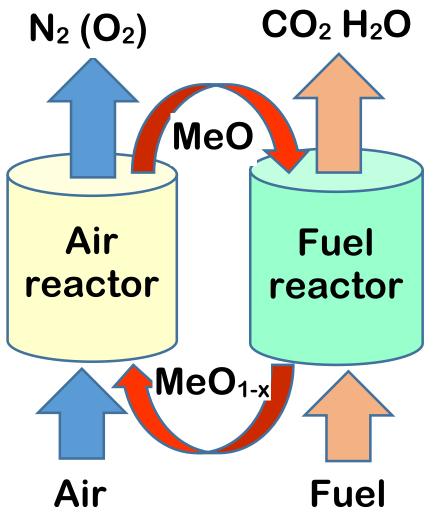
Chemical-Looping Combustion (CLC) of Solid Fuels (SF-CLC)
A Discussion of Operational Experiences, Costs, Upscaling Strategies and Negative Emissions (Bio-CLC)



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Melbourne

Negative CO_2
Negative CO_2 Emissions with Chemical-Looping Combustion of Biomass

Nordic Energy Research

Table 1: Overview hours of chemical-looping operation with different oxygen carrier materials.

Type	Oxygen carrier	**Total 2018**
Manufactured	NiO	**3291**
	CuO	**1485**
	Mn_3O_4	**91**
	Fe_2O_3	**1454**
	CoO	**178**
	Combined oxides	**1102**
Natural ore or waste material	Fe ore	**965**
	Ilmenite	**1240**
	Mn ore	**603**
	CaSO4	**75**
Total manufactured		**7601**
Total natural/waste		**2883**
Total		**10484**
Publications		181

Table 1: Overview hours of chemical-looping operation with different oxygen carrier materials.

Last five years

Type	Oxygen carrier	2014-2018		
Manufactured	NiO	491	13%	4
	CuO	858	23%	1
	Mn_3O_4	0	0%	
	Fe_2O_3	377	10%	
	CoO	0	0%	
	Combined oxides	557	15%	3
Natural ore or waste material	Fe ore	561	15%	2
	Ilmenite	430	12%	6
	Mn ore	455	12%	5
	CaSO4	0	0%	
	Total manufactured	2283	61%	
	Total natural/waste	1446	39%	
	Total	3729		
	Publications	66		

Table 12. Operation with of 39 CLC combustors , of which 21 solid fuel CLC

Location	Size	Hours of operation	Selected references	First reported
Chalmers	10 kW-GL	1650	[11] [12]	2004
KIER	50 kW	31	[13]	2004
CSIC	10 kW	120	[14]	2006
Chalmers	0.3 kW-GL	1520	[15]	2006
Chalmers	10 kW–SF	309	[16] [17]	2008
CSIC	0.5 kW-GL	1586	[18]	2009
KAIST	1 kW	8	[19]	2009
Vienna UT	140 kW	649	[20]	2009
Alstom, Fr	15 kW	100	[21]	2009
Nanjing	10 kW –SF	260	[22]	2009
KIER	50 kW	300	[23]	2010
Nanjing	1 kW – SF	195	[24] [25]	2010
IFP-Lyon	10 kW-GSF	578	[26] [27]	2010
Stuttgart	10 kW	1	[28]	2010
Xi'an Jiaotong	10 kW- Pr	15	[29]	2010
CSIC	1.5 kW-SF	594	[30]	2011
Chalmers	100 kW – SF	199	[31] [32]	2012
Hamburg	25 kW –SF	65	[33]	2012
Ohio	25 kW –SF	980	[34] [35]	2012
Nanjing	50 kW-Pr	19	[36]	2012
WKentuU	10 kW	24	[37]	2012
Tsinghua	0.2 kW	350	[38]	2013
Alstom, US	3 MW –SF	75	[39]	2014
CSIC	50 kW-SF	54	[40]	2014
Darmstadt	1 MW –GSF	195	[41] [42]	2015
Huazhong	5 kW-GSF	200	[43]	2015
Guangzhou	10 kW-G	62	[44]	2015
Nanjing	25 kW-G	13	[45]	2015
KIER	200 kW	100	[46]	2016
Huazhong	50 kW-SF	8	[47]	2016
Sintef	150 kW	8	[48]	2016
VTT	20 kW-SF	79	[49]	2016
NETL	50 kW	2	[50]	2016
Chalmers	1.4/10 MW	62	[51]	2016
Nanjing	20 kW-SF	70	[52]	2016
Zabrze	10 kW	3	[53]	2017
Vienna UT	80 kW-SF	20	[54]	2018
Tsinghua	30 kW-SF	100	[55]	2018
CSIRO	10 kW-SF	35	[56]	2018

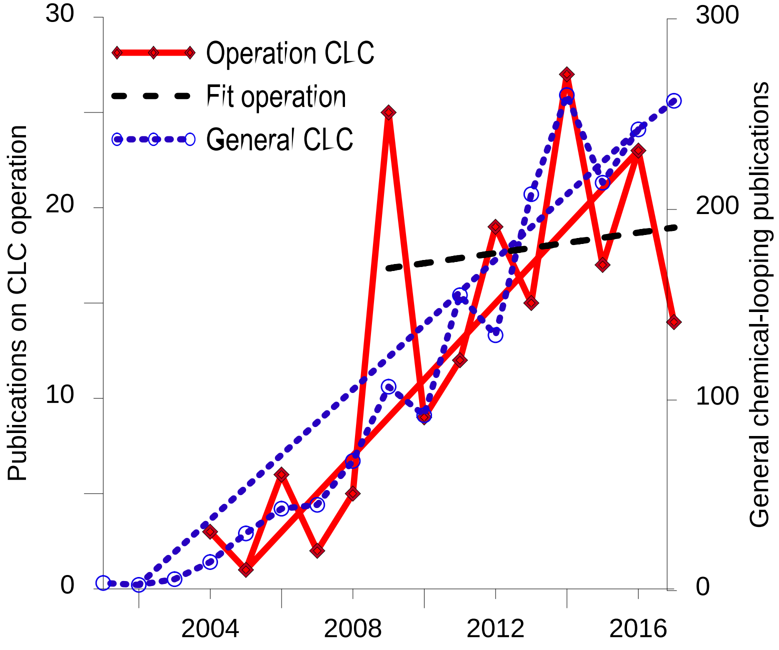
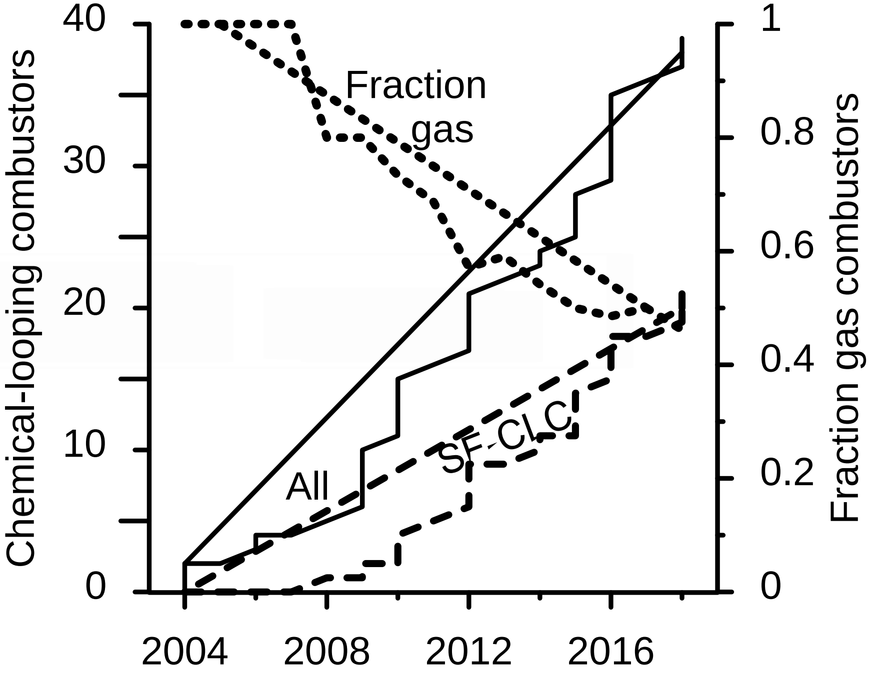


Figure 4. Publications on chemical-looping (Scopus) and CLC operation vs year published.



Figures 5. Number of chemical-looping combustors versus year

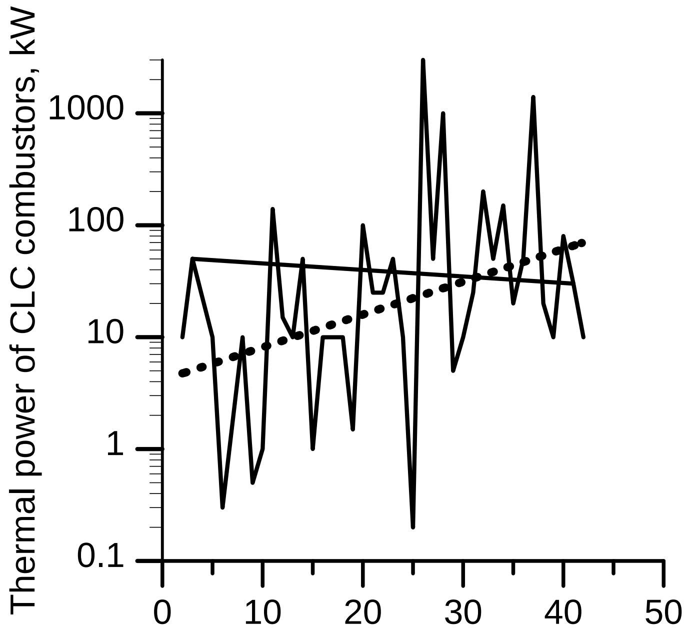


Figure 6. Size of chemical-looping combustors versus consecutive number.

Increased challenges with

- Larger units
- Solid fuels
- Oxygen carriers with more complex composition
    - natural ores
    - combined oxides

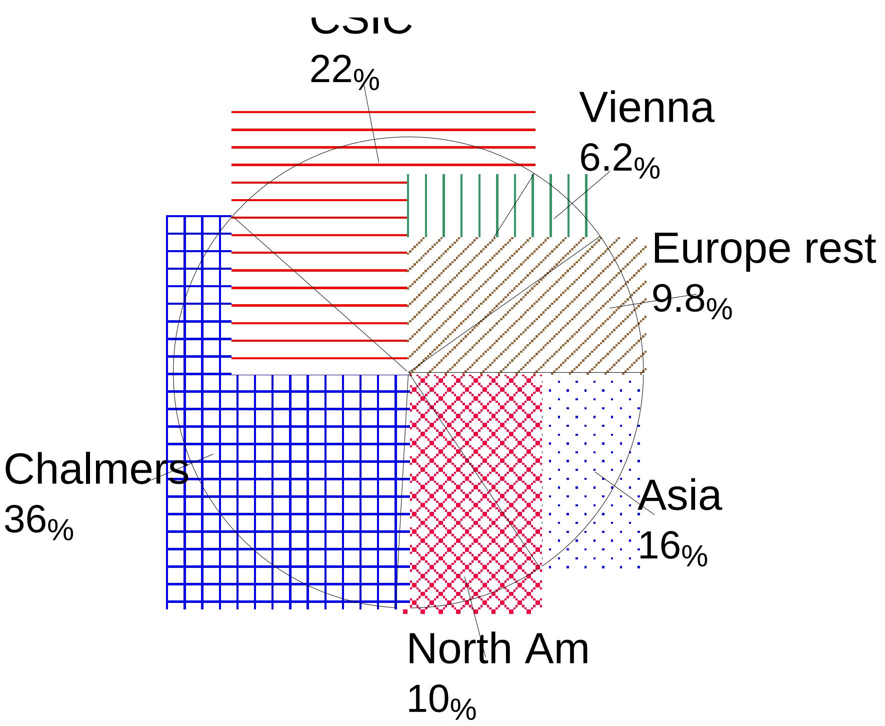


Figure 7. Operation versus location.

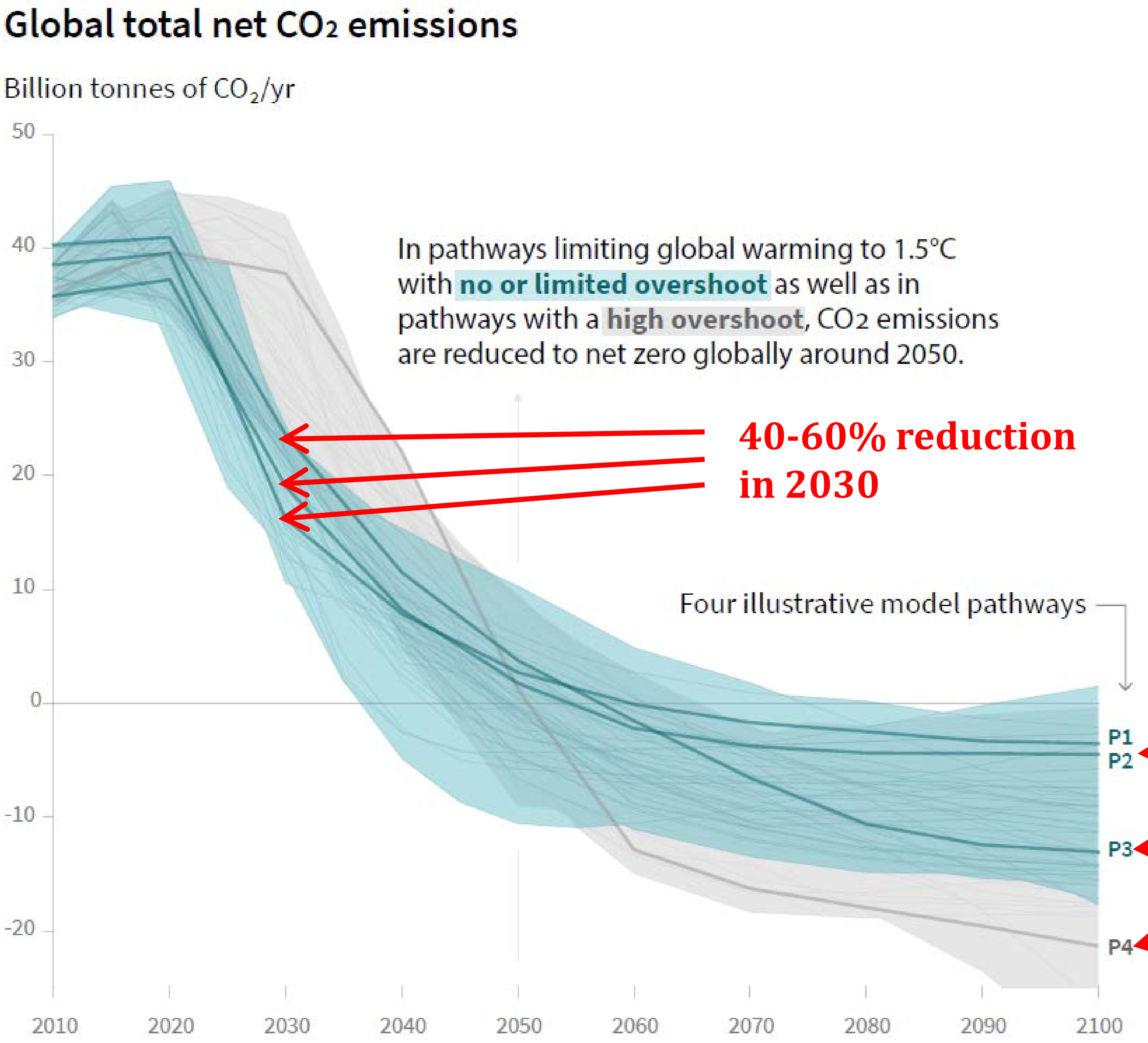
Conclusion 1

CLC with solid fuels well proven in small pilot scale

No reason why it should’t work in larger scale

But scale-up is large barrier

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

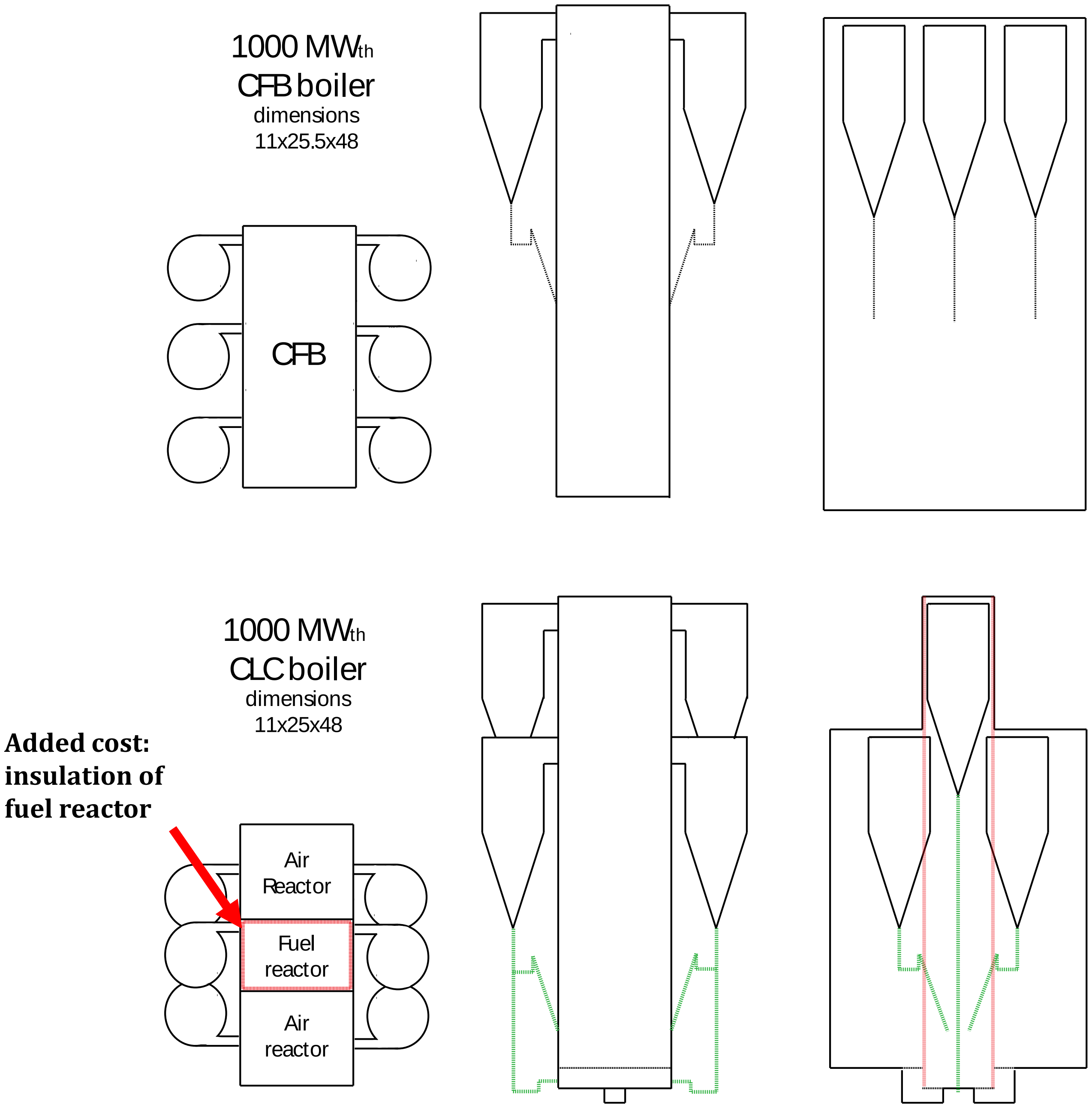
large negative emissions

very large negative emissions

Conclusion 2

We need negative emissions

CLC with biomass is of great interest



Walls of fuel reactor, cyclones, ducts and post-oxidation chamber:

→ 2500 m²

Cost: 1500 €/m²

<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., <u>A 1000 MWth Boiler for Chemical-Looping Combustion of Solid Fuels - Discussion of Design and Costs</u>, ***Applied Energy*** **<u>157</u> (2015) 475-487** ***(Open Access)***

Ways to scale-up

big cost

•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

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

Conclusions 3

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

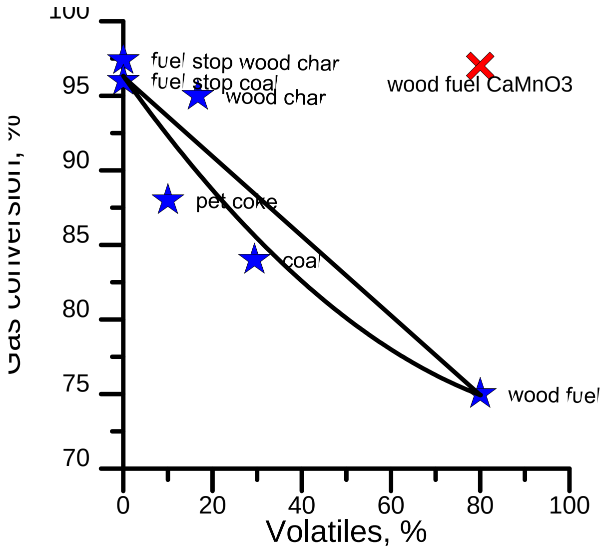
Pilot operational results with crushed biomass pellets

Table 1: Key results from tests in pilot units. Nomenclature: Mn ore = manganese ore, wwp = white wood pellets, bwp = black wood pellets treated by steam explosion provided by Arbaflame, wc = wood char

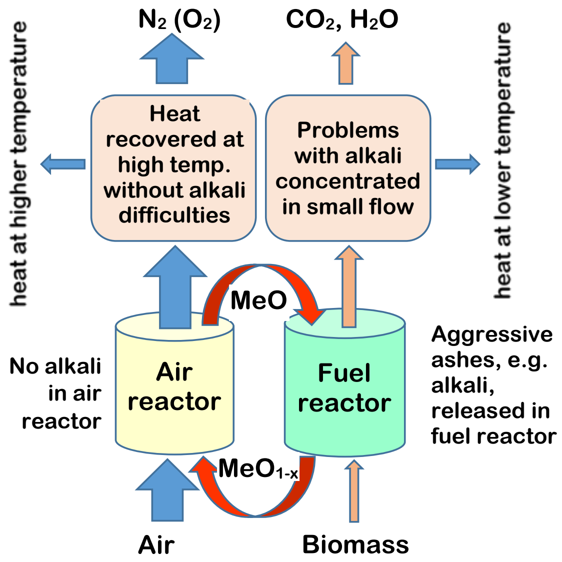
Unit	Oxygen carrier	Fuel	Fuel power (kW_{th})	Carbon capture rate (%)	Oxygen demand (%)	Fuel reactor temperature (°C)	Time of operation with fuel (h)
VTT 50 kW	Ilmenite (Titania A/S)	wwp, bwp	9 – 22	83 – 96	29 – 41	840 – 863	16
VTT 50 kW	Mn ore ("Sibelco Braunite")	wwp, bwp, wc	22 – 60	72 – 96	11 – 31	838 – 897	23
Chalmers 100 kW	Mn ore ("Sibelco Calcined")	wwp, bwp	29 – 67	99	25	940 – 975	7
SINTEF 150 kW	Ilmenite (Titania A/S)	bwp	140	94 – 97	23 – 28	960 – 980	10
Chalmers Research Boiler	Mn ore ("Sibelco Calcined")	wwp	2400	NA	≈ 40	810 – 830	500

Biomass in CLC

High volatiles content could give problems with gas conversion



Biomass difficult fuel alkali gives low ash-melting temperature

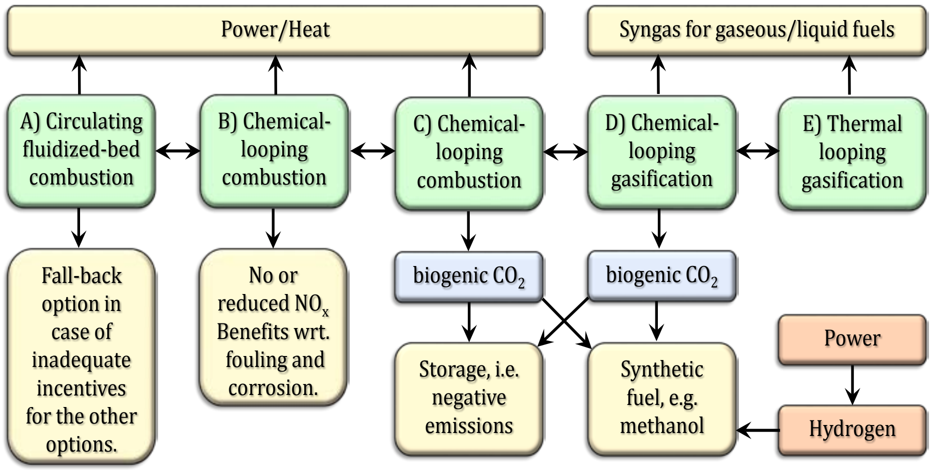


Could low ash content make manufactured oxygen carriers possible ?

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

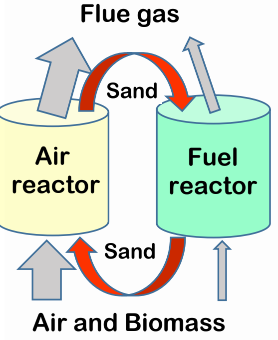
Could range of possible fuels be extended?

Multipurpose Dual Fluidized Bed

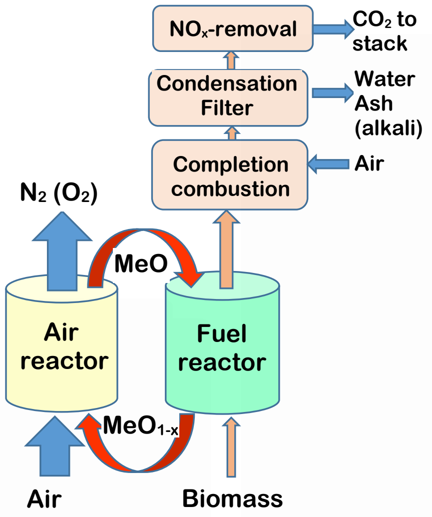


Three cases with heat extraction only

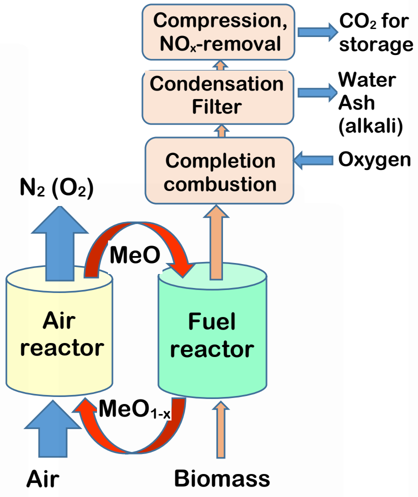
Two cases where heat extraction is minimized, in order to get high fuel output



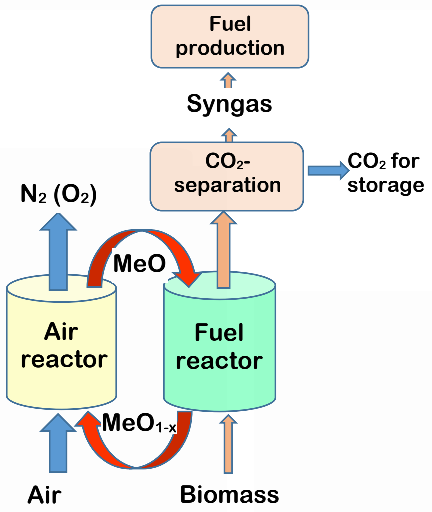
4A MDFB-boiler– normal combustion



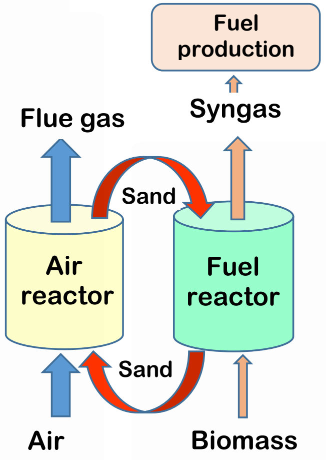
4B Chemical looping to reduce NO_x and alkali problems



4C Chemical looping for negative emissions

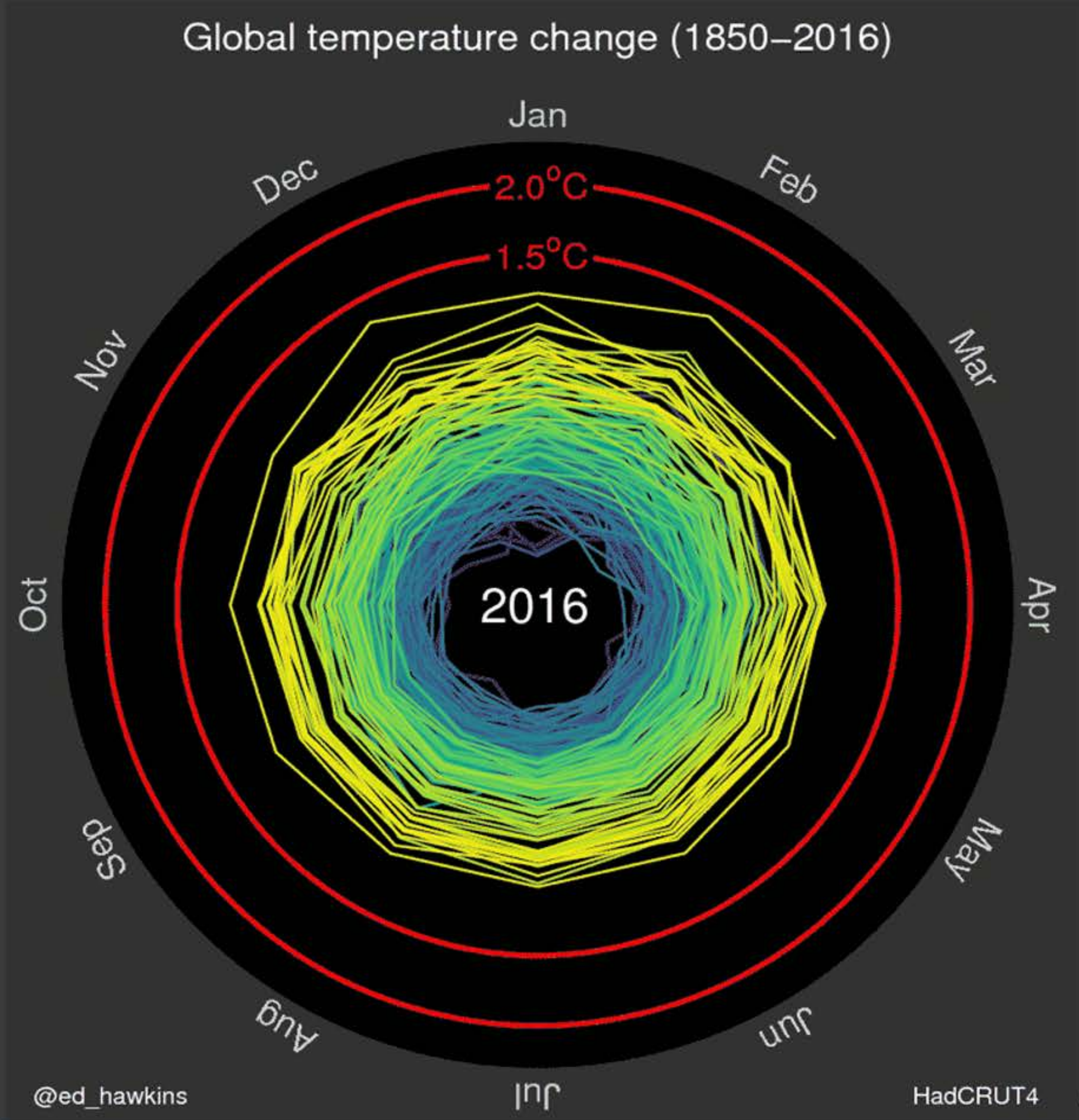


4D Chemical Looping Gasification – for Fuel Production and Negative Emissions.

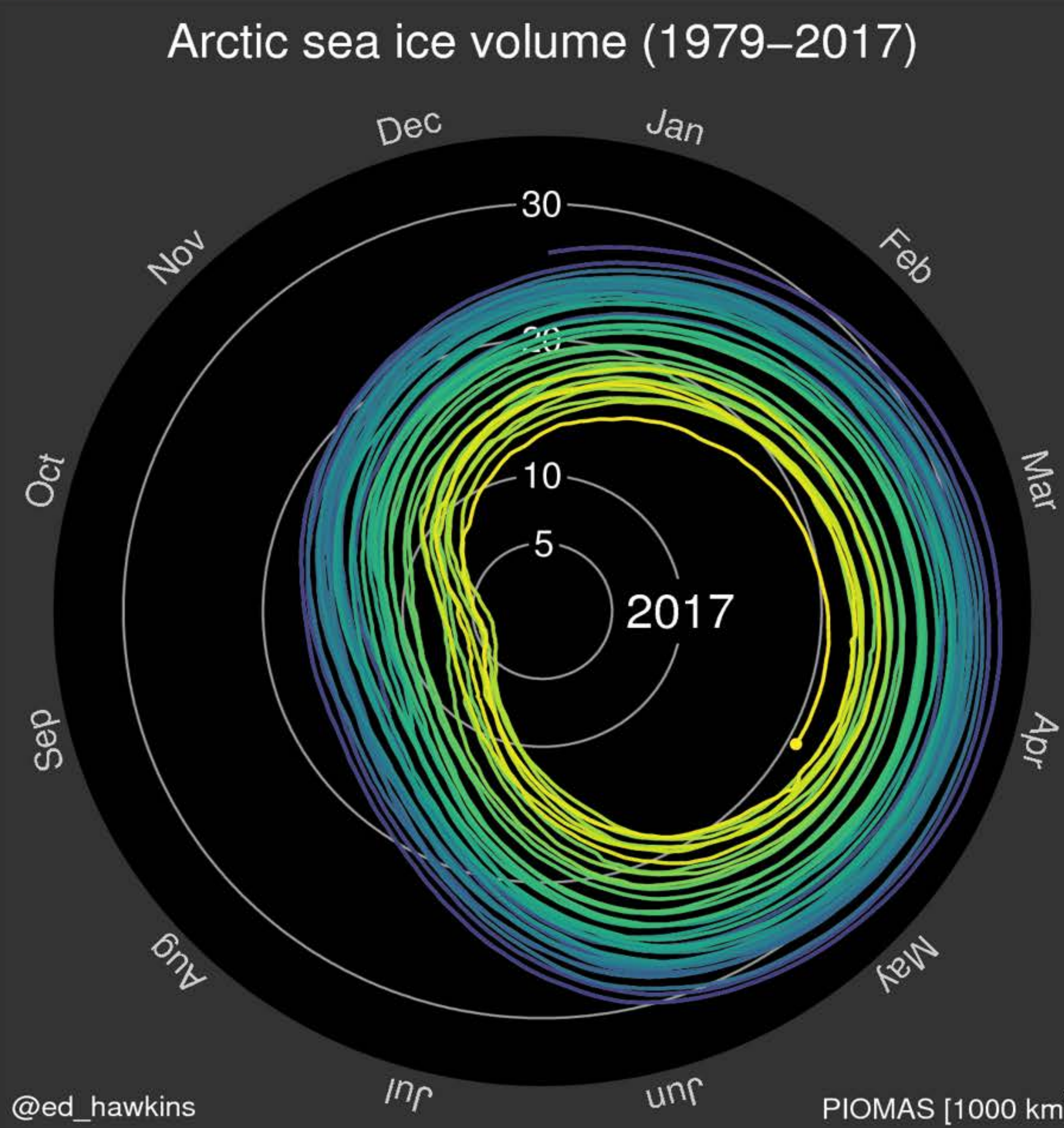


4E Thermal gasification - fuel production only

Thank you!



Global temperature change (1850–2016)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2.0°C
1.5°C
2016
@ed_hawkins
HadCRUT4



Arctic sea ice volume (1979–2017)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
30
10
5
2017
@ed_hawkins
PIOMAS [1000 km