CO_2 capture and supply

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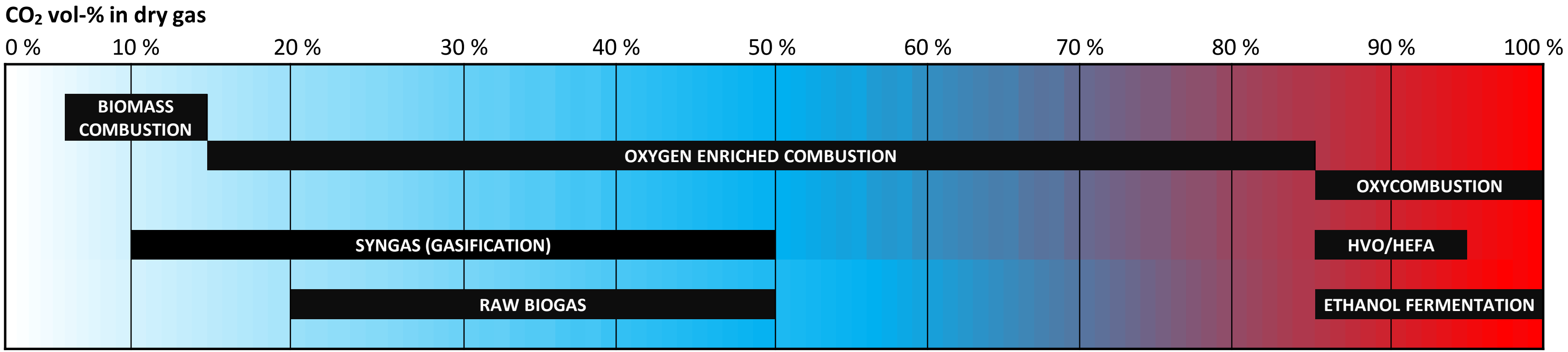
Biogenic CO_2 emissions targeted in BECCU

- We target **biogenic CO_2** due to climate benefit and high potential of bio-CCUS in Finland



Industrial emission point sources we focused on in BECCU:

- post-combustion capture from biogenic emission sources, e.g., thermal power stations, CHP
- raw biogas purification / biogas upgrading
- biofuel production processes, e.g., bioethanol, HVO, BtL

Conclusions from a literature review on post-combustion capture

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- Numerous carbon capture technologies based on different capture methods are in development.
- There are no distinctive breakthrough-technologies. Wide portfolio of technology options available with roughly similar techno-economic performance
- Suitable technologies for a certain application is mainly determined by process conditions and end-use application of the captured CO_2.
- Commercial-scale operation ongoing mainly with amines in fossil-CCS. Several demonstration projects are upcoming in the near future for emerging technologies.
- Capture costs are decreasing as technologies advance and as novel technologies emerge.

CO_2 capture cost in post-combustion capture
- all reviewed technologies: 34–80 €/tCO_2
- on average: 40–60 €/tCO_2

Technology		Energy requirement per CO_2 tonne	Capture cost per CO_2 tonne	
			Solid fuel	Gaseous fuel
Liquid absorbents	MEA	3.3–3.7 GJ [1]	44 € [2]	64 € [2]
	PZ+AMP	2.5 [2]; 3.2 GJ [3]	34 € [2]	56 € [2]
	KS-1	2.6 GJ [4]	$59 [5]	-
	KS-21	2.6 GJ [6]	$55 [5]	-
	CANSOLV	2.3 [7]	-	-
Multi-phase absorbents	Aq. NH_3	2.5 GJ [8]	$53 [8]	-
	CAP	2.2 GJ [9]	-	-
	UNO MK 3	2.0–2.5 GJ [10]	$45 [11]	-
	Hot-CAP	1.8 GJ [12]	-	-
	DMX	<2.5 GJ [13]	39 € [2]	-
Water-lean solvents	eCO2Sol	2.3 GJ [14] 2.0 GJ (exp.) [14]	$47 [15]	-
Solid adsorbents	PSA	>2.3 GJ [2]	$40 [16]	-
	VSA	1.7 GJ [17]	-	-
	VeloxoTherm	1.5 GJ [18]	41 € [2]	-
Membranes	MTR Polaris	1.0 GJ [19]	47 € [2] $30 (exp.) [20]	80 € [2]
Hybrid systems	Membrane-sorbent	-	$36 [2]	-
Electrochemical separation	NGCC-MCFC hybrid-cycle	-	-	34 € [21]

Ref: 1) GCCSI in Svendsen 2014; 2) IEAGHG 2019a; 3) Rabensteiner et al. 2016; 4) Yagi et al. in IEAGHG 2019a; 5) Carroll 2017 Tanaka et al. 2018; 7) Singh & Stéphenne 2014; 8) Li et al. 2016; 9) Augustsson et al. 2017; 10) Smith et al. 2014; 11) UNO 2014; Lu et al. 2014; 13) Broutin et al. 2017; 14) Zhou et al. 2018; 15) Lail 2016; 16) Ritter et al. 2015; 17) Krishnamurthy et al. 2014; CCJ 2011; 19) Baker et al. 2018; 20) Merkel 2018; 21) IEAGHG 2019b

Three novel Finnish CO_2 capture technologies tested

- Bioenergy with carbon capture was experimented at small pilot-scale in the autumn of 2020 at VTT's test facilities in Jyväskylä using three novel post-combustion capture technologies and VTT's 50 kW CFB-pilot combustor. Objective of the tests was to validate the technologies in realistic operating conditions and to evaluate capture performance with different types of feed gas sources.

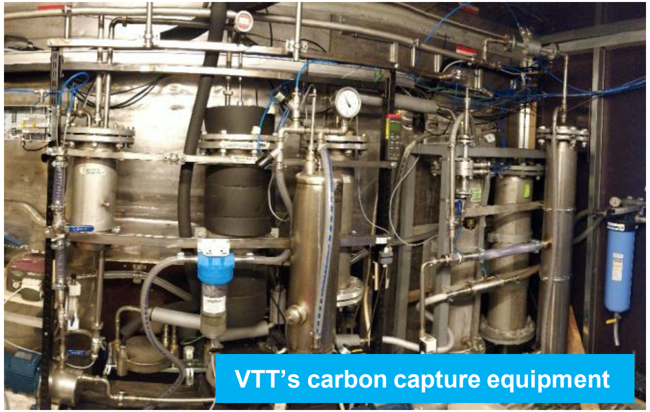
Technology	Enhanced water scrubbing	Enhanced soda scrubbing	Kleener-liquid
Technology readiness	Pilot (TRL 6)	Validated (TRL 5)	Validated (TRL 5)
Phenomenon	Physical absorption	Chemical absorption	Chemical absorption
Absorbent	Tap water	Aqueuos sodium carbonate (Na_2CO_3)	A novel ash-based capture solution
Absorber	Bubble-type absorption column	VTT's novel microbubble generator	VTT's equipment used in BECCU tests
Absorption conditions	5 °C, 4–5 bar	30–40 °C, atm	50–65 °C, atm
Regeneration	Flashing at ~0.4 bar	60–80 °C, 0.2–0.5 bar	60–80 °C, 0.2–0.5 bar
Energy supply	Electricity	Low-grade heat for regeneration Electricity for auxiliaries (pumps etc.)	Low-grade heat for regeneration Electricity for auxiliaries (pumps etc.)

Environmentally-friendly and safe-to-handle alternatives to conventional amines!

Bioenergy with carbon capture piloted at Jyväskylä

Test site and the pilot containers

Week	CO_2 source	Tested technologies	Test objectives
#36	Synthetic gas mixtures	VTT Soda CarbonReUse	- Validating proper function of the test equipment - Evaluating capture performance with modifiable gas compositions
#37	Pine chips (flue gas)	VTT Soda CarbonReUse Kleener-liquid	- Validating technologies in post-combustion capture at realistic conditions and comparison of technology performance
#38	Washed straw (flue gas)	VTT Soda CarbonReUse	- Effect of flue gas originating from an “impure” biomass
#40	Spruce bark (flue gas) Raw biogas	VTT Soda	- Effect of a third biomass type - Testing VTT’s soda process for CO_2 capture in biogas purification


VTT’s carbon capture equipment

Results from the carbon capture pilot tests

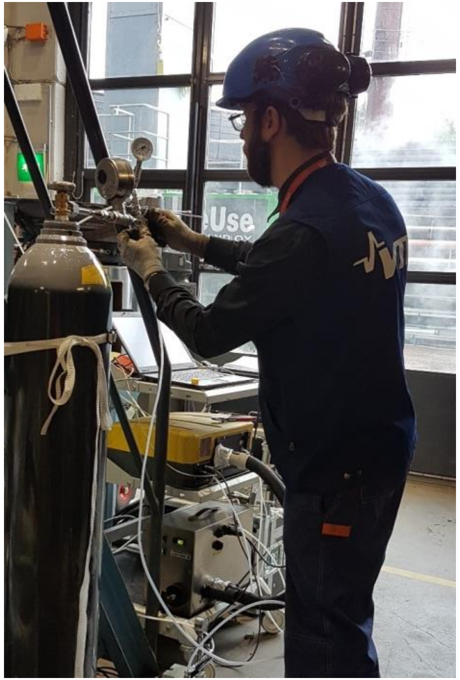
Mean purity of the captured CO_2 [vol-% in dry gas]

	CarbonReUse	Kleener	VTT Soda
Synthetic gas 15 vol-% CO_2	95.1	-	96.7
Synthetic gas 30 vol-% CO_2	98.3	-	-
Pine chips (flue gas)	97.1	94.2*	95.9
Washed straw (flue gas)	96.0	-	96.6
Spruce bark (flue gas)	-	-	96.5
Raw biogas	-	-	93.6

Capture rate [%] (calculated via mass balances)

	CarbonReUse	Kleener	VTT Soda
Synthetic gas 15 vol-% CO_2	74	-	83–86
Synthetic gas 30 vol-% CO_2	86	-	-
Pine chips (flue gas)	72–76	69–71*	74–79
Washed straw (flue gas)	64–70	-	78–83
Spruce bark (flue gas)	-	-	88-90
Raw biogas	-	-	97–98

*A diluted version of Kleener-liquid (25 wt-% solution vs. the normal 50 wt-% solution) was tested in BECCU test runs. Capture perfomance is better with the 50 wt-% formula, which has been validated in other test runs.



- All three technologies validated in post-combustion capture at realistic conditions
- Mainly N_2 and O_2 were present as impurities in the captured CO_2 streams
- Any harmful solvent-based emissions or other pollutants did not occur!

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Carbon capture from high CO_2 concentration sources

- Processes producing exhaust streams with naturally high CO_2 concentration often yield the lowest capture costs of all carbon capture pathways, but few emission point sources are of such nature.
  - Potential applications are, e.g., ethanol fermentation, HVO, natural gas processing

- Often CO_2 separation is not required but some conditioning is needed, e.g., dehydration, desulphurization and removal of volatiles and non-condensables. Capture cost depends on the level of conditioning required.

Case-study: preliminary feasibility assessment of carbon capture from a high CO_2 concentration source

- Case: production of hydrotreated vegetable oils (HVO), i.e., renewable diesel
  - Exhaust stream: 90 vol-% CO_2, 9 vol-% H_2O, 1 vol-% other (H_2, light HC's, very small volumes H_2S)
  - Annual emissions: 60 ktCO_2 (biogenic)
  - In-situ utilization of CO_2 via BECCU concept is assumed, no CO_2 transportation

- Proposed conditioning: 1) compression to 8-30 bar and dehydration with inter-stage cooling, 2) deep desulphurization (<0.1 ppm) using adsorbents, e.g., activated carbon or metal oxides

- Estimated cost of conditioning: **8–23 €/tCO_2** → a low-hanging fruit of biogenic CO_2!

Conclusions and proposed future work

CONCLUSIONS

- Status and performance of various post-combustion capture technologies were assessed based on literature. The market is developing rapidly and there is a wide portfolio of technologies in development, with roughly similar techno-economic performance.

- Carbon capture technologies by CarbonReUse, Kleener and VTT were validated in post-combustion capture at realistic conditions using pilot equipment, achieving promising performance that is in align with other carbon capture technologies at similar scale. The test results were utilized to improve process models.

- High CO_2 concentration emission point sources have high potential for bio-CCUS. Our preliminary case-study on carbon capture in production of HVO’s resulted in capture cost of 8–23 €/tCO_2.

PROPOSED FUTURE WORK

- Market monitoring and further mapping of carbon capture technology options.

- Co-operation with industrial parties to identify emission sources and facilities with high potential for carbon capture implementation.

- Further development of process models of the carbon capture technologies for optimization of process conditions and assessment of techno-economic performance for various applications at large scale.

- Long-term (>1000 h) carbon capture pilot experiments at relevant industrial site to validate smooth continuous operation and to identify risks and technology bottlenecks.

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