Satom CCS Outline Design

RAMBOLL

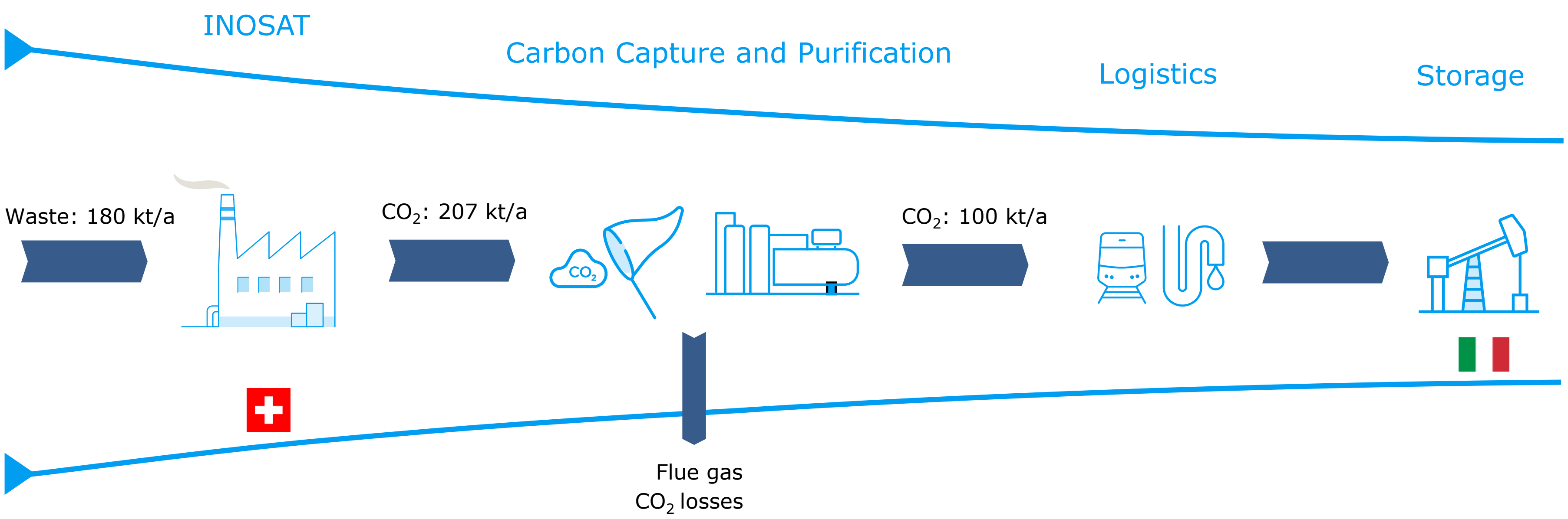
Bright ideas.
Sustainable change.

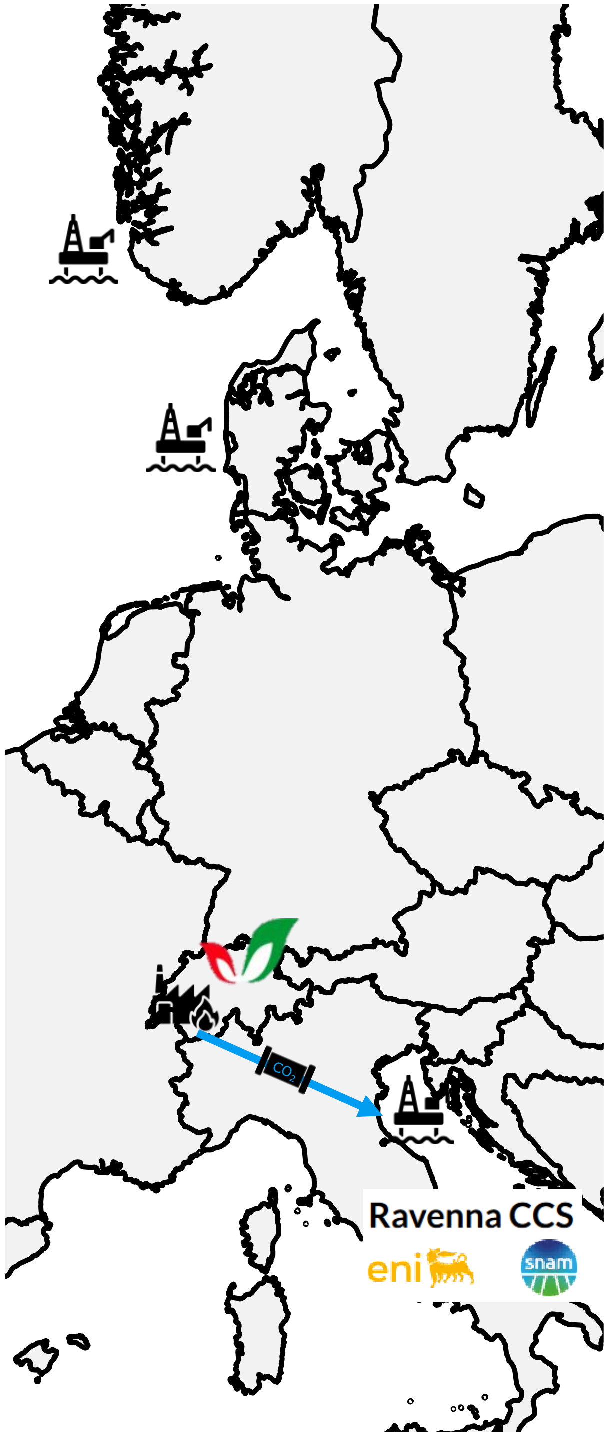
Design Basis

01

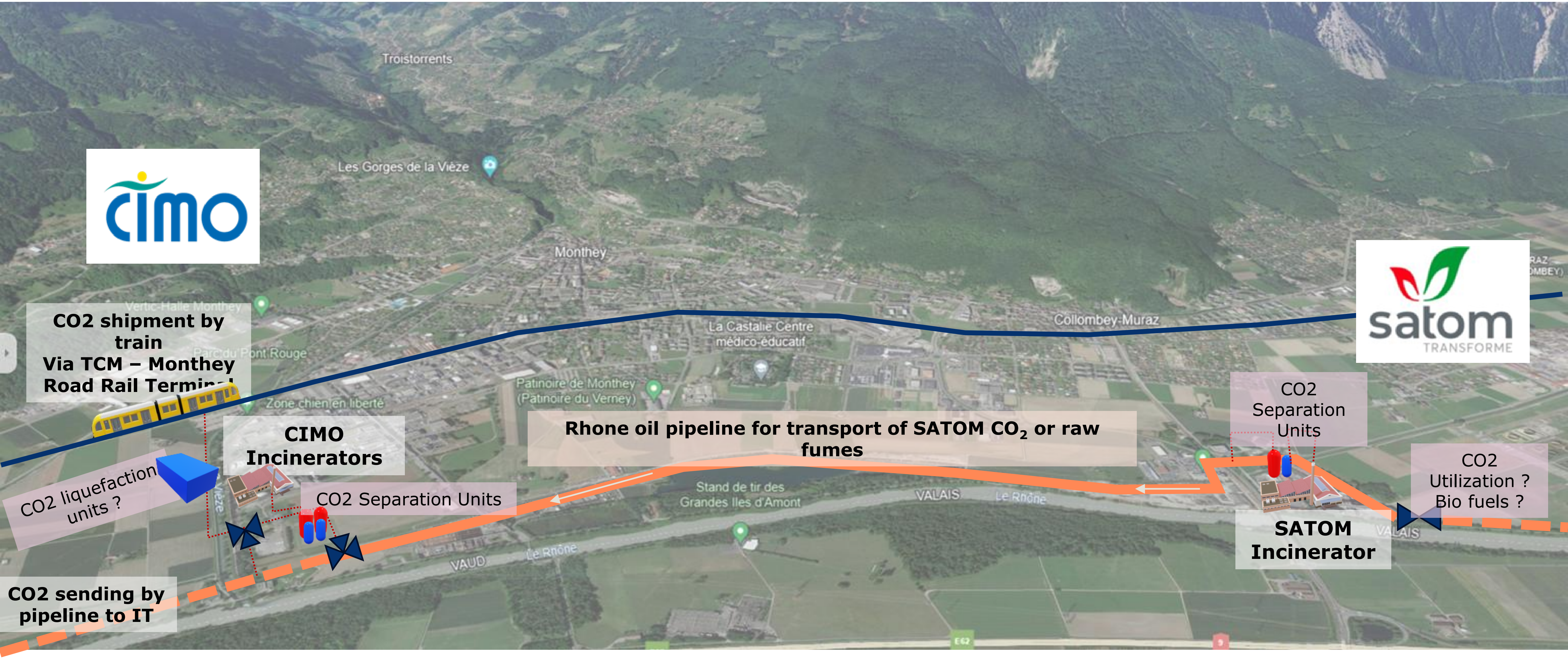
Design basis for CC suppliers

- Capturing 110’000 t_{CO2}/8’000h at Satom EfW INOSAT (so that 100 kt/a can be stored reliably)
- Flue gas volume flow 102’000 Nm³/h dry @ 10-12 vol-% CO_2
- Temperature after INOSAT flue gas condensation 40 °C
- No specification of separation efficiency from flue gas for suppliers
- CO_2 purity meeting ENI pipeline and Ravenna storage requirements
- Gaseous transport in pipeline (40 bar)

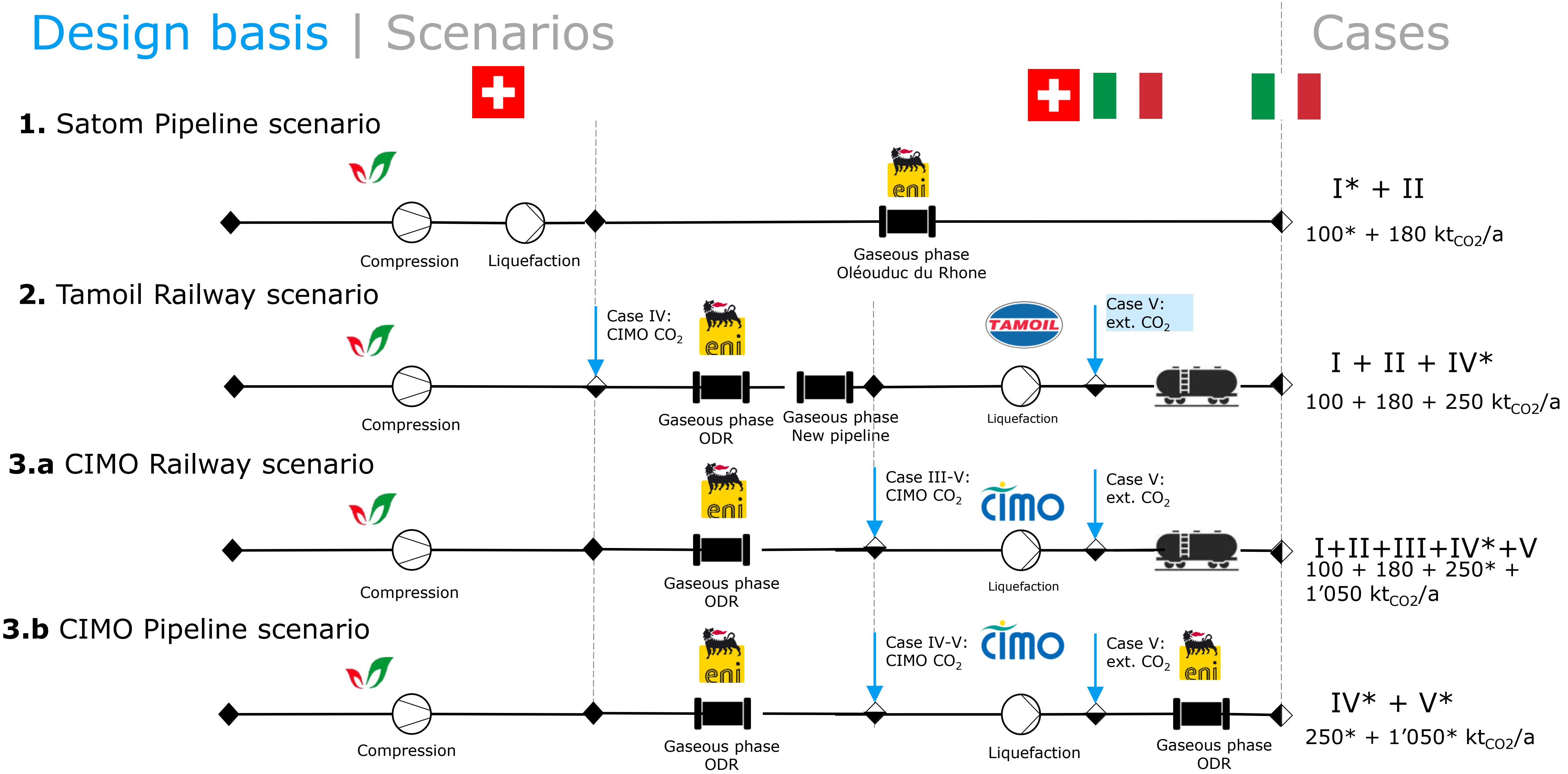




Ecosystème CO_2 Chablais



Design basis | Scenarios



*included as 3D models in final results

Carbon Capture

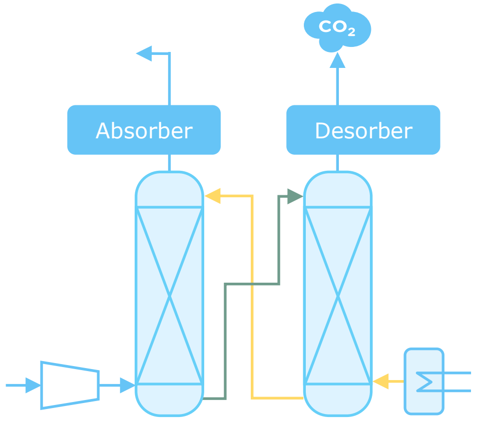
02

Post-Combustion Technologies

Absorption

In absorption, CO_2 is selectively removed through physical or chemical interaction with a regenerable liquid solution.

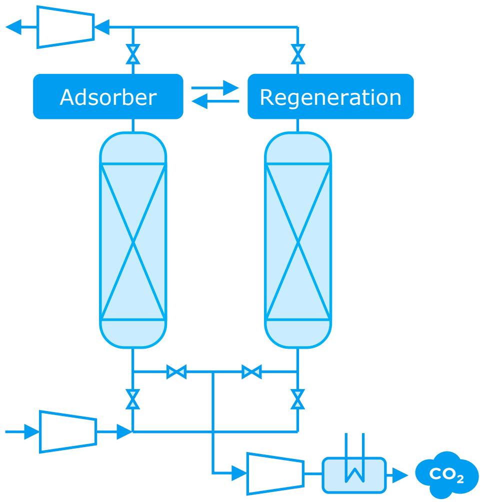
The solvents used are amines, potassium carbonate, and physical solvents.



Adsorption

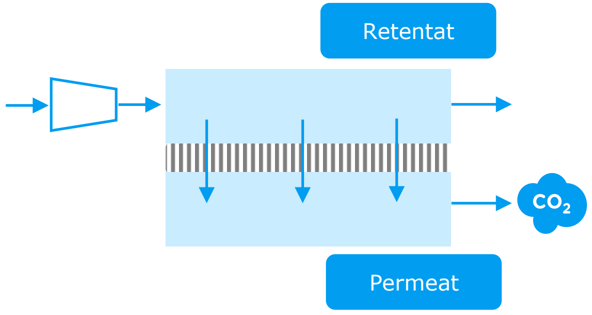
The CO_2 is selectively bound to the surface of a solid material in batch operation through chemical or physical bonds.

The solid material is then regenerated by heat or pressure, releasing the CO_2.



Membrane

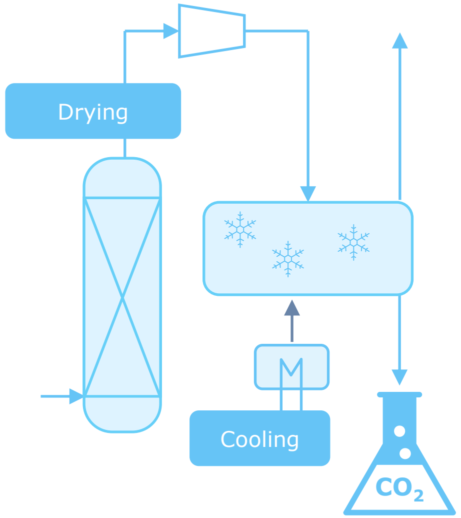
Membrane technology uses materials that selectively allow CO_2 to pass through a thin barrier medium under the influence of a driving force, such as a pressure difference.



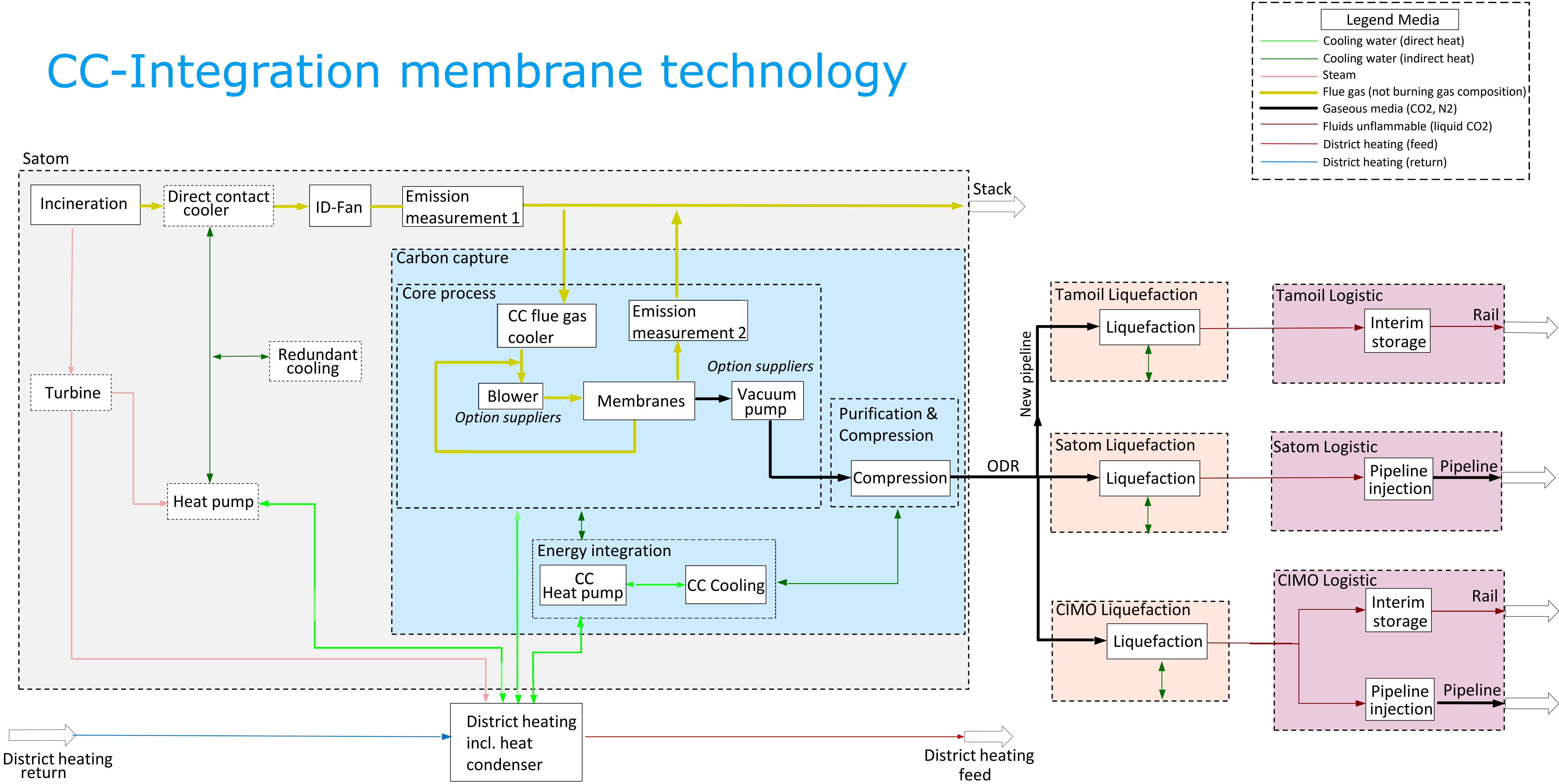
Cryogenic separation

Cryogenic technologies separate CO_2 by cooling it to very low temperatures, which liquefies the CO_2 and separates it from other, non-condensed gases.

Not suitable for EfW plants, as high CO_2 concentrations are required!



CC-Integration membrane technology

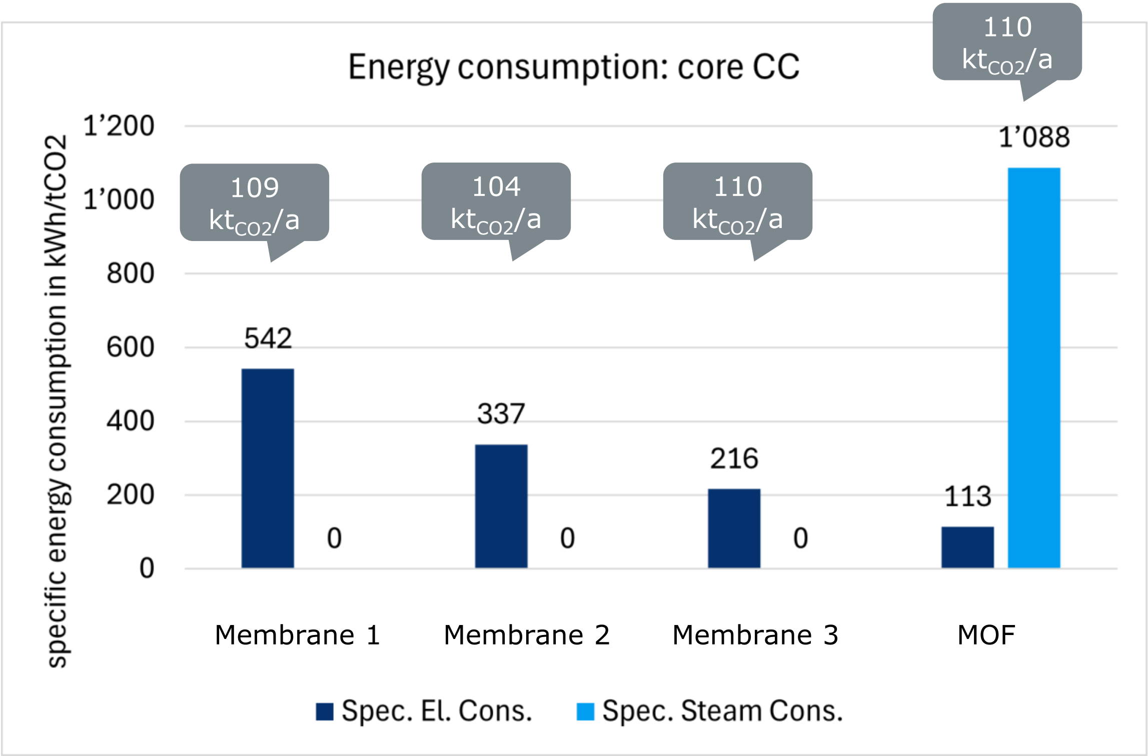


*simplified version, for detailed depiction please refer to the PFD

Results

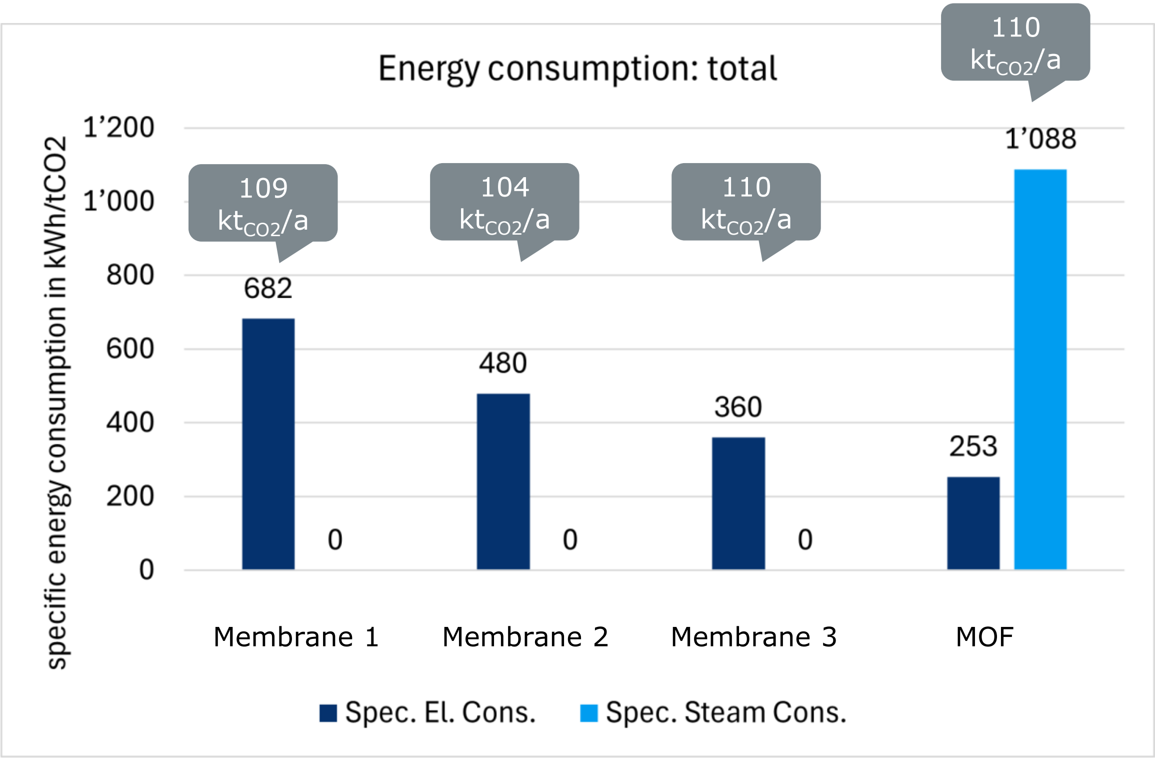
03

Specific energy consumption (in kWh/t_{CO2}) based on supplier data and corrections by Ramboll



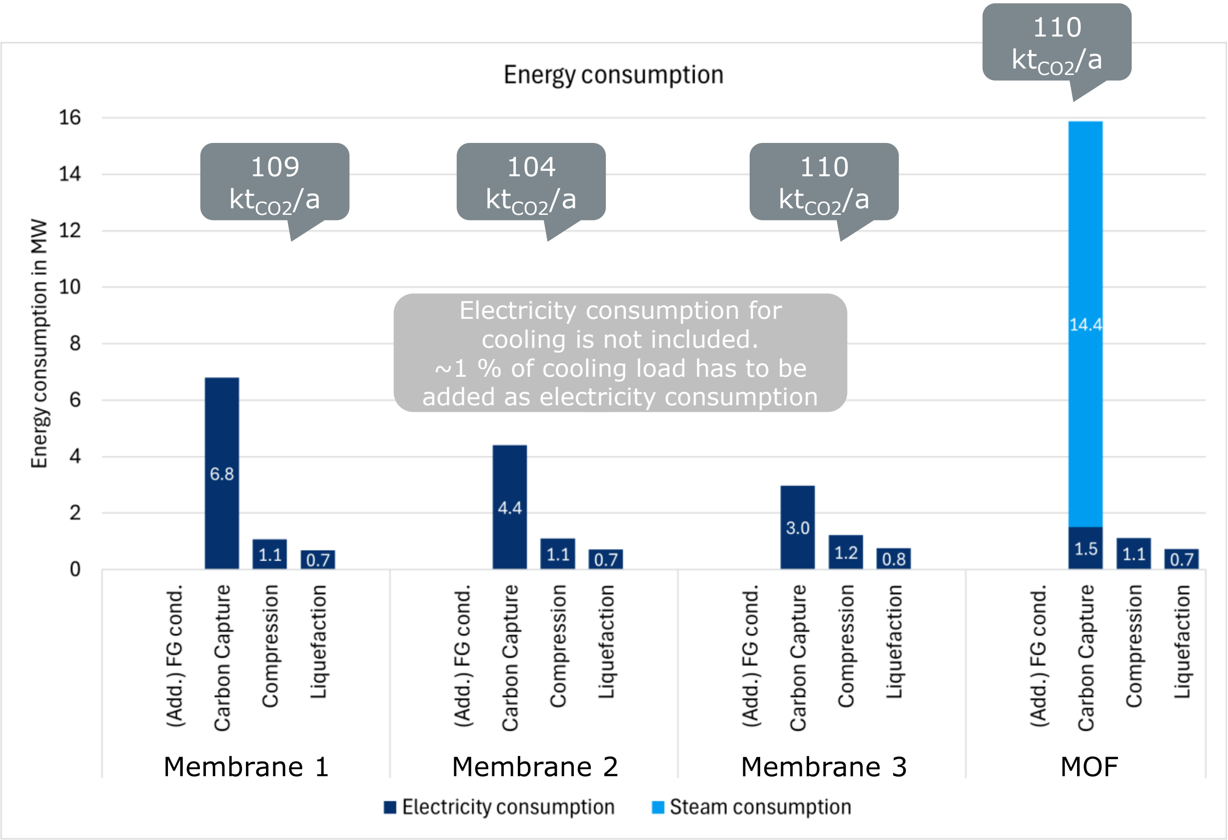
Amines: 30-50
HPC: 230-290

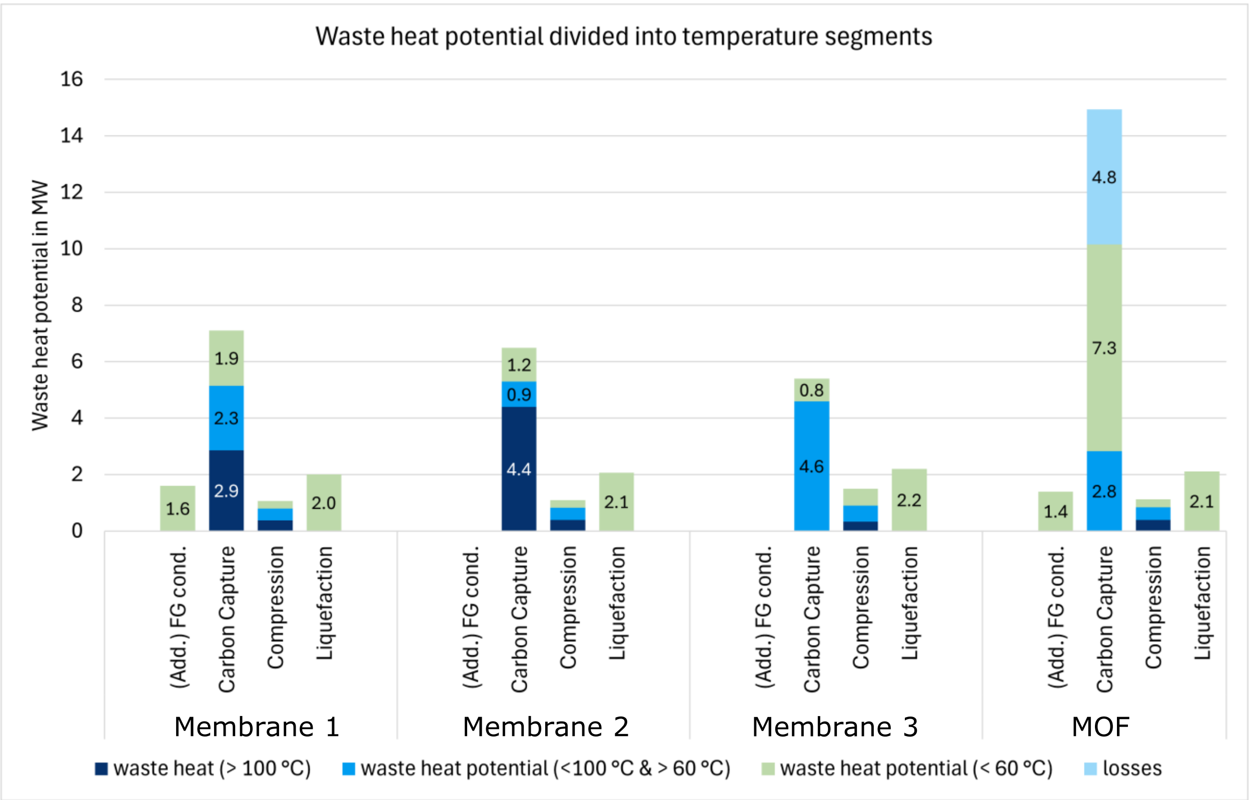
Amines: 990-1'170
HPC: 0-630



- Electricity consumption for cooling is not included → ~1 % of cooling load has to be added as electricity consumption
- Heat pump is not included (see next slides for energy integration)

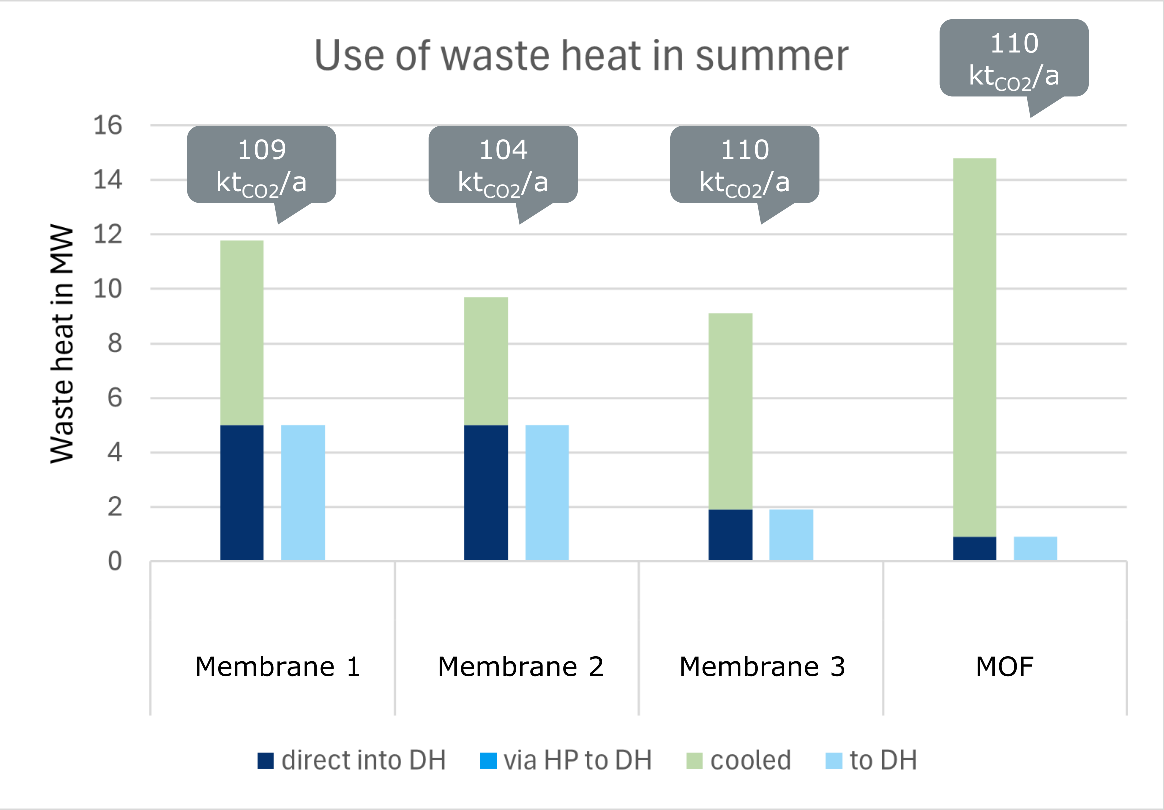
Summary energy consumption and waste heat potential

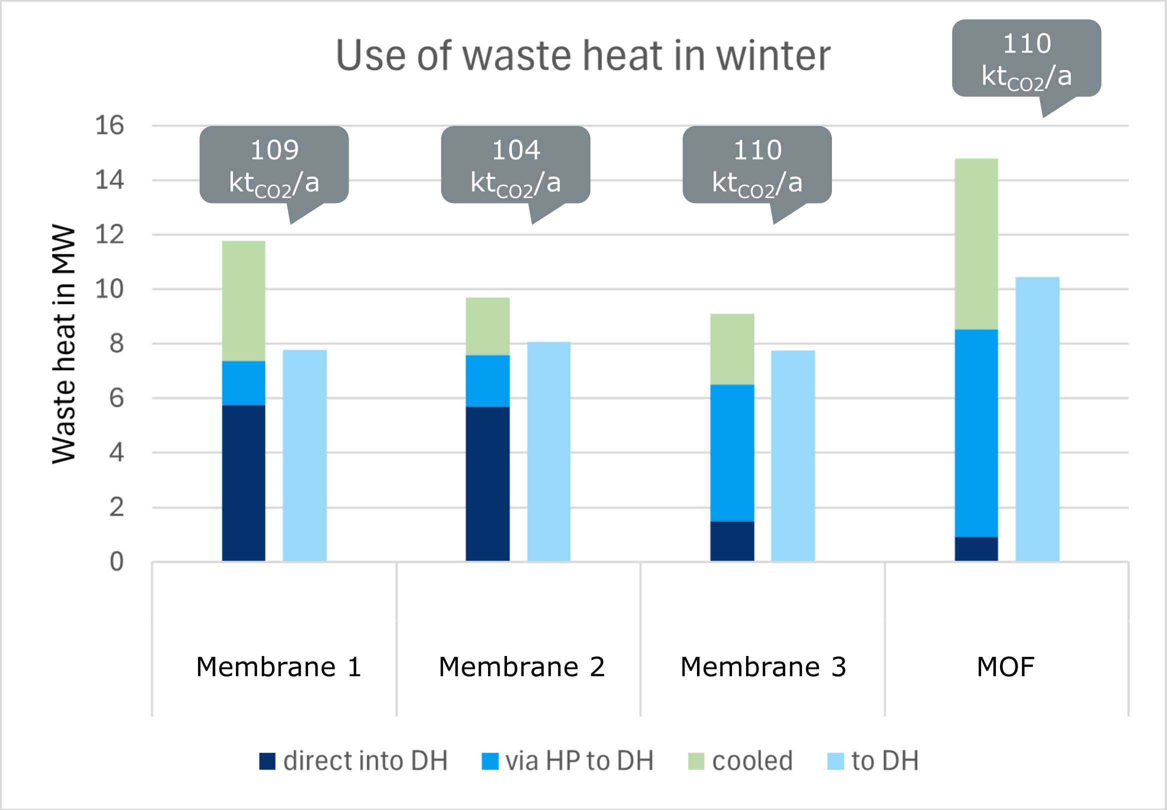




- **Losses:** MOF uses ambient air to cool and dry the adsorbent after the regeneration process → the heated air is blown into the stack
- **Waste heat potential > energy consumption:** Flue gas stream is entering the CC plant at 40 °C and 1 bar, while CO_2 leaves the plant in liquid phase; Additionally, water (from the flue gas stream) condenses

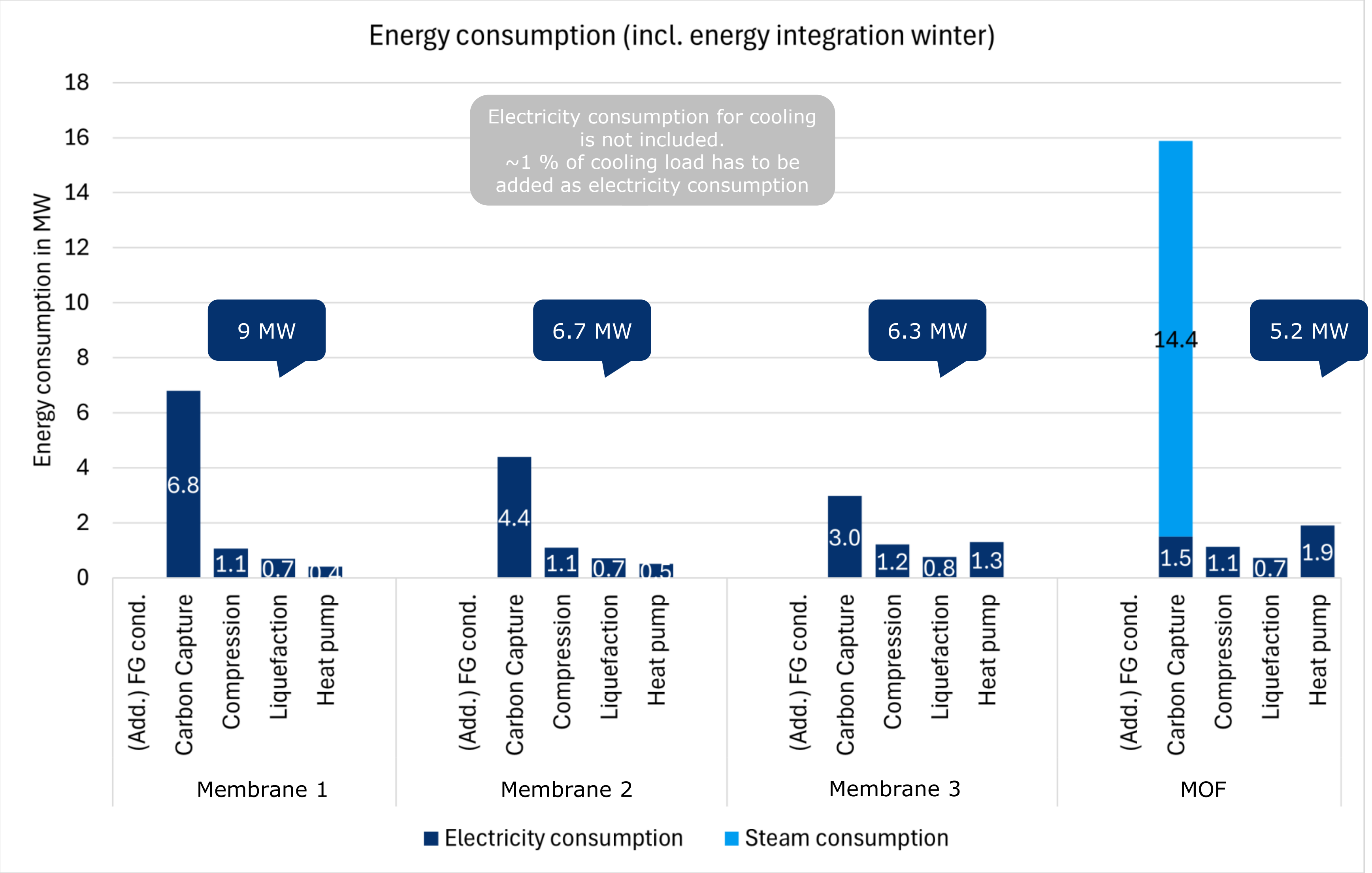
Summary of energy integration





- Depicted waste heat covers (add.) flue gas condensation, carbon capture, CO_2 compression and CO_2 liquefaction.
- Electricity consumption for heat pump needs to be added separately.
- Difference in winter is supplied by HeiKo (and absorption HP INOSAT)

Summary energy consumption (incl. heat pump in winter)



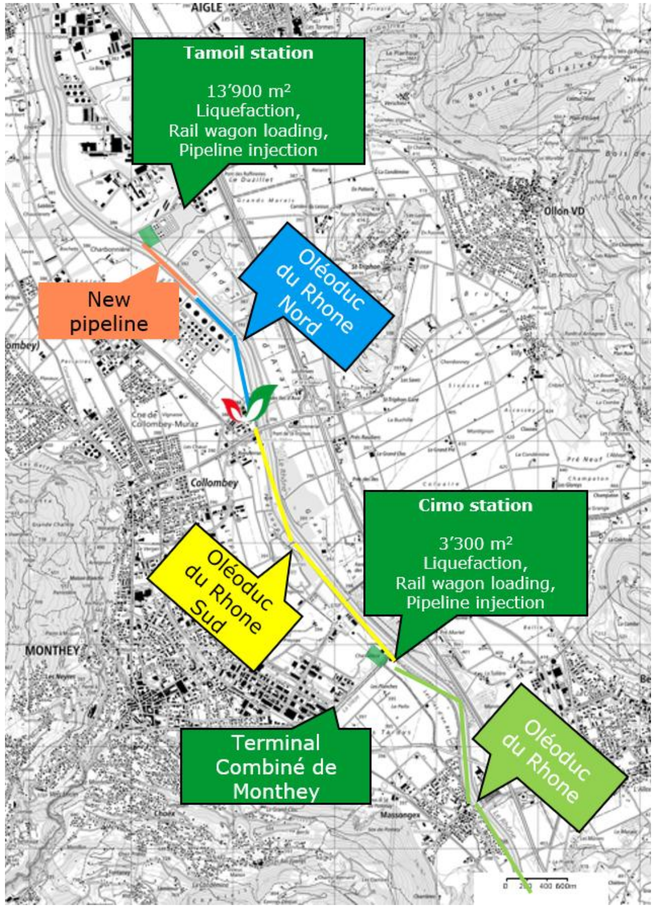
Economics
CAPEX

Basis/Assumptions:

- Cost estimation for core process by suppliers
- Ramboll experience for whole process chain
- Cost reference year: 2025
- Accuracy Estimate AACE 4: -30/+50 %
- Costs for acquiring construction site, any demolitions, financing, ancillary building, planning, reserve (3%) and unforeseen (15%) in **total CAPEX** included
- Market maturity is lowest for Carbon Capture, biggest development expected
- Compression and liquefaction identical for all suppliers (interface and quality)
- Scope: FG integration until logistics (Pipeline/Railway)

Assumptions for pipeline CAPEX:

- New pipeline to Tamoil: Pipeline needs to be constructed (total costs included)
- Oleoduc du Rhone (Nord/Sud): ENI will be Owner, Satom will modernize Pipeline and operate it



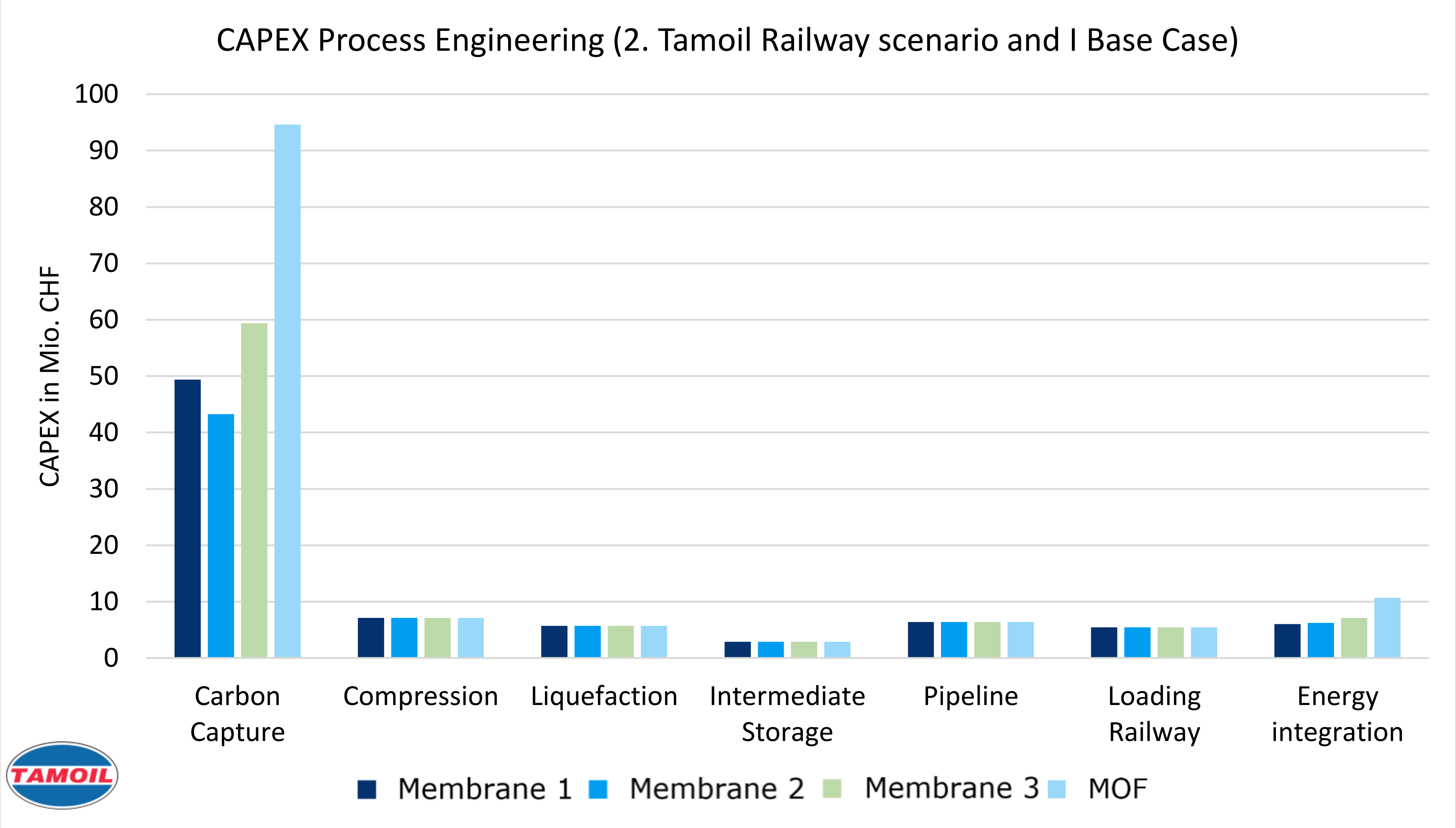
Economics
CAPEX – Investment costs (2. Scenario, I Base Case)

Total CAPEX:

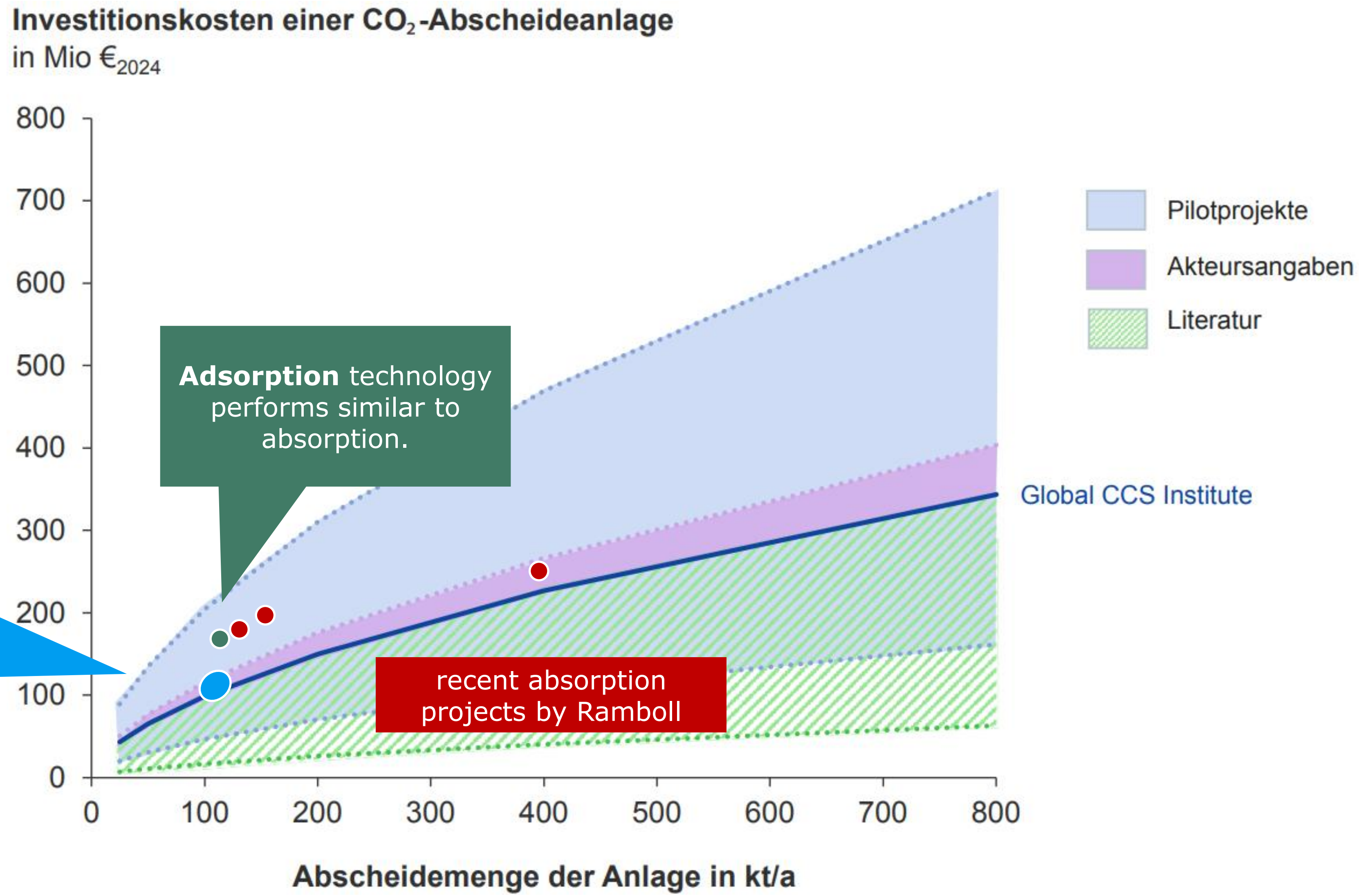
- Membrane 1: 120.0 Mio. CHF
- Membrane 2: 112.3 Mio. CHF
- Membrane 3: 134.6 Mio. CHF
- MOF: 185.7 Mio. CHF

Remarks:

- New pipeline to Tamoil required
- Storage capacity due to railway transport needed



Economics
CAPEX



The cost calculation shows that **membrane** technology is very competitive compared to other CC projects.

Based on: MVV Energie AG (2025): Wege zur Skalierung von Negativemissionstechnologien – Empfehlungen für Marktdesign, Infrastruktur und Finanzierung. Mannheim

Economics
OPEX

- Heat integration **revenue** is **not included**

Parameter	Unit	Value
Operational hours winter	h/a	4’000
Operational hours summer	h/a	4’000
Operational hours total	h/a	8’000
Electricity consumption for cooling	-	1%
maintenance costs	-	3%
Depreciation rate	-	3%
Depreciation period	a	20

Parameter	Unit	Value
Electricity price (Oct-Mar): winter	CHF/MWh	90
Electricity price (Apr-Sep): summer	CHF/MWh	60
External electricity price: winter	CHF/MWh	270
External electricity price: summer	CHF/MWh	190
Steam price	CHF/MWh	50
DH price winter	CHF/MWh	-48
DH price summer	CHF/MWh	-48
cooling water price	CHF/m^3	10

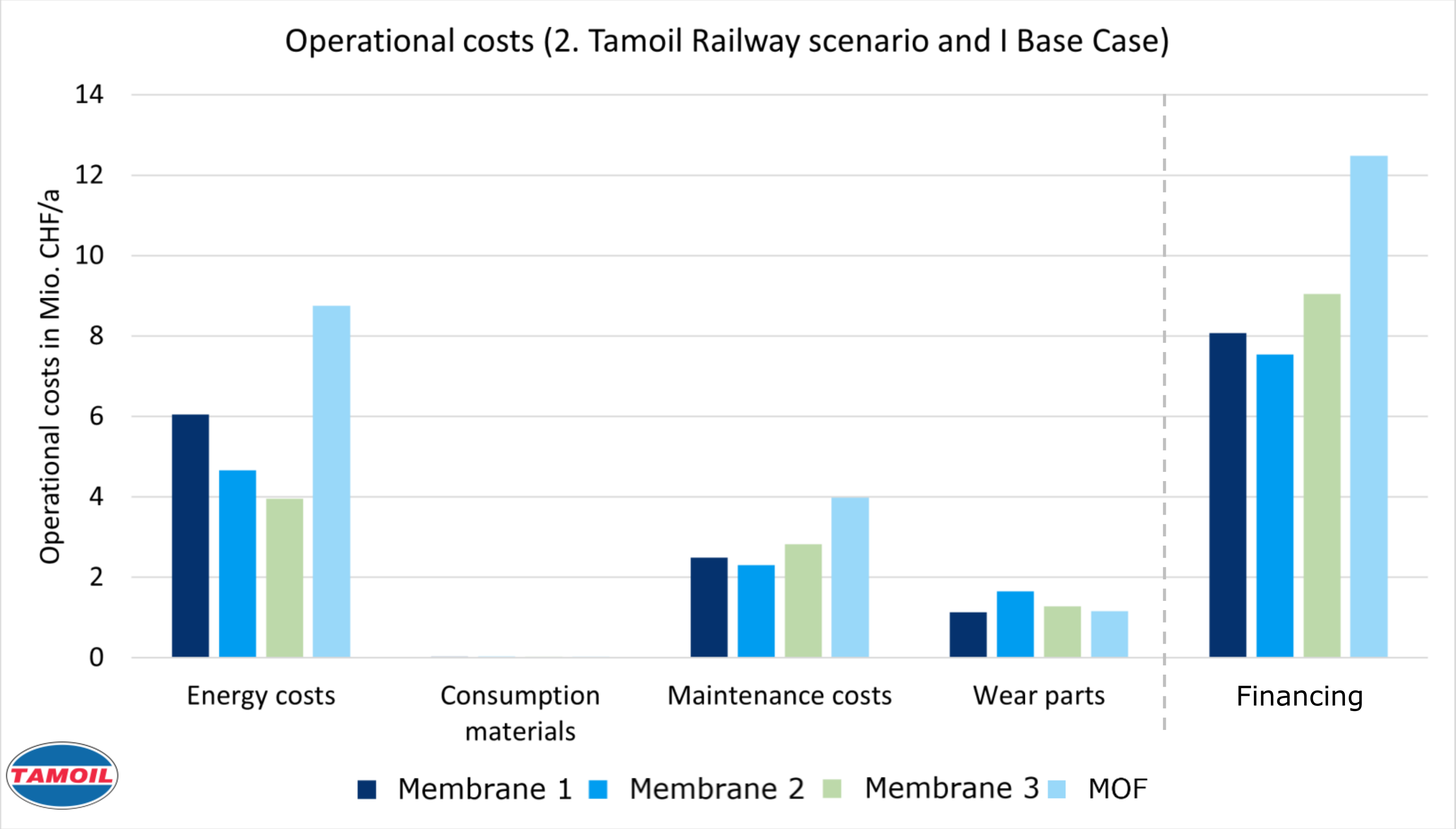
Economics
Operational costs (2. Scenario, I Base Case)

OPEX:

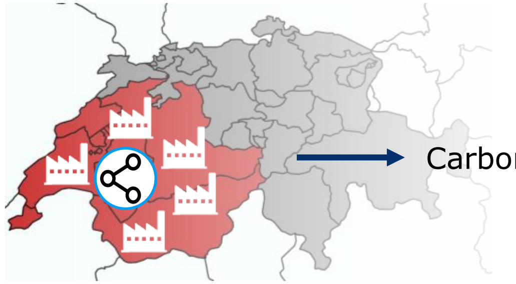
- Membrane 1: 17.8 Mio. CHF/a
- Membrane 2: 16.2 Mio. CHF/a
- Membrane 3: 17.1 Mio. CHF/a
- MOF: 26.4 Mio. CHF/a

Remarks:

- Energy costs are higher because of external price for electricity demand



Tamoil Hub Case



Carbon Capture

CO_2 distribution and logistics to **Hub**

Section of ODR pipeline retrofitting and building of new pipeline for connection to Tamoil area

Retrofitting of the railway freight station. Check how long the tank cars will be used (note the maximum dwell time during shunting).

Pipeline Constraint

(valid for ODR and new pipeline)

- 40 bar, DN300, Booster station every 20 km
- CO_2 velocity < 10-15 m/s

→ approx. **1'200 kt/a** for 8'000 h/a

Railway Constraint

- Available space for un-/loading: 2x10 wagons = 1'100 tCO2
- Loading speed: 1'100 t / 2 h = 550 t/h

*Un-/Loading availability**

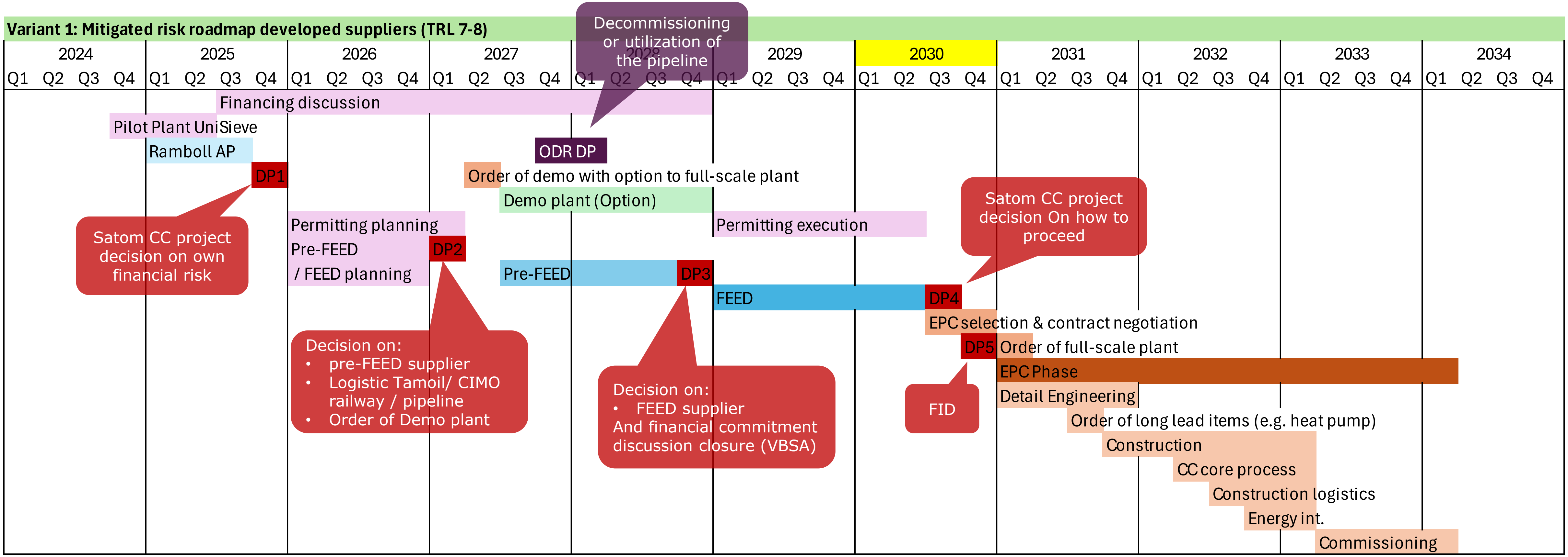
➔ ~ 24 h/d approx. 4'400 kt/a
➔ ~ 16 h/d approx. **2'900 kt/a**
➔ ~ 8 h/d approx. 1'500 kt/a

*during CC-plant uptime (i.e. 8'000 h/a)

Conclusion:

- ODR is capable of transporting the defined hub case quantities. → Dense phase needed for higher quantity.
- Railway would be able to transport more → Complex and challenging infrastructure
- Process engineering (liquefaction, compressor, etc.) will fit → Layout dependent on railway/pipeline composition

Roadmap: Mitigated Risk



Summary and next steps

- Carbon Capture is technically and spatially feasible at the Satom EfW plant
- High potential for CC and logistic with the available space (green field Satom, Tamoil and CIMO), potential pipeline transport ODR and excellent connection to railway network (especially Tamoil)
- All suppliers are highly interested in project realization within given limited time frame
- The energy integration is supplier dependent and closely linked to the ongoing projects (e.g., INOSAT), potentials for waste heat utilization and integration with a CC heat pump could be quantified ranging from 5.4 to 10.1 MW
- Investment costs range from 93.2 to 166.6 Mio. CHF (Membrane 2, MOF, both 1. and I) resulting in a range from 60 CHF/t_{CO2} to 102 CHF/t_{CO2} (based on 20 a and 3 %)

- Supplier studies on feasibility level with corresponding costs inaccuracy – follow up studies for higher cost accuracy and optimized space and energy integration (for a fee)
- Reduction of scope for cases and locations, final scenarios decision depending on several factors (utilization of ODR, hub case possibilities, political framework)
- Decision point end of year for the FEED/pre-FEED planning necessary and financing

Driving the Transformation to Net-Zero Industries

using high-performance membrane technology

UniSieve

satom TRANSFORME

Final report

Membrane Based Carbon Capture Testing Campaign

July 2025

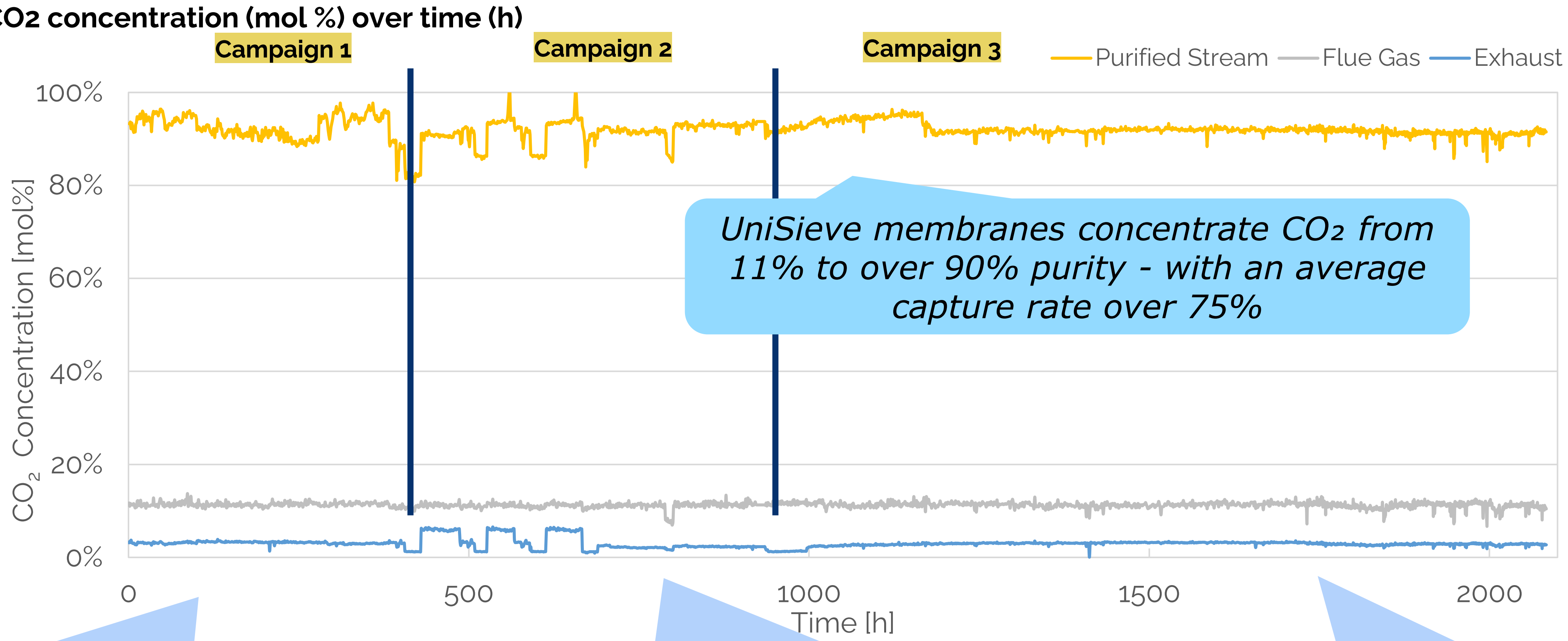
From November 2024 to July 2025, UniSieve has been conducting membrane-based carbon capture at KVA Satom

Pilot unit designed to capture **100 kg of CO_2 per year** from flue gas

Two-stage membrane system for **carbon capture from 11% CO_2 to >90 %** - *suitable for liquefaction*

Three testing campaigns to validate key design parameters for scale ups

Over 2000 hours of operation were completed across three campaigns to validate key design parameters

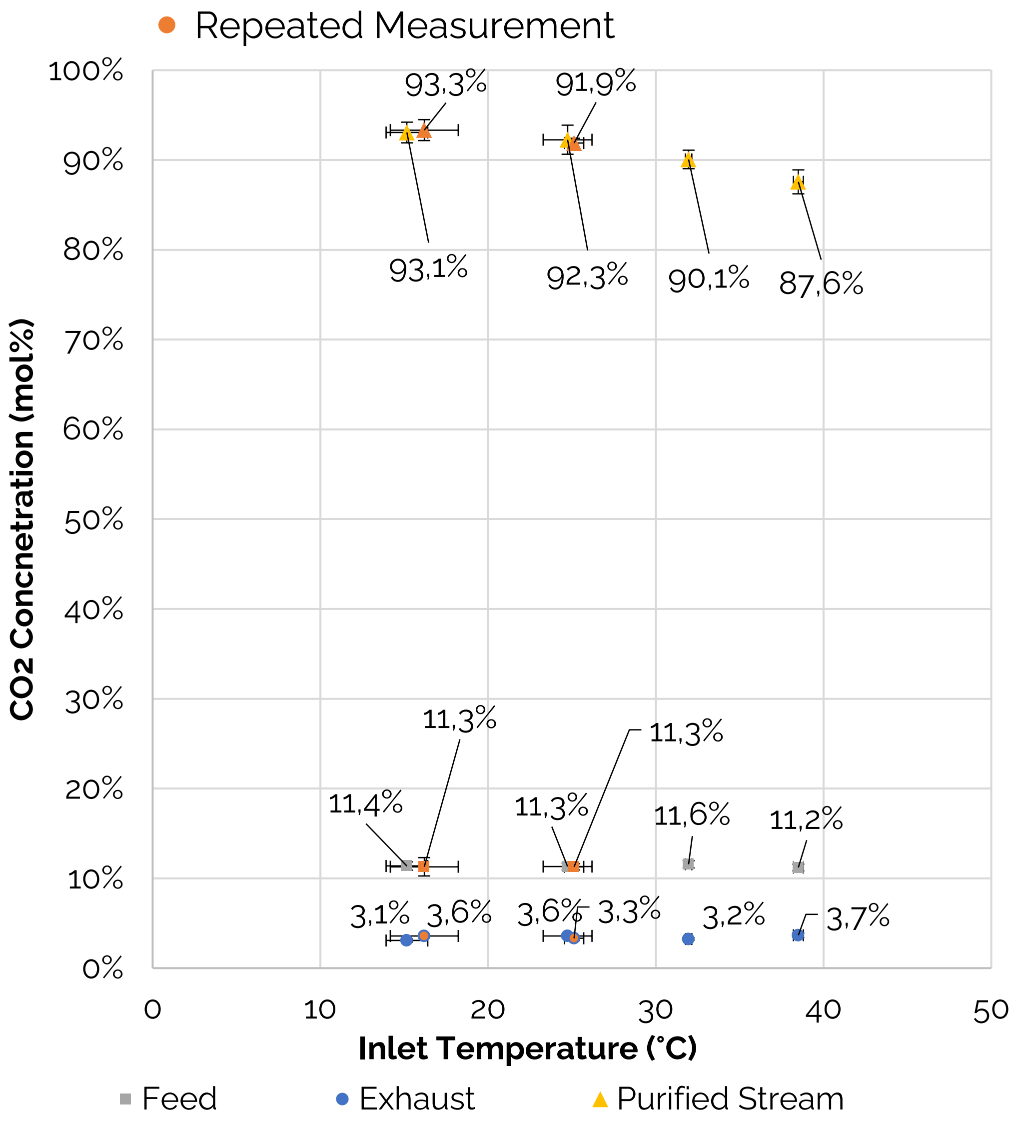


Campaign 1 - Vary flue gas inlet temperature between 15 to 40°C
All tested temperatures achieved CO_2 purity levels suitable for liquefaction

Campaign 2 - Vary CO2 Capture rates from 50 to 90%
Purity target suitable for liquefaction achieved across all capture rates - Demonstrates flexible operation, allowing load following operation

Campaign 3 - Vary filter size from 0.3 um to no filter
Stable operation and similar CO2 purity observed with different filter sizes

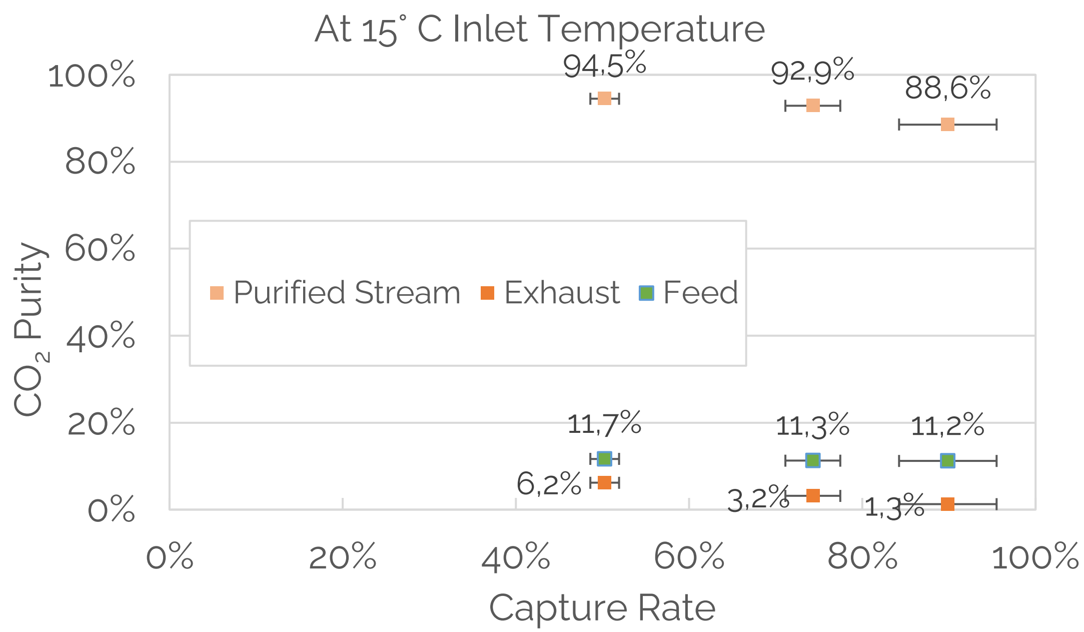
Campaign 1 – Flue gas inlet temperature variation results

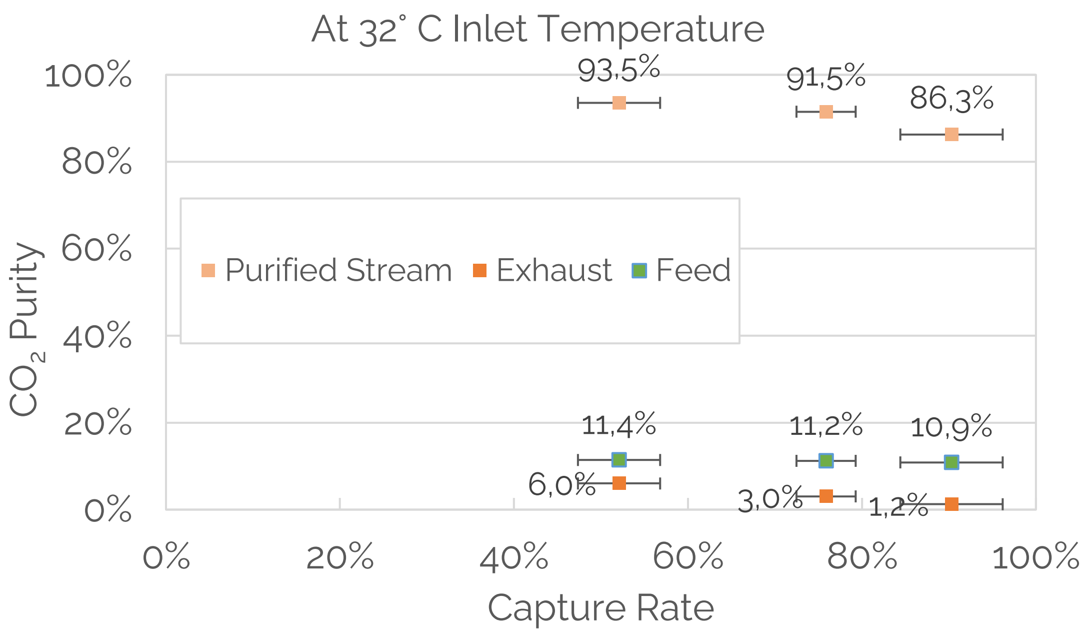


<u>**Overview**</u>

- **Vary flue gas inlet temperature between 15 to 40°C – each test was run for 100 h**
- **All tested temperatures achieved CO_2 purity levels suitable for liquefaction**
- **The lower the inlet temperature the higher the CO2 concentration at outlet**

Campaign 2 - Capture rate variation results



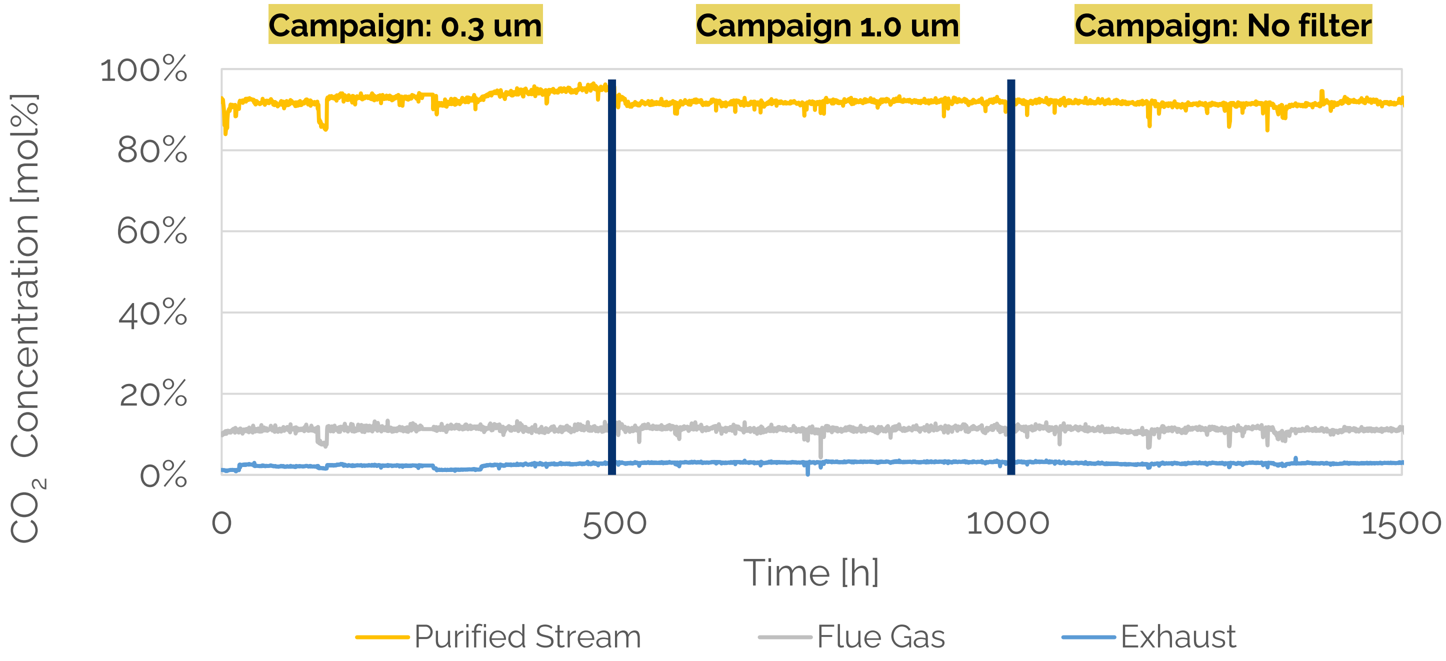


Conclusions:

- Different capture rates (50%, 75%, 95%) at varying temperatures (15°C, 32°C) validated
- Purity target suitable for liquefaction achieved across all capture rates - Demonstrates flexible operation, allowing load following operation

Campaign 3 - Filter testing campaign – All tests

CO2 concentration (mol %) over time (h)



Observations:

- Stable operation of the system with different filter sizes
- Similar CO2 purity, recovery were observed for over 1500 hours of continuous operation with 0.3um, 1.0um, and without strainer

Campaign 3 - Filter testing campaign – All tests

Filtration rate Comparison

Filtration Rate	um	0.3	1.0	no filter
Permeate Flow	nL/h	5.88	6.08	6.03
CO_2 Permeate	mol %	92.86	91.83	91.54
Recovery	%	75.59	74.75	75.52

Observations:

At the same inlet process conditions, similar CO_2 purity, recovery, and permeate flow were observed for over 1500 hours of continuous operation with 0.3um, 1.0um, and without strainer

Key learnings:

- Large filtration 1.0 um is suitable for continuous operation
- Opex can be reduced ~ 0.5% by adopting adopting larger filtration rate (1.0 um)

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