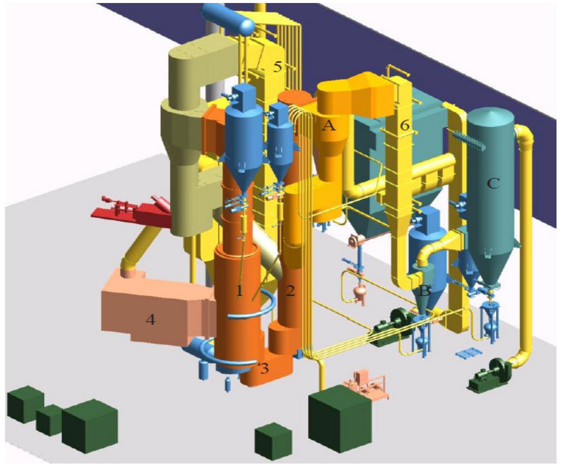


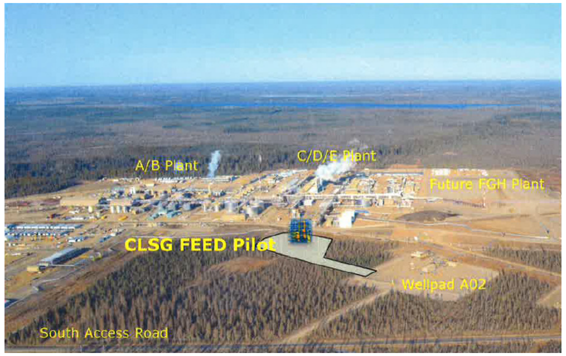
WP6 - Upscaling and implementation

Involved partners: VTT, Chalmers, Bellona, SINTEF ER, SINTEF MC, Åbo Akademi
Work Package Leader: Matti Nieminen, VTT

Based on the results from WP2-WP5 a plan for how Bio-CLC could be implemented in the Nordic countries will be devised.

- Fundamental plant design.
- Techno-economic analysis, including the whole CCS chain, with profitability analyzed according to different market situations and policy frameworks.
- Prospect of providing funding to demonstration plant, possibility of co-funding between industrial end-user and funding agencies.
- Mapping of potential sites for demonstration plant.
- Feasibility of “low-risk demonstration” plant.





WP7 - Bio-CLC in a low-carbon Nordic energy system

Involved partners: VTT, Bellona
Work Package Leader: Tomi J. Lindroos, VTT

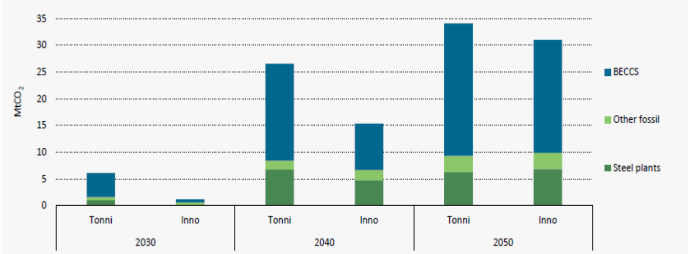
Economic performance and emission removal potential of Bio-CLC in the future Nordic energy system will be studied with energy system models, cost-benefit analysis and cost-effectiveness analysis.

- Main tool will be VTT's energy system model TIMES-VTT.
- Updated input parameters will be provided mainly by WP6, which is based on WP2-WP5.
- Multiple scenarios will be crafted.
- The final results will be compared and benchmarked to other studies of Nordic energy systems, including IEA Nordic Energy Technology Perspectives 2016.

"In the long term, CCS seems to be the most important single technology to reduce industrial CO_2 emissions. It would become particularly important if future policies were to include BECCS as an option to reduce greenhouse gases."

- Nordic Energy Technology Perspectives 2013

Figure 4.10 Industrial CCS in the Nordic countries in the Tonni and Inno scenarios



Notes: Tg = teragrams = 1012 g = 106 tonnes. Includes CCS in Denmark, Finland, Norway and Sweden.
Source: VTT Scenario calculations with the TIMES-VTT model. Includes CCS in Denmark, Finland, Norway and Sweden.

WP8 - Dissemination

Involved partners: Bellona, Chalmers, SINTEF ER, SINTEF MC, VTT, Åbo Akademi
Work Package Leader: Hallstein Havåg, Bellona

The key objectives are to communicate the project content, findings and conclusions to the widest possible audience, place these in the wider context of low-carbon and carbon-negative technologies, and emphasize the potential of and need for carbon-negative solutions. Methods that will be used:

- Annual public workshop, preferably in connection with larger Nordic events.
- The Advisory Board, which provides a regular opportunity for researchers, relevant industry, policy makers and NGO's to interact throughout the course of the project.
- Project web-site. Primary source of information on the project for the public.
- Traditional publication in scientific journals and presentations at conferences.
- An external relations and representation strategy to actively reach out to important stakeholders. Bellona has years of experience engaging Nordic and European public officials on the topics of CCS and biomass utilization.

List of Milestones

Table C. Progress Plan

Milestone (listed by work package)	Year	Quarter
1.1 Scientific Board and Advisory Board formed	2015	4
1.2 Consortium agreement signed by all partners	2015	4
2.1 Test campaign at VTT’s pilot completed (bed material and ash samples for WP5)	2016	2
2.2 Preparations for biomass operation and first testing of SINTEF’’s pilot unit completed	2017	1
2.3 Test campaign in Chalmers 100 kW_{th} CLC pilot completed (with oxygen polishing for WP4)	2017	3
2.4 Test campaign at SINTEF’s pilot completed (using mineral based oxygen carrier)	2017	4
2.5 Test campaign at VTT’s’ pilot completed (including alkali chemistry for WP5)	2018	1
2.6 Bio-CLC demonstration at semi-commercial scale in Chalmers research boiler completed	2018	1
2.7 Test campaign at SINTEF’s pilot completed (using the optimal oxygen carrier from WP3)	2018	4
2.8 Final report on results from WP2 and implications to reactor design and performance	2019	1
3.1 Selection of first batch Fe-Mn minerals candidates for examination in pilot campaigns	2016	1
3.2 Report on first batch of materials, second selection based on test results and availability	2016	3
3.3 Report on second batch of materials, selection of optimal candidate for pilot testing	2017	1
3.4 Report on the impact of biomass ash components on fuel conversion rate	2018	1
3.5 Market assessment on the cost and availability of suitable oxygen carriers completed	2018	3
3.6 Report on the use of synthetic particles as oxygen carrier for Bio-CLC	2019	2
3.7 Final report on material testing including long term tests and post characterisation	2019	3
4.1 O_2 polishing - proposed design for Chalmers 100 kW_{th} CLC pilot available	2016	2
4.2 O_2 polishing - experiments in Chalmers 100 kW_{th} CLC pilot completed	2017	3
4.3 NO_x and SO_x removal - proposed design for gas cleaning in demonstration unit available	2018	4
5.1 Corrosion experiments at laboratory scale completed	2017	2
5.2 Lab scale studies on interaction between oxygen carriers and ash components completed	2017	4
5.3 Report on corrosion in laboratory experiments and pilot units completed	2018	4
5.4 Report on interaction between oxygen carriers and biomass ash completed	2019	1
6.1 Fundamental design and analysis of a 100 MW_{th} Bio-CLC plant completed	2016	2
6.2 First report of the techno-economic evaluation of Bio-CLC completed	2016	4
6.3 Data gathering from other WP’s for final techno-economic evaluation completed	2018	1
6.4 Final report concerning the techno-economic evaluation of Bio-CLC completed	2018	3
6.5 Report on the possibilities for realizing a Bio-CLC demo plant in the Nordic countries	2019	4
7.1 Bio-CLC in a low-carbon Nordic energy system – preliminary examination completed	2016	1
7.2 Bio-CLC in a low-carbon Nordic energy system – scenarios crafted and comment round	2018	3
7.3 Bio-CLC in a low-carbon Nordic energy system – final report completed	2019	3
8.1 Dissemination infrastructure and procedures established	2015	4

33 milestones, in addition to regular reports and newsletters.

Questions?

Points of discussion?