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BECCS as part of a future CO_2 neutral energy system – A case study from Aalborg, Denmark

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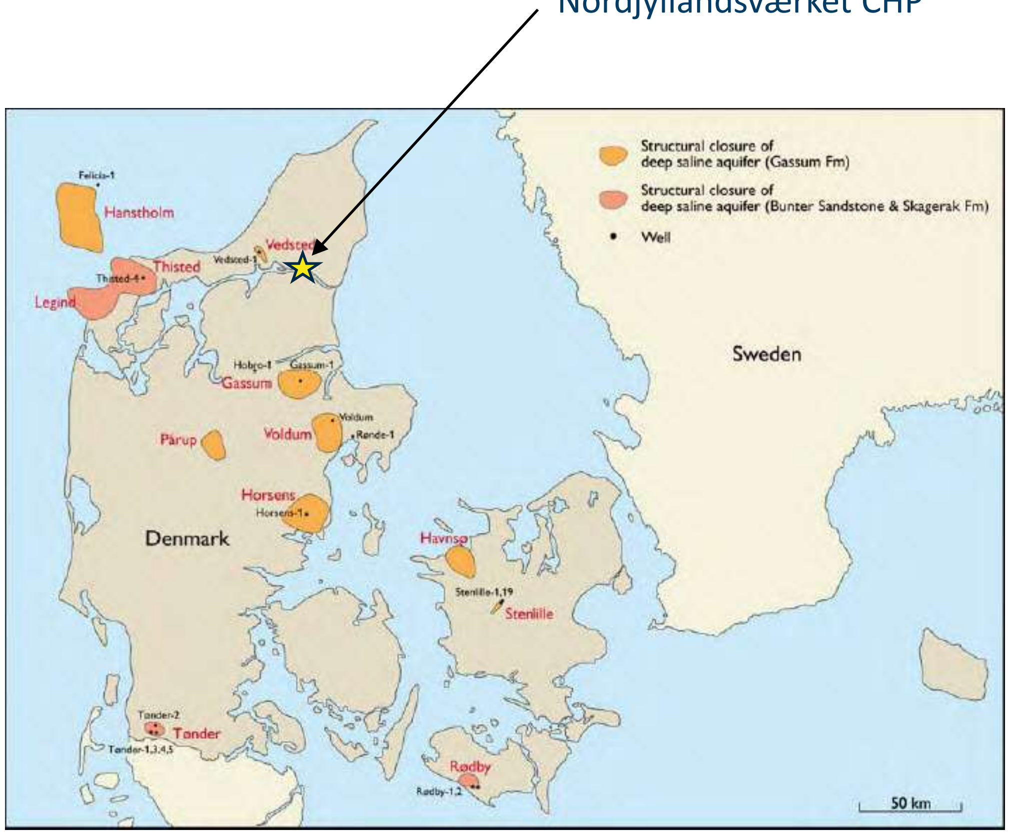
Outline

- Background – Conditions for BECCS in Aalborg, Denmark
- Techno-economic analysis of CO_2 capture on a bio-combined heat&power plant
- CO_2 storage site characterisation and CO_2 injection analysis
- Concluding remarks

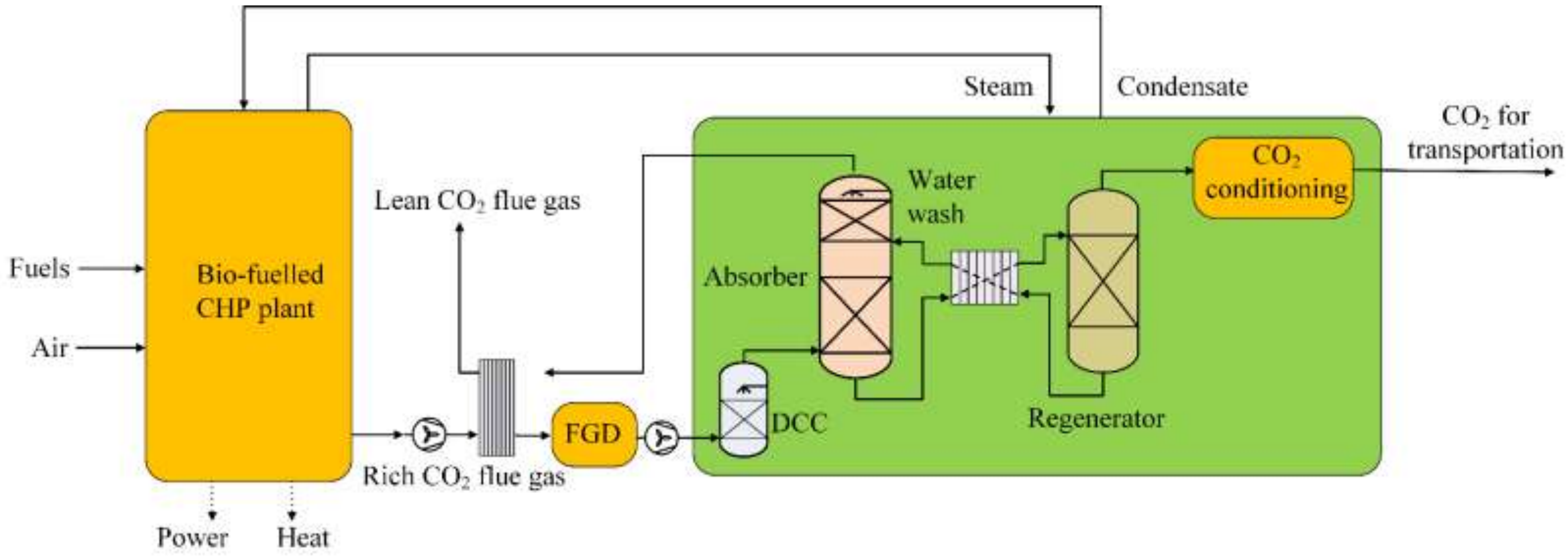
Conditions for BECCS in Aalborg, Denmark



- Denmark is gradually converting their heat and electricity production from fossil-fired combined heat&power (CHP) plants to renewables, supplimented with bio-CHP plants
- Nordjyllandsværket in Aalborg municipality – CHP plant presently running on coal
  - Ongoing dicussions and evaluations on conversion to biomass-fired
- Several geological formations with suitable reservoir properties for storage in proximity to Aalborg

Bio-CHP with absorption-based CO_2 capture

- Focus on back-pressure operation
  - Plant operated to maximize heat production with surplus electricity generation
- Steam from power plant required in the CO_2 capture plant (MEA-based CO_2 absorption)
- Thermal CHPs in Denmark rarely operate at maxmimum capacity
  - Part-load operation of interest
  - Appropriate size of capture plant



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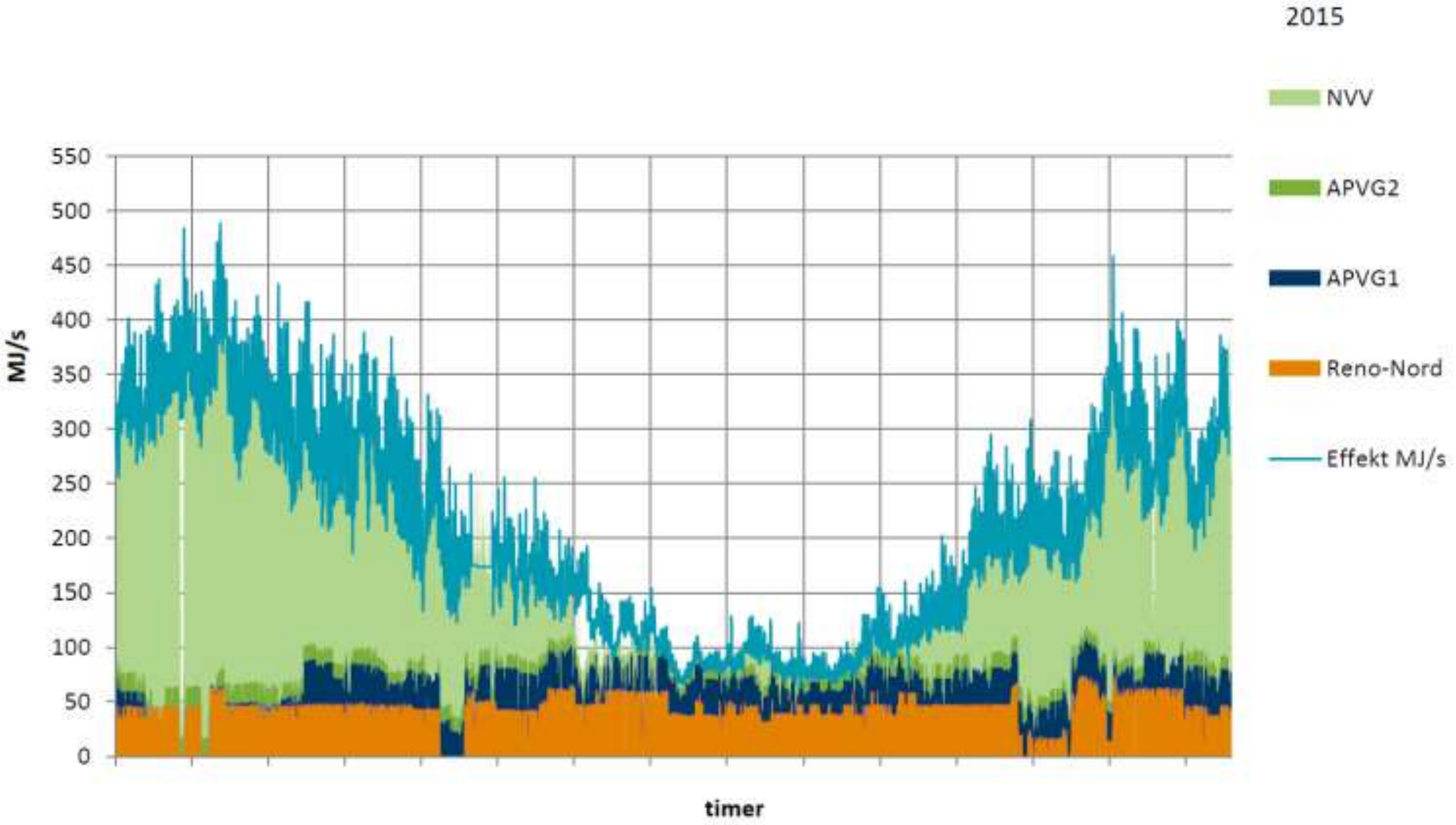
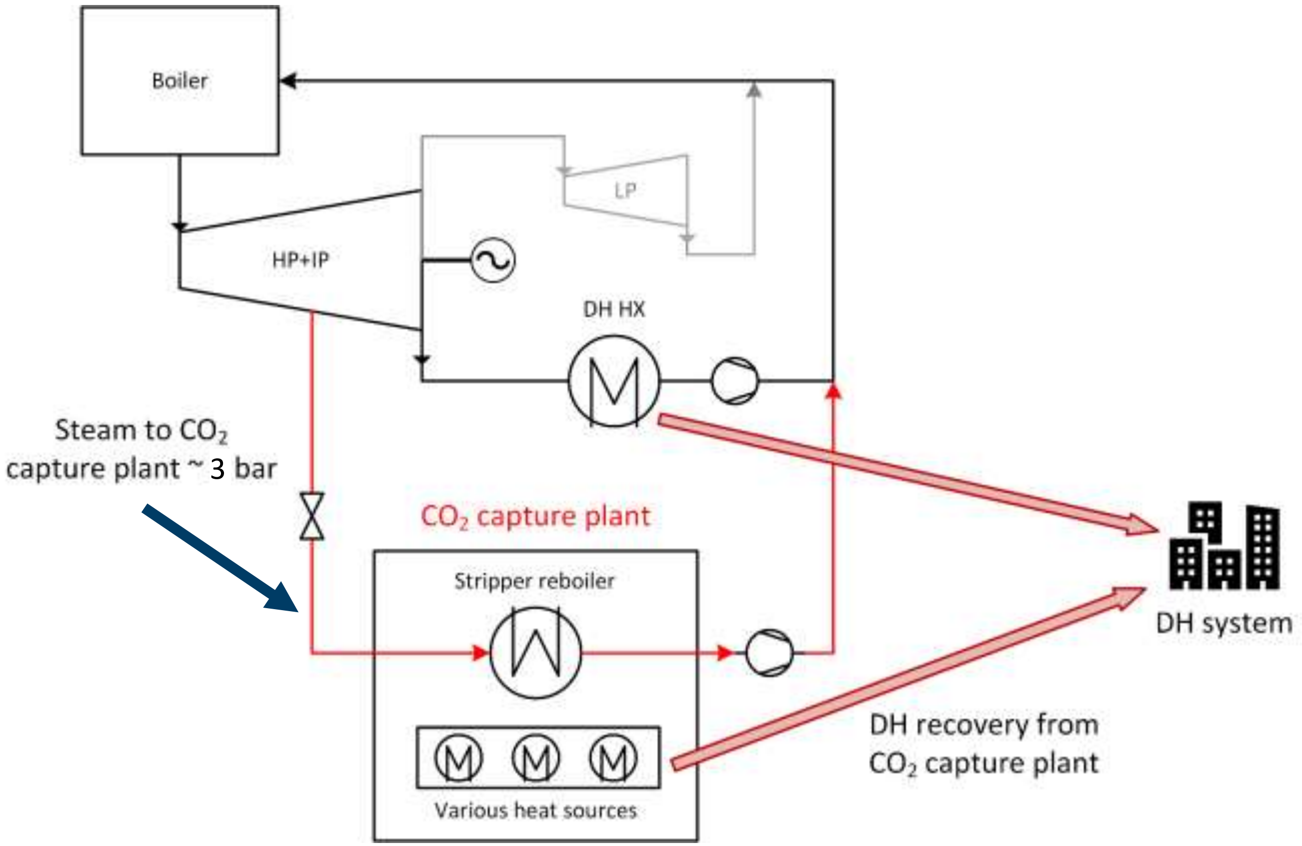
The role of CHPs in district heat production

Example of yearly DH production in the Aalborg municipality



Integration of CO_2 capture with the steam cycle and DH system



Potential for considerable heat recovery from CO_2 capture plant to DH system

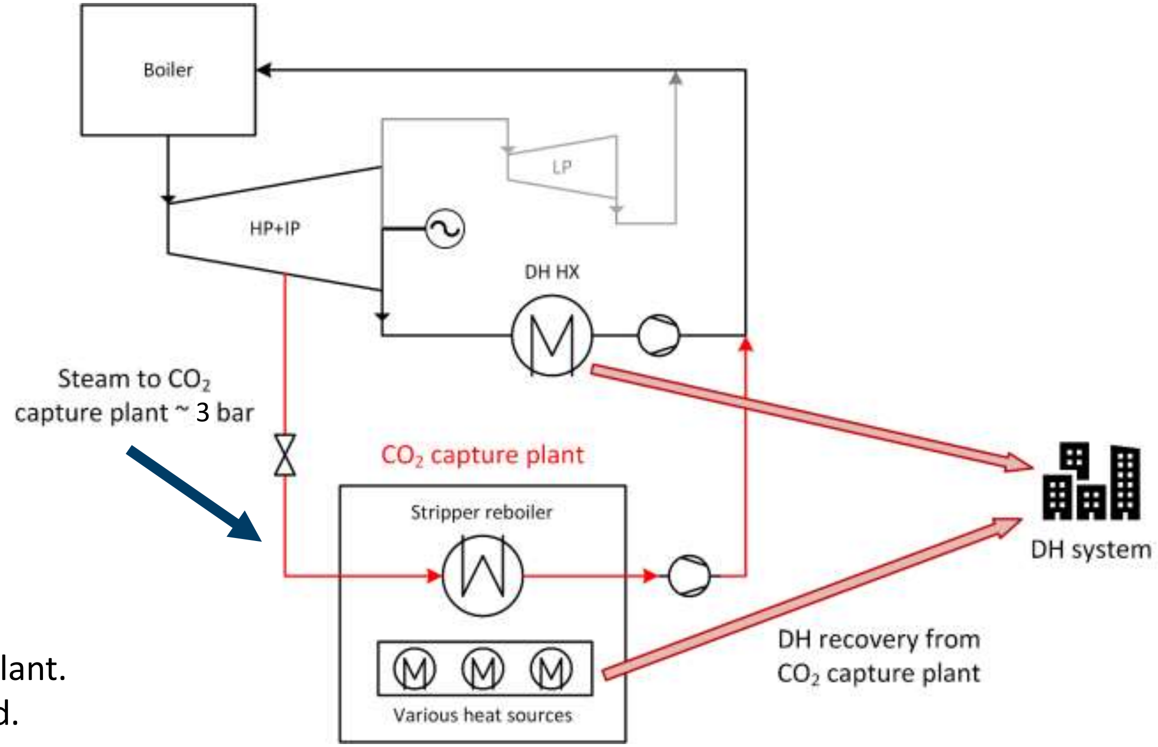
→ should improve plant efficiency and economics (CAPEX ↑ < OPEX↓)

Definition of capture cases

Techno-economic evaluation of four different cases

Case no.	Boiler load	DH recovery in CO_2 capture plant	Net CO_2 capture rate
0	100%	No	90%
1	100%	Yes	90%
2	75%	Yes	90%
3	100%	Yes	71%*

*90% CO_2 capture from a **slip flue gas stream**, the remainder by-passes the capture plant. Same size of capture plant in case 3 as in case 2, i.e. same amount of t CO_2/h captured.



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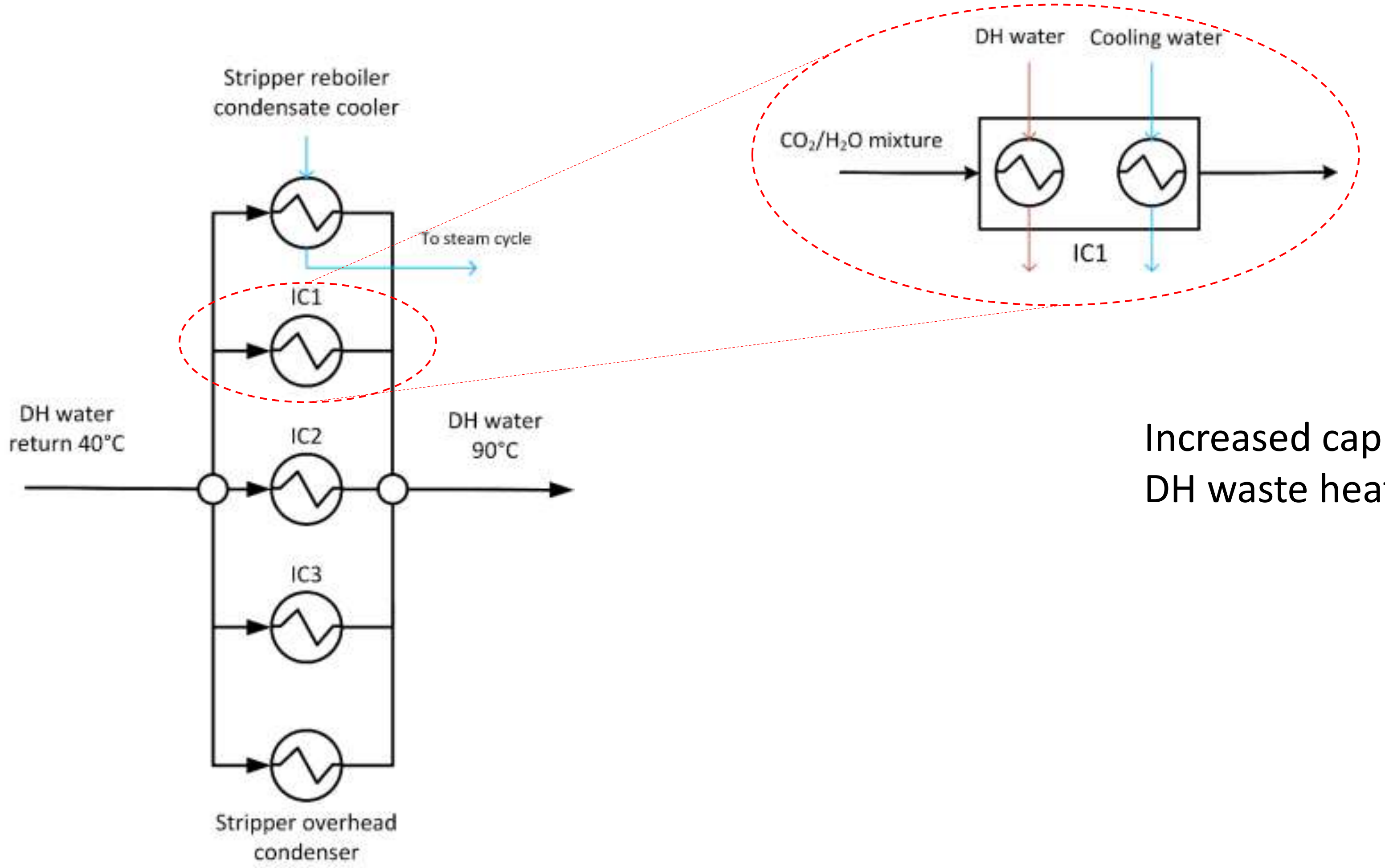
External heat recovery HX network



Increased capital costs from addition of DH waste heat recovery network

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Process modeling

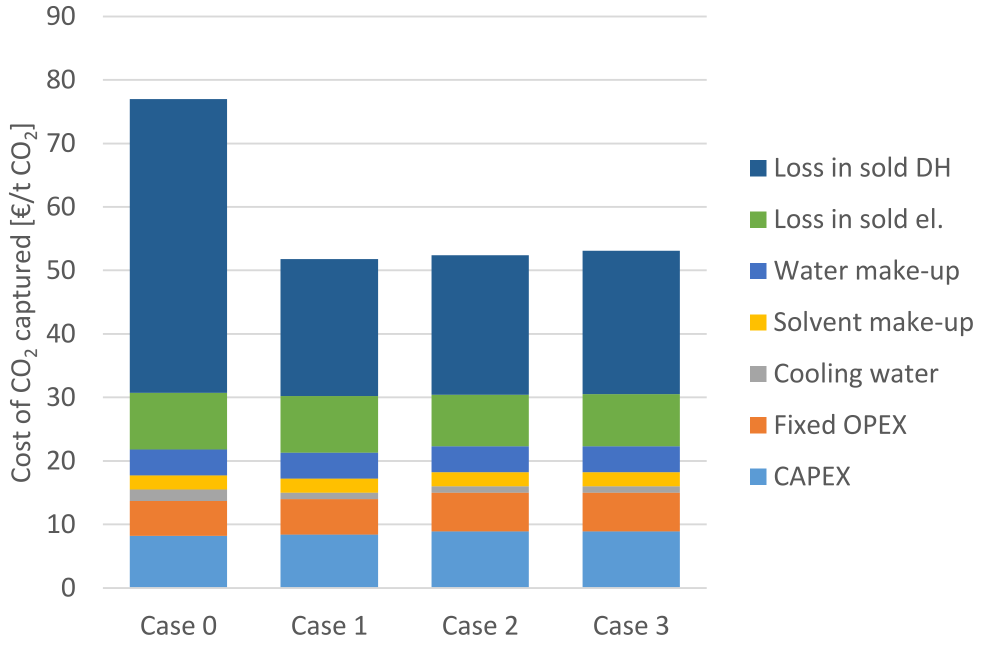
Boiler load	Fuel input [MW_{th}]	Temperature, °C	Mass flow, t/h	Molar compositions (%)				
				CO_2	N_2	O_2	H_2O	Ar
100%	640	56	1120	12.9	66.3	4.4	15.5	0.8
75%	497	56	878	12.8	66.4	4.6	15.5	0.8

- **Inputs**: Flue gas data from Avadøre 1, CHP converted from coal to 100% wood pellets
- **Process simulators**:
  - Power plant: Rambøll in-house mass&energy balance modeling tool (Mopeds)
  - CO_2 capture plant: Aspen HYSYS V9

Heat recovery from the capture process has a stronger effect than part-load operation and capture plant size

Parameter	Case 0	Case 1	Case 2	Case 3
Boiler load [%]	100	100	75	100
Heat recovery from capture process	No	Yes	Yes	Yes
η_{el} [%]	25.2	25.2	25.7	27.6
$\eta_{thermal}$ [%]	56.2	66.9	67.1	71.8
CO_2 captured** [Mtpa]	1.6	1.6	1.3	1.3
Effective CO_2 capture rate [%]*	90	90	90	71

* The CO_2 capture plant always operates with 90% CO2 capture rate
** With 8400 operating hours per year



Important cost assumptions:
- Electricity price: 30 €/MWh
- District heat price: 50 €/MWh

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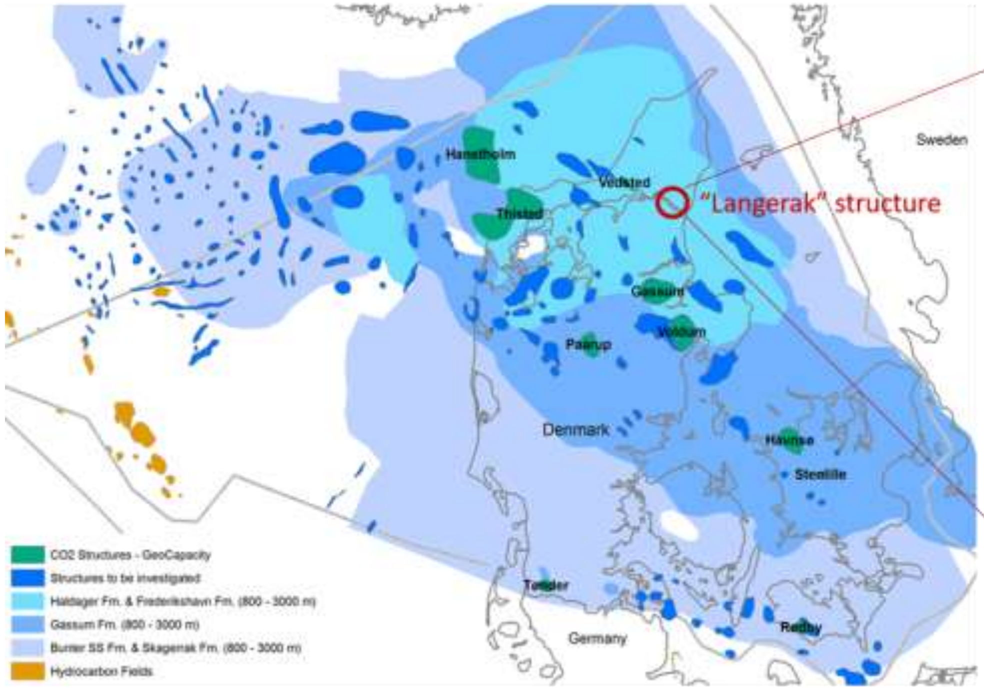
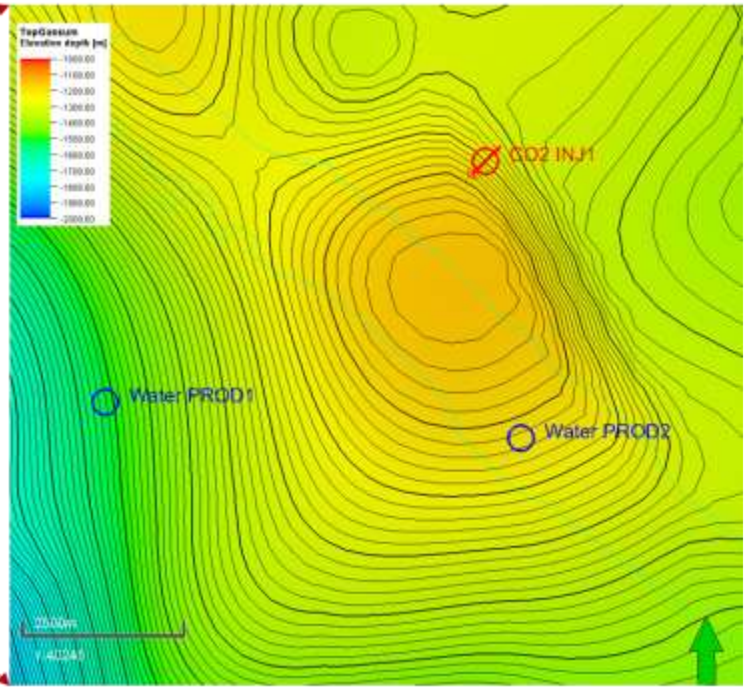
CO_2 storage site in the 'Langerak' structure, 6 km SE of the plant

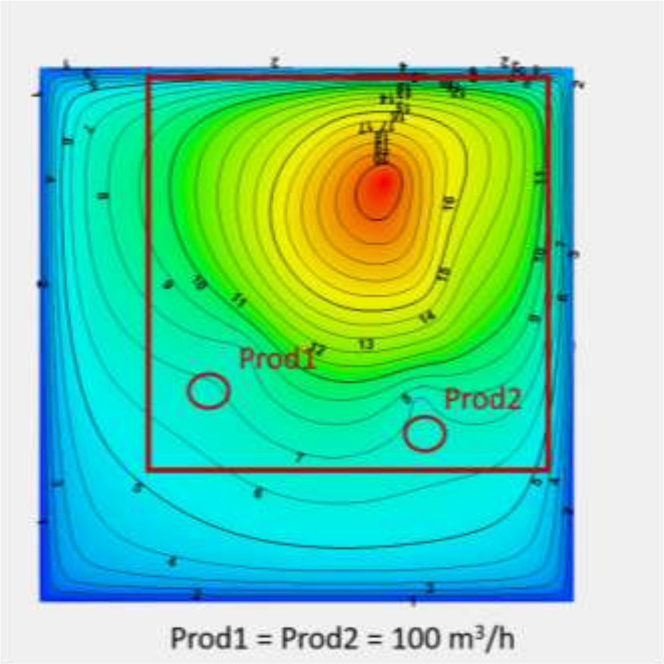
- Gassum Formation (Sandstones of Upper Triassic – Lower Jurassic age)
- 4-way closure with good reservoir properties (permeabiliy ~50-200 mD)
- 1 injection well, 1 to 2 water producton wells for pressure management

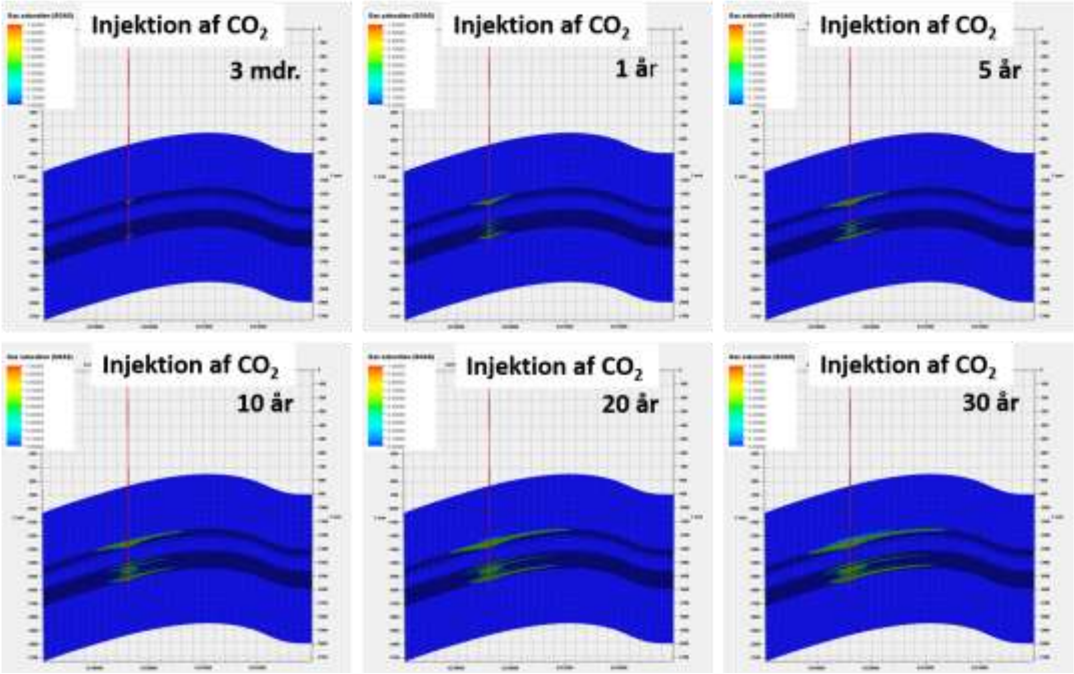




CO_2 plume and pressure development after 30 years of injection, injection rate = 1 Mtpa

- A voidage replacement of approx. 50% could maintain the pressure increase below 5 bar at the boundary of the storage complex for two production wells. A pressure increase below 1 bar required voidage replacement of 70%.
- Unresolved regulatory issues on how much the pressure is allowed to increase
- Heat from produced water can potentially be used in the district heating system





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Concluding remarks

- Techno-economic evaluation of MEA-based CO_2 capture integrated in a bio-CHP plant
  - Effect of heat recovery to district heat system, CHP load conditions and size of CO_2 capture plant were investigated

- Capture costs calculated in the range of 52-77 €/t CO_2
  - Heat recovery from CO_2 capture process for DH utilization significantly improves the techno-economic performance of the integrated system → results in ~30% reduction in CO_2 capture cost, from 77 to 52 €/t CO_2
  - Not strongly affected by capture plant size and boiler load in the range of 75-100% boiler load

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Concluding remarks

- A promising storage site, the Langerak structure in the Gassum formation, in proximity to the Nordjyllandsværket CHP
  - Injection of up to 1 Mtpa of CO_2 for 30 years is feasible from one injection well

- The investigated bio-CHP + CO_2 capture plant is an example of BECCS application
  - Potential to be CO_2-negative, given proper management of biomass supply chain

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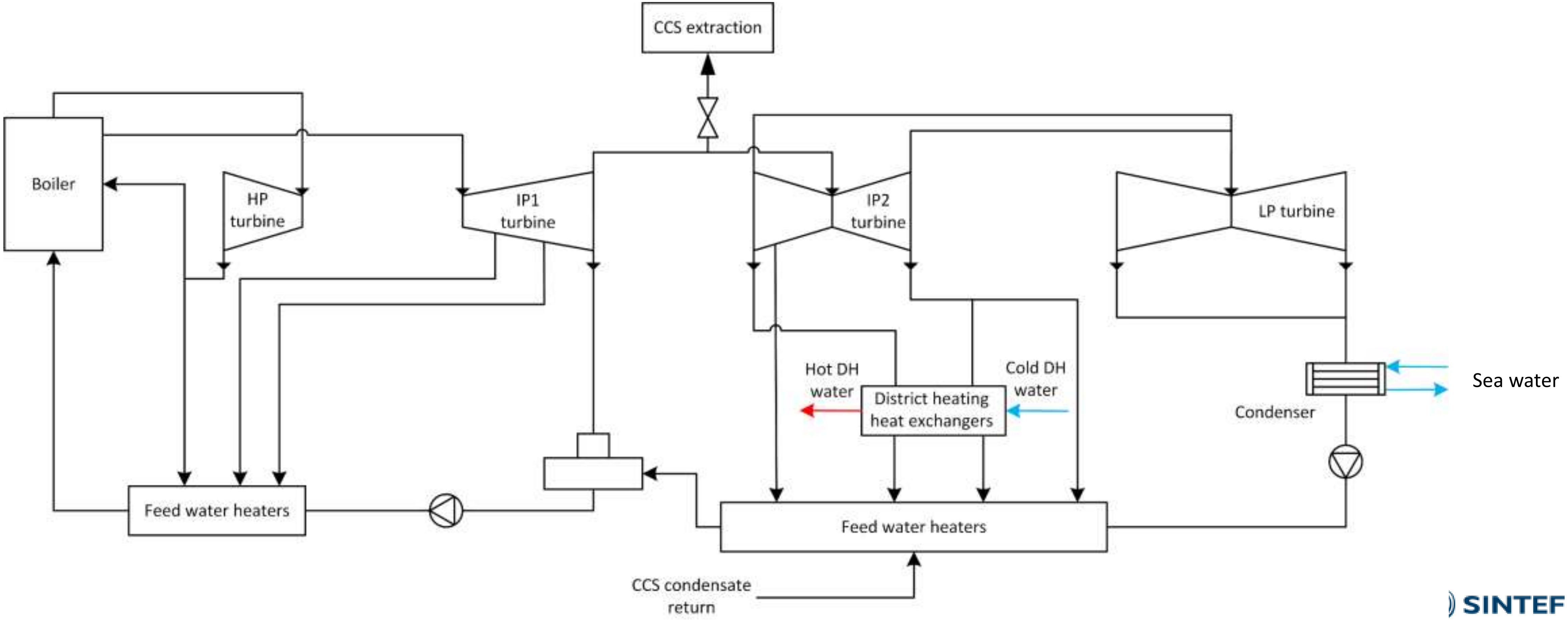
Process flow diagram for the bio-CHP steam cycle



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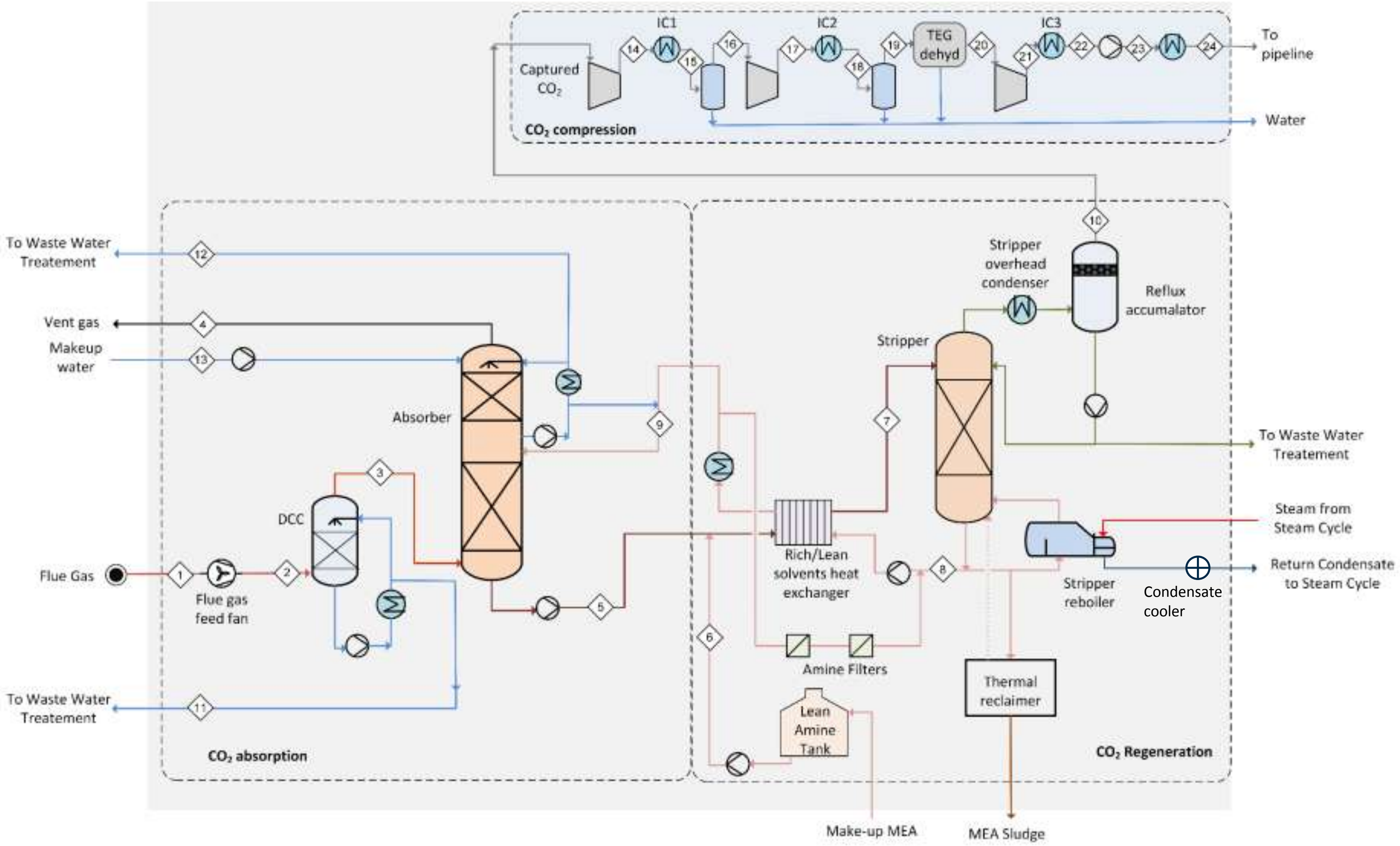
Process flow diagram for MEA capture process



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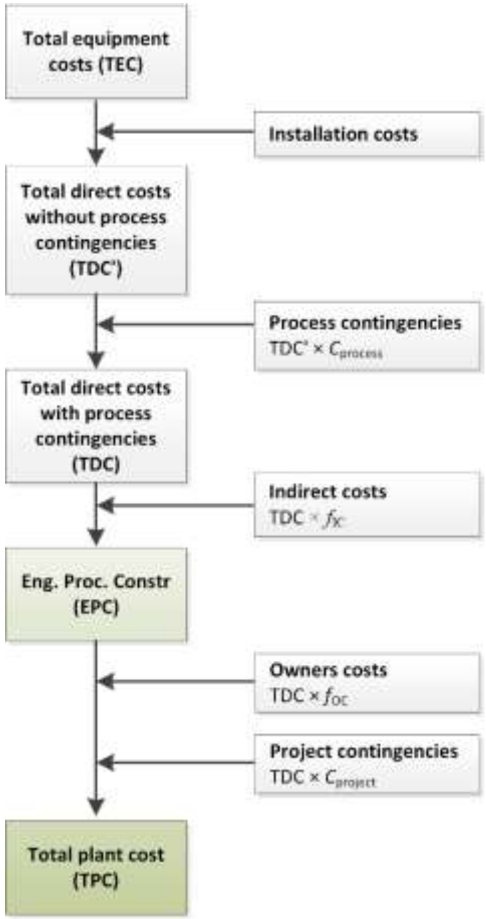
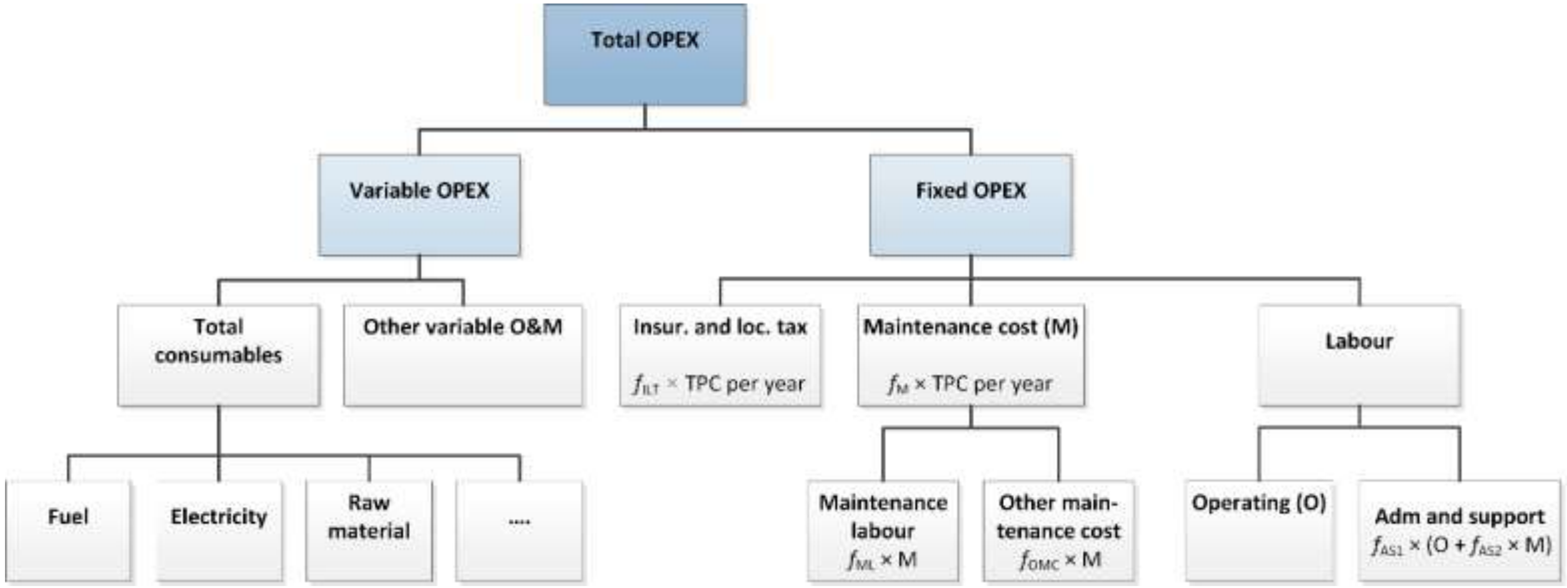
Cost estimation method – Bottom-up analysis

CAPEX:



OPEX:



Technical results – CO_2 absorption

Parameter	Value
CO_2 product purity [mol%]	99.4
Purified flue gas temperature [°C]	64
Purified flue gas pressure [bar]	1.02
Specific stripper reboiler duty [MJ/kg CO_2]	3.83
Stripper reboiler temperature [°C]	119.3
Specific power consumption [MJ/kg CO_2]	0.53
Specific cooling demand, w/o heat recovery for DH [MJ/kg CO_2]	4.2
Specific MEA make-up [kg/t CO_2]	2
Specific process water make-up [kg/t CO_2]	615

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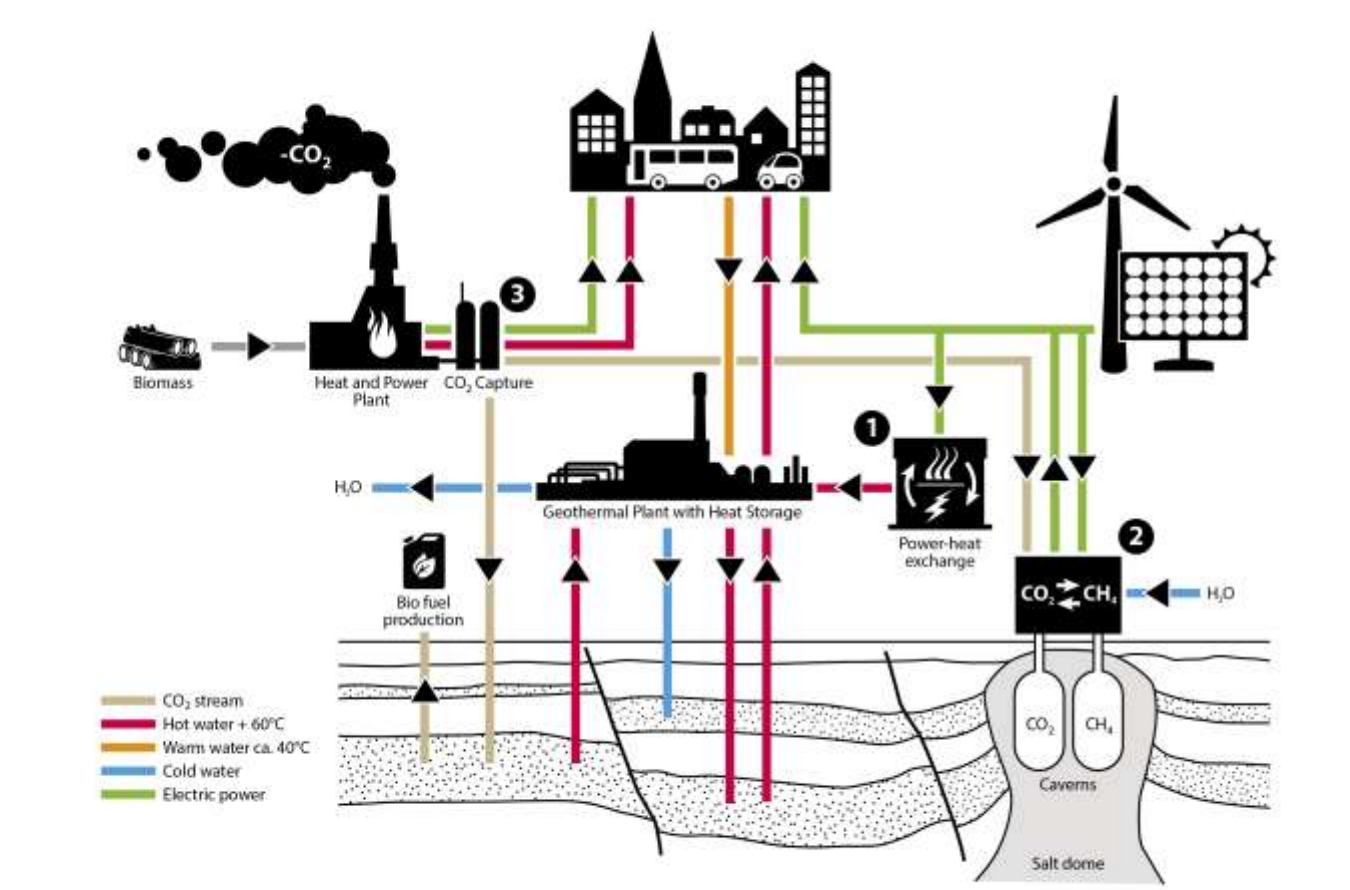
Cost assumptions overview

General	
Cost basis	€$_{2015}$
Operational life [years]	25
Plant construction time [years]	3
Discounted cash flow rate [%]	8
Yearly operating hours [h]	8400
CAPEX	
Process contingencies [% TDC']	18
Indirect costs [% TDC]	14
Owner's costs [% TDC]	7
Project contingencies [% TDC]	15
OPEX	
Insurance and local taxes [% TPC]	2
Maintenance cost with maintenance labour [% TPC]	2.5
Operating labour, number of persons in capture plant	20
Cost of operating labour [k€/person/year]	60
Maintenance labour cost [% of maintenance cost]	40
Administrative labour cost [% O&M labour cost]	30
Cooling water [€/m^3]	0.02
MEA [€/t]	1450
Process water [€/m^3]	6.65
Electricity [€/MWh]	30.1
District heat [€/MWh]	49.9

Technical results – AVV 1 with CO_2 capture

Parameter	100% load, no CCS	75% load, no CCS	Case 0	Case 1	Case 2	Case 3
Fuel input [MW_{th}]	640	497	640	640	497	640
Gross power [MW_{el}]	234	180	203	203	160	213
Power consumption, CO_2 capture plant [MW_{el}]	0	0	29	29	23	23
Net power [MW_{el}]	219	170	161	161	128	177
District heat from power plant [MW_{th}]	352	273	170	170	129	206
District heat from CO_2 capture plant [MW_{th}]	0	0	0	97	76	76
Heat for CO_2 capture [MW_{th}]	0	0	209	209	164	164
$\eta_{thermal,net}$ [%]	89.2	89.2	56.2	66.9	67.1	71.8
$\eta_{electrical,net}$ [%]	34.3	34.2	25.2	25.2	25.7	27.6
CO_2 captured [t/h]	0	0	196	196	155	155
Net CO_2 capture rate [%]	-	0	90	90	90	71

The CONvert concept



1. Surplus EL to heat
2. Surplus EL to CO_2/CH_4
3. CO_2 capture from biomass CHP and option for future synthetic fuel production

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Methodology for techno-economic assessment

Power plant data → CO_2 capture process simulations (energy and mass balances) → Cost estimations (CAPEX + OPEX) → Cost of CO_2 captured/avoided

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