ESTEP SPRING DISSEMINATION EVENT

5-6 JUNE 2025 KRAKOW (POLAND)

Power4Steel with MemKoWI:

separation of CO_2 and H_2 from process gases
by advancing membrane technology
from R&D to pilot-testing

Susanne Bethlehem-Seidel (Dillinger Hüttenwerke)

ESTEP

HOTEL ★★★★ GALAXY JORDAN GROUP

Łukasiewicz GIT

R&D&I for low- CO_2 steel production

Power4Steel with MemKoWI:

separation of CO_2 and H_2 from process gases
by advancing membrane technology from R&D to pilot-testing
in Steel-, Cement- and Biomass-plants

→ There are steel-producer in Europe with huge investment in low-CO_2 steel production and high engagement in synergetic R&D&I in progress to find solution for technology gaps!

Susanne Bethlehem-Seidel, Nico Neuber (Dillinger)
Torsten Brinkmann, Jan Pohlmann (Hereon)
Tim van Gestel, Karl-Ernst Gerhards, Wilhelm A. Meulenberg, Kai Wilkner (FZ Jülich)

Power4Steel Funding:

Ministerium für Wirtschaft, Innovation, Digitales und Energie SAARLAND

Federal Ministry for Economic Affairs and Energy

MemKoWI Funding:
(FKZ: 03EE5115)

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Conventional ore-based steel production route at DILLINGER:

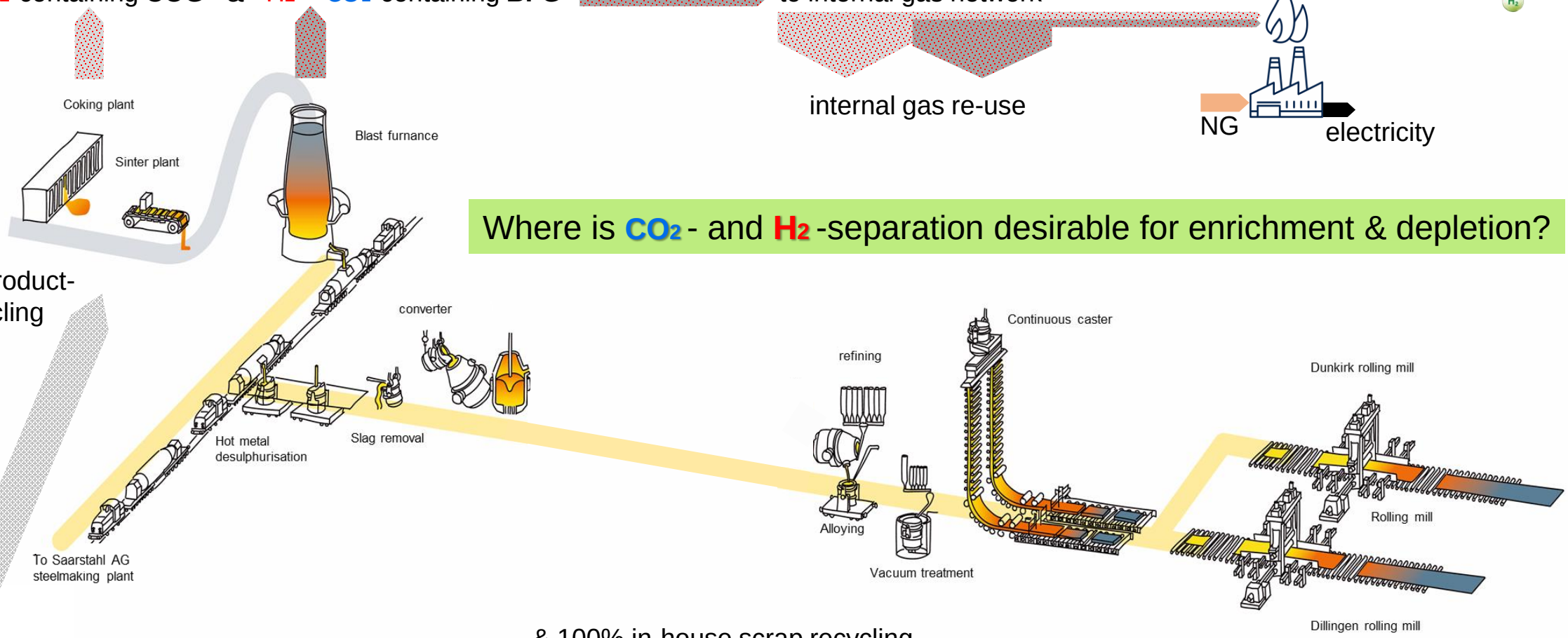
Efficient steel production with internal gas reuse and high internal recycling-rates

H_2-containing **COG** & H_2 + CO_2-containing **BFG** → to internal gas network

internal gas re-use

NG → electricity

Where is CO_2 - and H_2 -separation desirable for enrichment & depletion?



~95% by-product-recycling

& 100% in-house scrap recycling

internal pre-treatment of Fe-by-products (dust, sludge, scale, iron in slag)

Slag for cement industry, road construction,…

~5% landfill from by-products

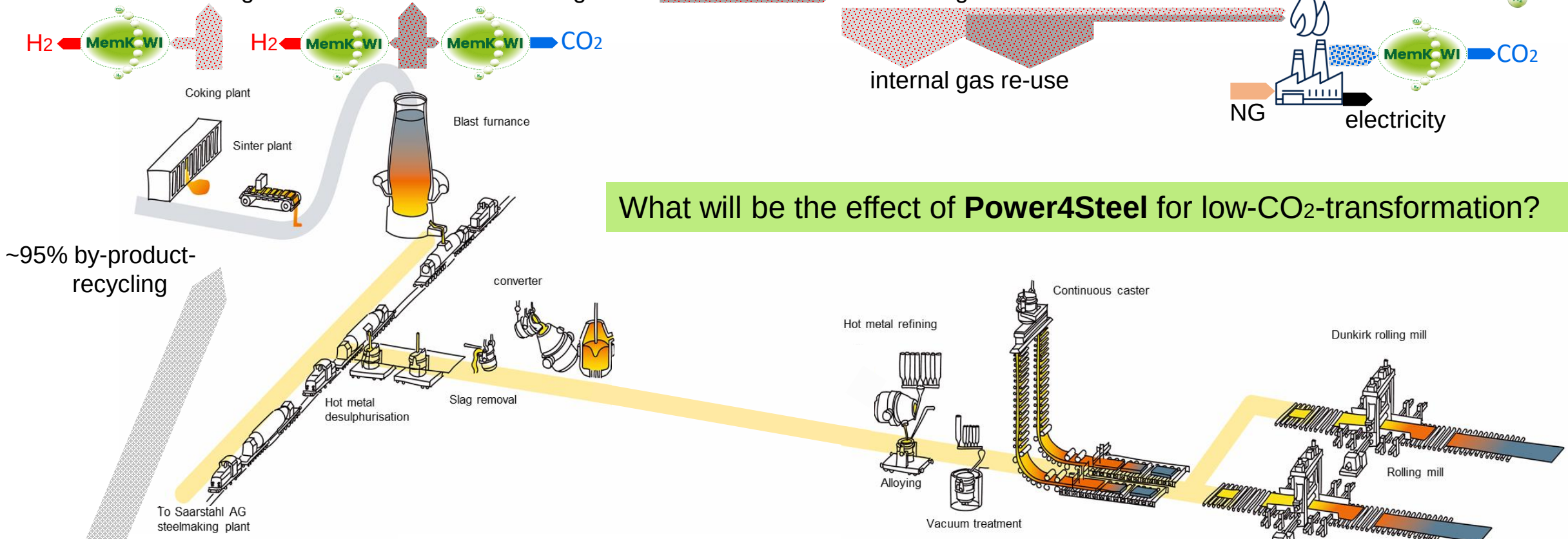
Conventional steel production route at DILLINGER with **MemKoWI**:

Optimization for reuse of H_2 and CO_2 -containing gases including sector coupling

H_2-containing **COG** & H_2 + CO_2-containing **BFG** → to internal gas network

internal gas re-use

NG, electricity, CO_2



What will be the effect of **Power4Steel** for low-CO_2-transformation?

~95% by-product-recycling

& 100% in-house scrap recycling

CO_2

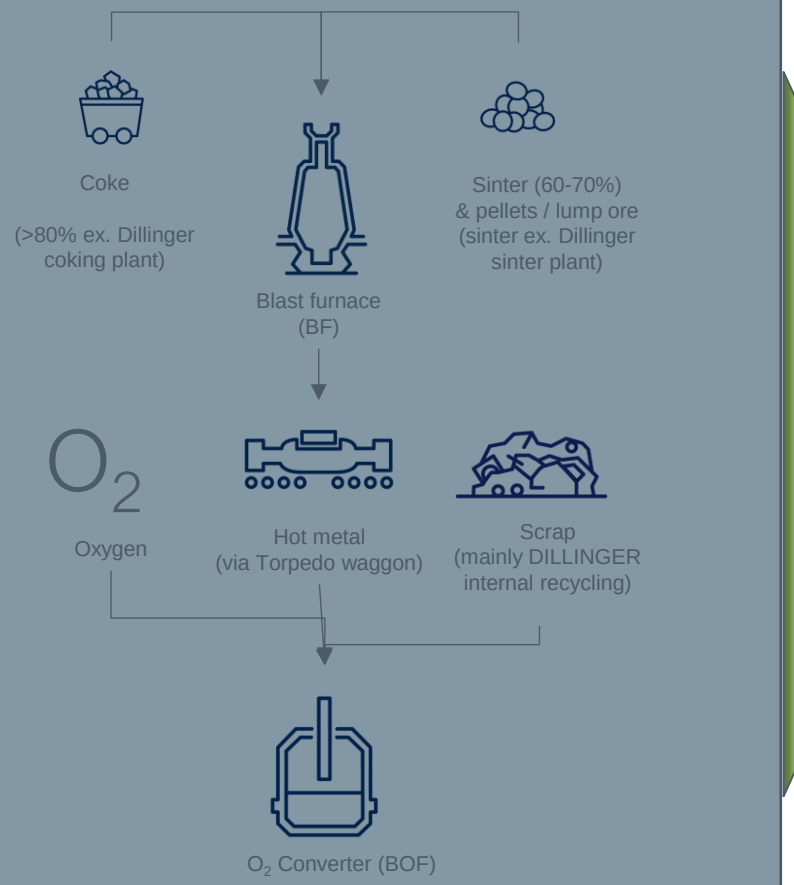
Slag for cement industry, road construction,…

internal pre-treatment of Fe-by-products (dust, sludge, scale, iron in slag)

~5% landfill from by-products

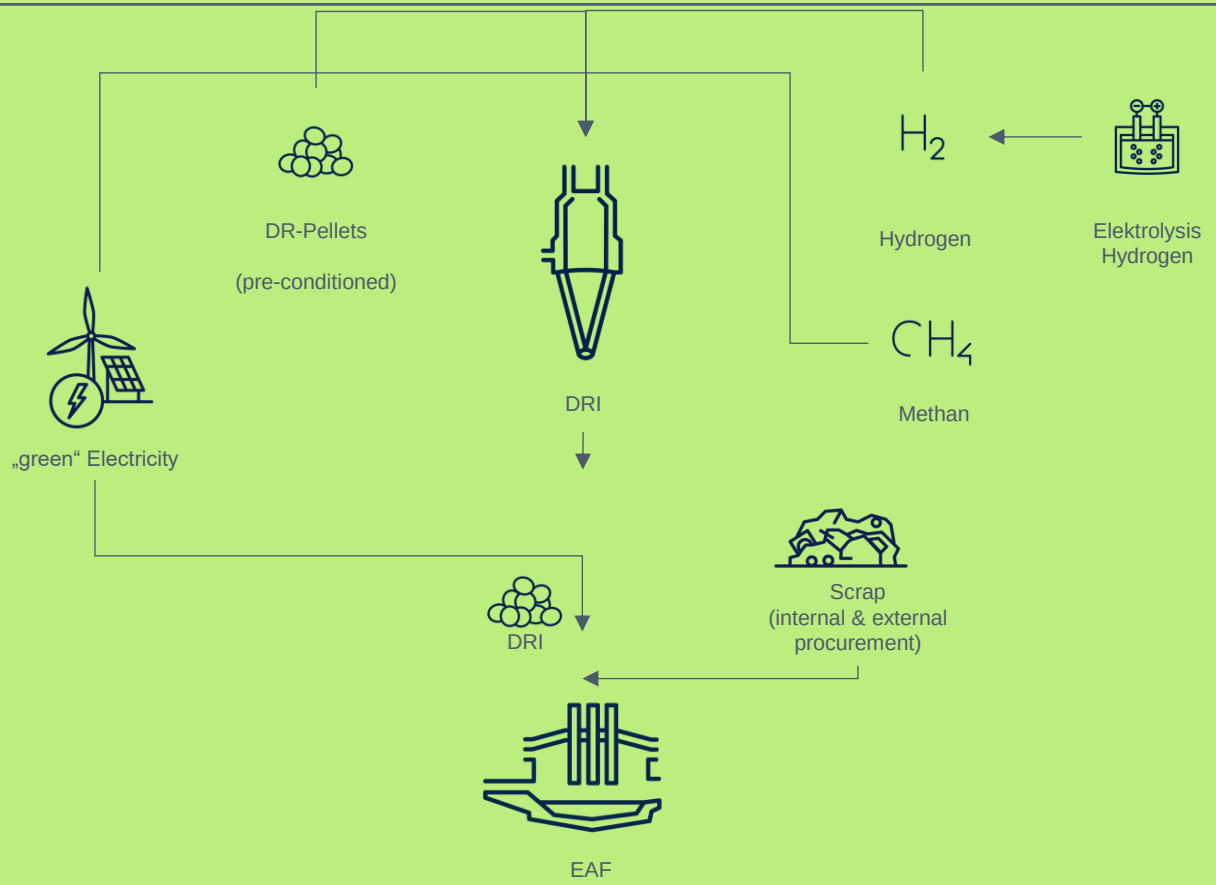
Steel production from „conventional“ to „green" (= low CO_2)

Ore-based BF-BOF-route



→ CO_2-Emissions 1.921 kg CO_2/t

Ore-based DRI-EAF-Route



→ CO_2-Emissionen 339 kg CO_2/t (“green” electricity)

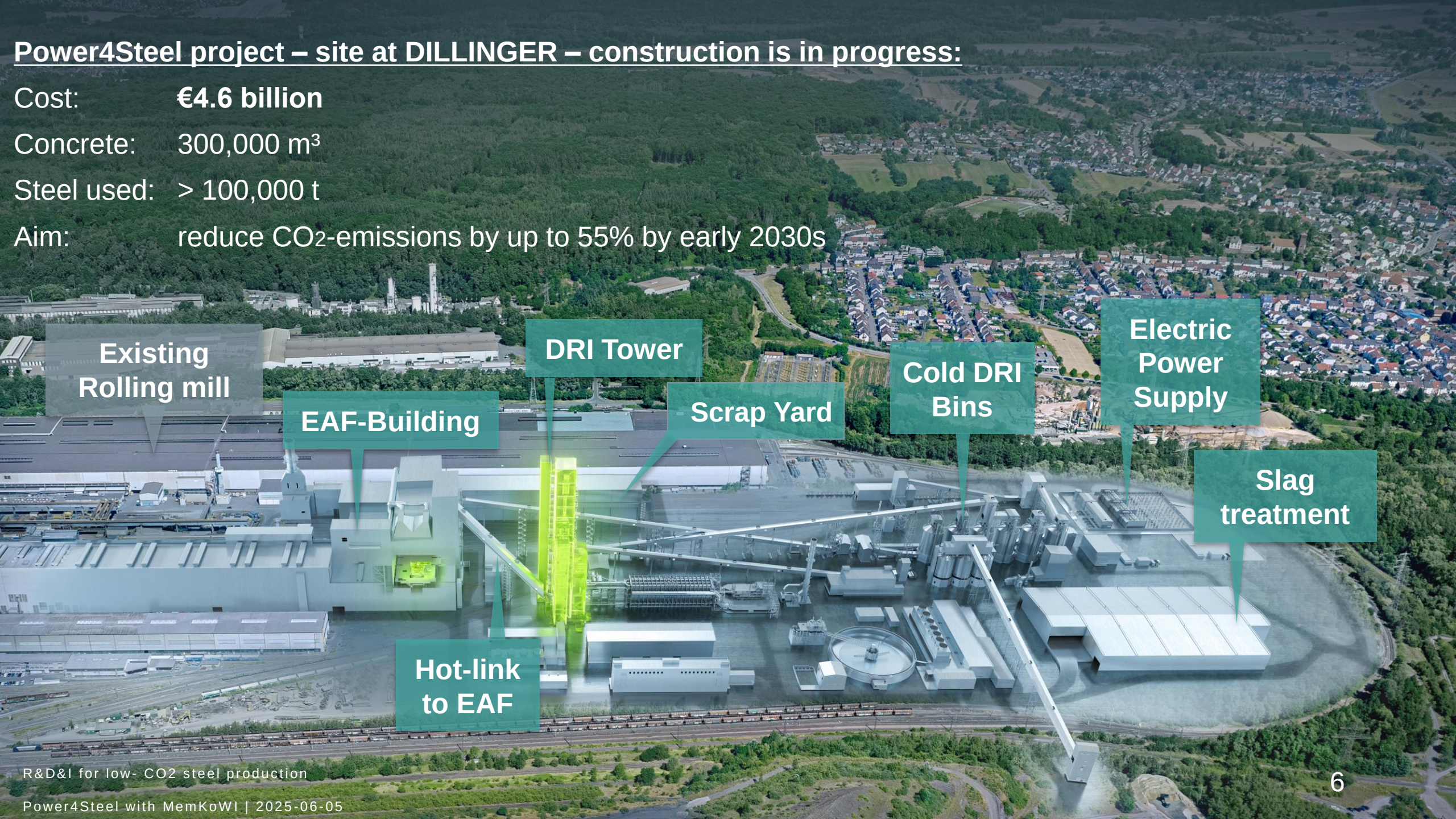
Power4Steel project – site at DILLINGER – construction is in progress:

Cost: **€4.6 billion**

Concrete: 300,000 m³

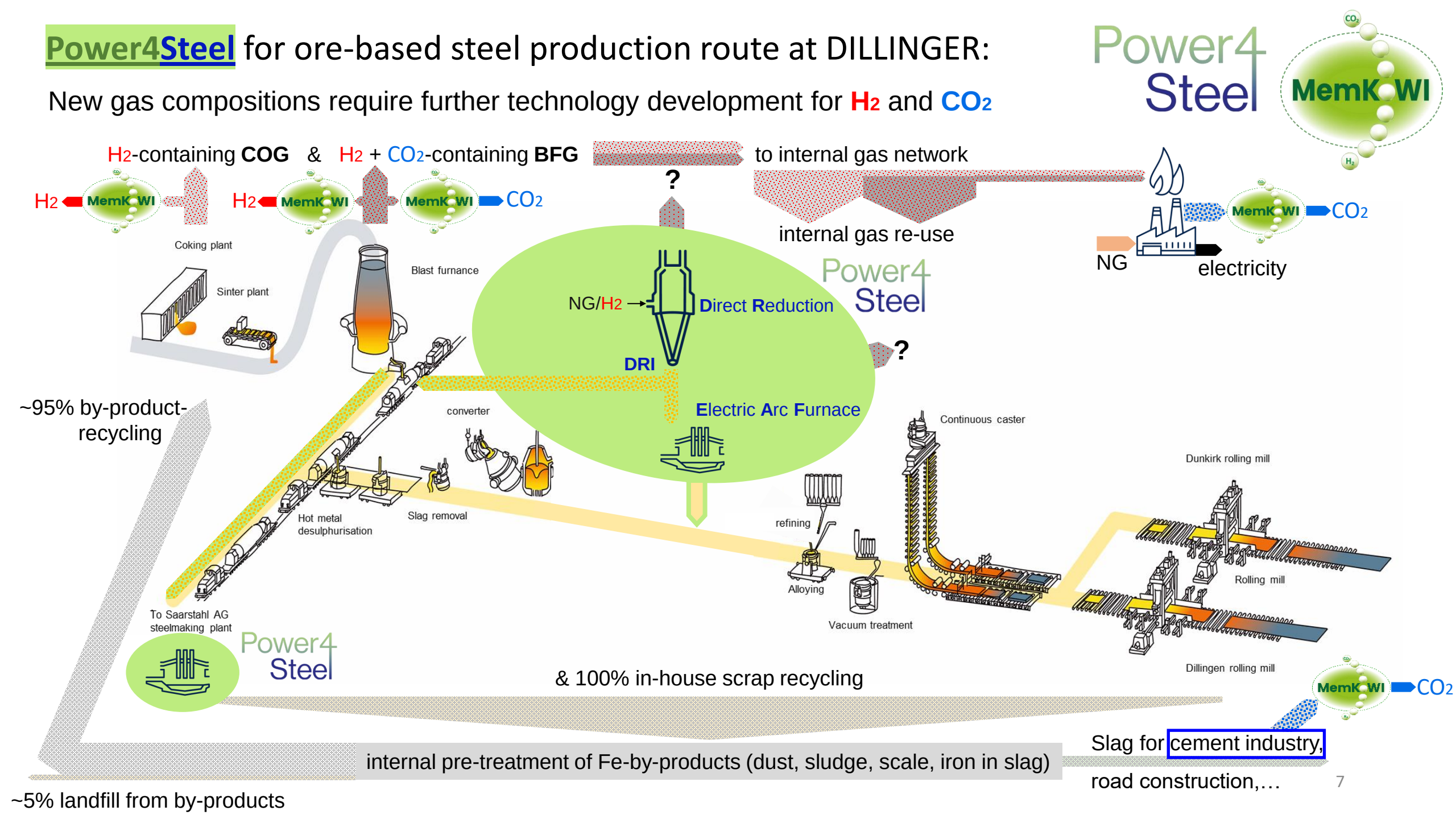
Steel used: > 100,000 t

Aim: reduce CO_2-emissions by up to 55% by early 2030s



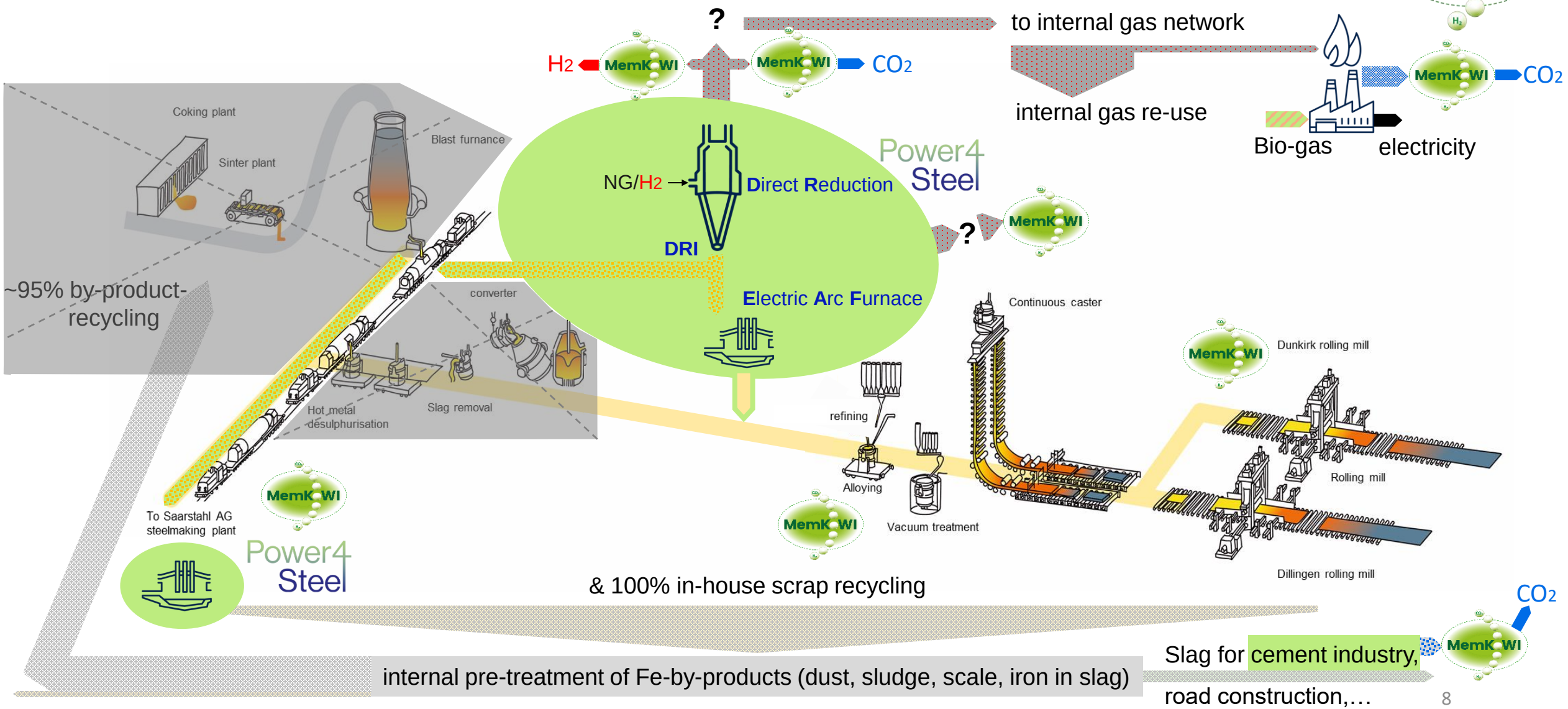
Power4Steel for ore-based steel production route at DILLINGER:

New gas compositions require further technology development for H_2 and CO_2



Power4Steel final step at DILLINGER with MemKoWI-potential:

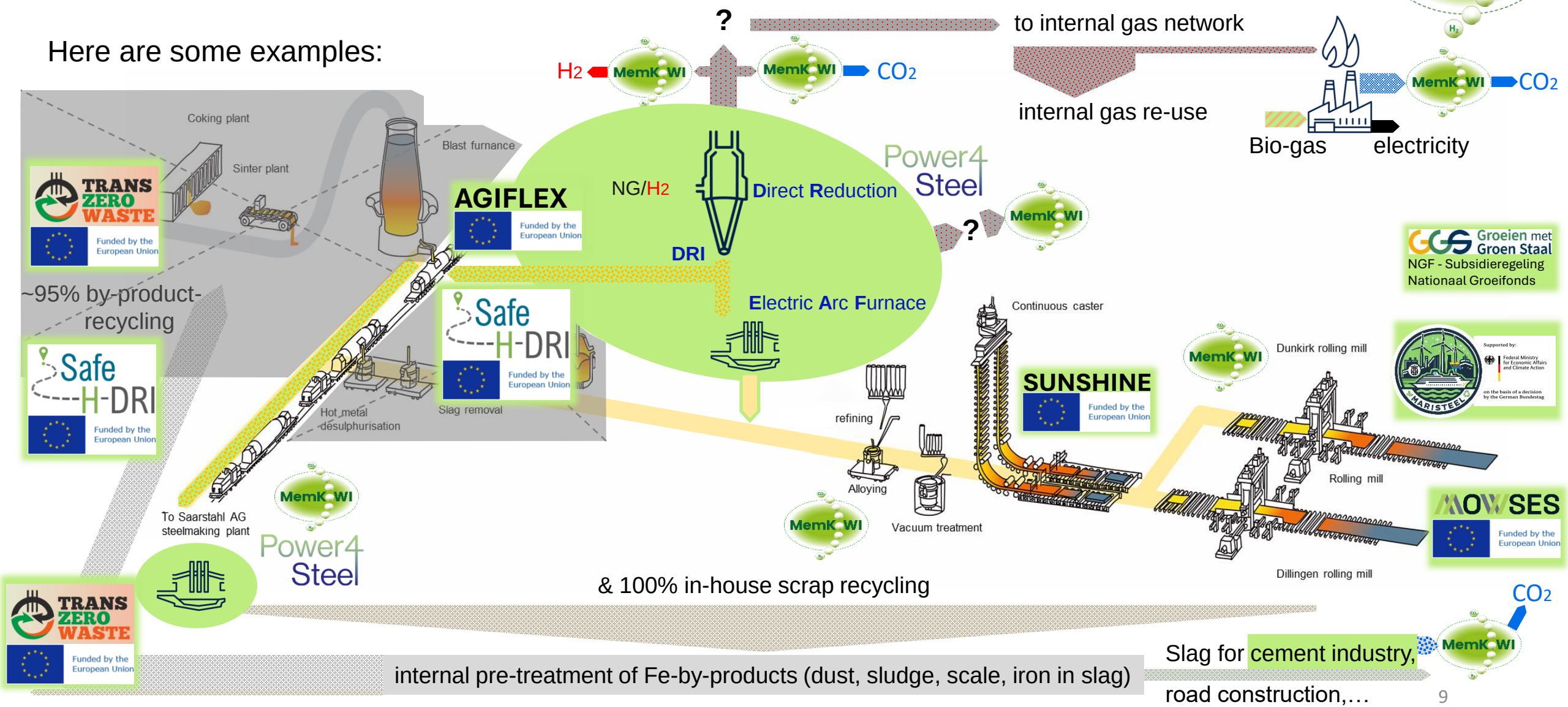
New challenges and technology gaps will emerge → further R&D&I is essential



Power4Steel final step at DILLINGER with R&D&I-projects support:

Power4Steel with synergetic R&D&I finds solutions to challenges and technology gaps!

Here are some examples:



The MemKoWI consortium – cross sectorial experts

Power4 Steel

MemKoWI

Research

Membranes/Polymer

Helmholtz-Zentrum hereon

Steel industry

BFI Angewandte Spitzenforschung

Membranes/Ceramic

JÜLICH Forschungszentrum

Gas technologies

DVGW | ebi

Steel industry

DILLINGER

Cement industry / Plant design

thyssenkrupp

Polysius

Membrane production

atech innovations gmbh

Regenerative energies

iqony

Engineering

Linde

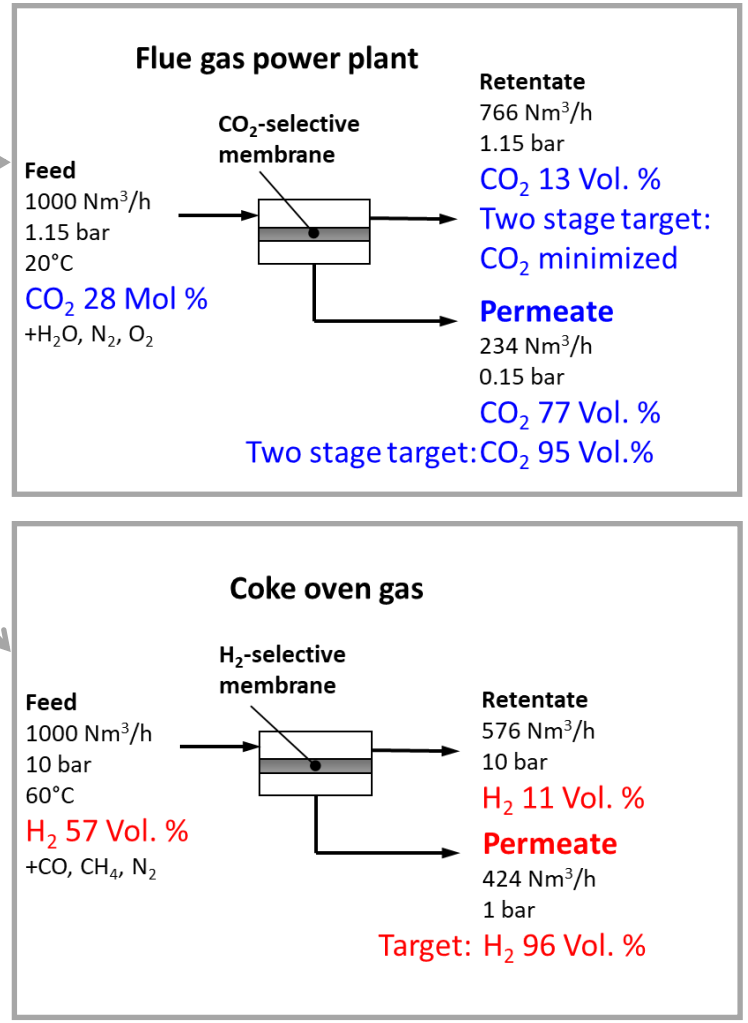
The project MemKoWI – cross sectorial challenges & targets

- **Testing & optimizing gas separation membrane technology** for CO_2 and H_2 separation in different industries
  - Steel
    - Blast furnace gas power plant, CO_2
    - Blast furnace gas, CO_2 und H_2
    - Coke oven gas, H_2
  - Cement & biomass power plant, CO_2

- **Optimized membranes and membrane modules**
  - Polymers
  - Ceramics

- **Digitalisation** and **modelling**

- **Expected outcome**
  - ➢ Up-scaling of membrane-technology for separation of CO_2 und H_2
  - ➢ Move TRL: 3-5 → 6/7 with concept for TRL 9
  - ➢ Provide an important element for sector coupling

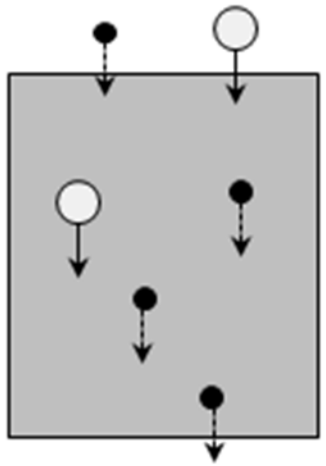


CO_2 and H_2 selective membranes – theoretical basis for gas separation

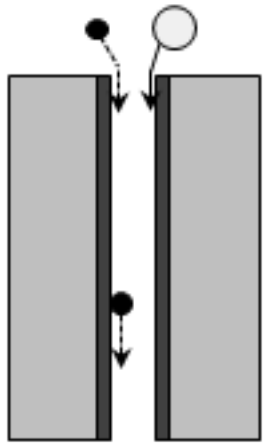
- Polymer Transport mechanism:
  - Solution into polymer
  - Diffusion through polymer
  - Desorption from polymer
  - Rubbery polymers: selective for CO_2
  - Glassy polymers: selective for H_2

- Ceramics Transport mechanism:
  - Dependent on the pore dimension
  - > 1 nm : Knudsen diffusion, low selectivity
  - < 1 nm : Surface diffusion via adsorption and desorption, selective for CO_2
  - < 0.5 nm : Molecular sieving, selective for H_2

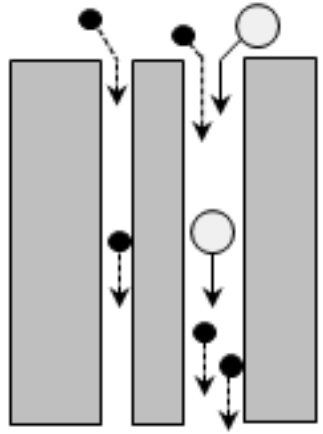
Solution-Diffusion



Surface Diffusion



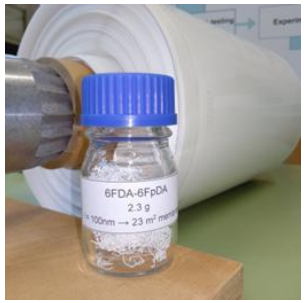
Molecular Sieving



Membrane manufacturing – at research partners laboratories

- **Polymer membranes**

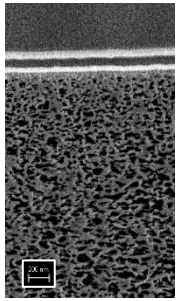
Polymer



Membrane coating machine

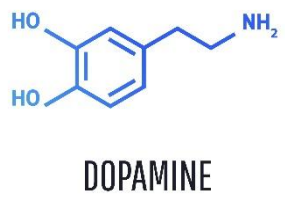
Roller coating

SEM cross section of membrane layers



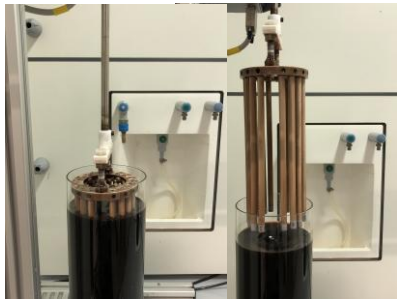
- **Ceramic membrane basis with coating**

Polymer precursor



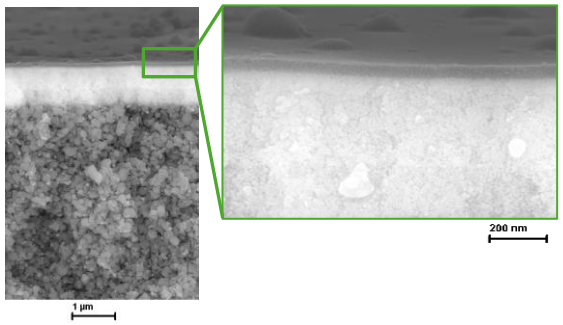
DOPAMINE

Dip-Coating for selective layer



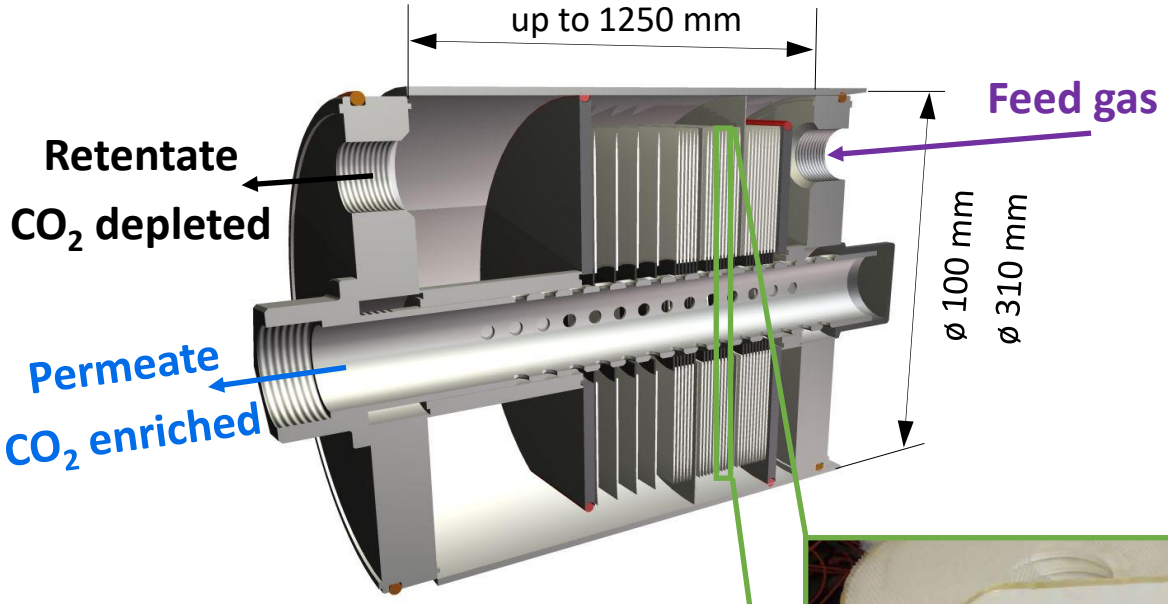
Polymer to Carbon Conversion

SEM cross section of membrane layers



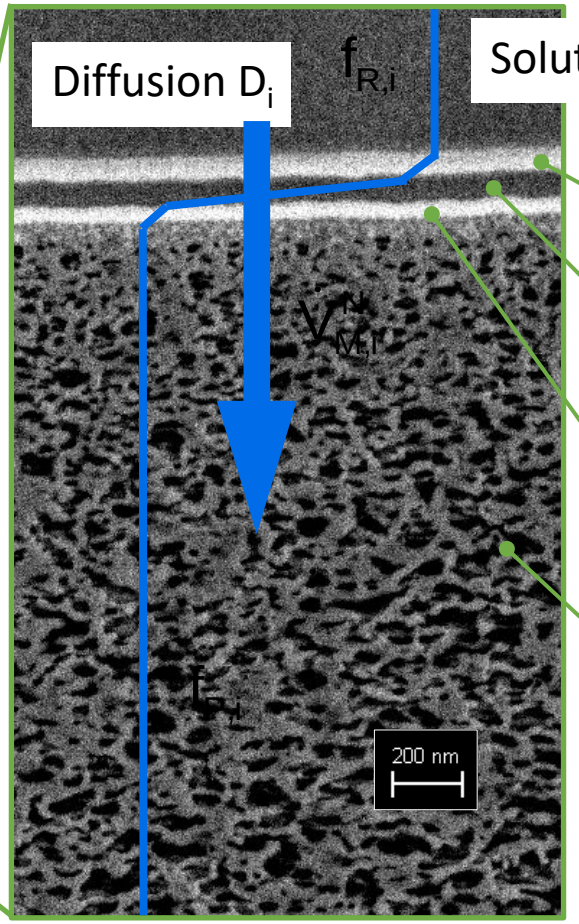
Membrane module and membrane – polymeric membranes

Envelope type membrane module



Membrane envelopes

Cross section of thin film composite membrane



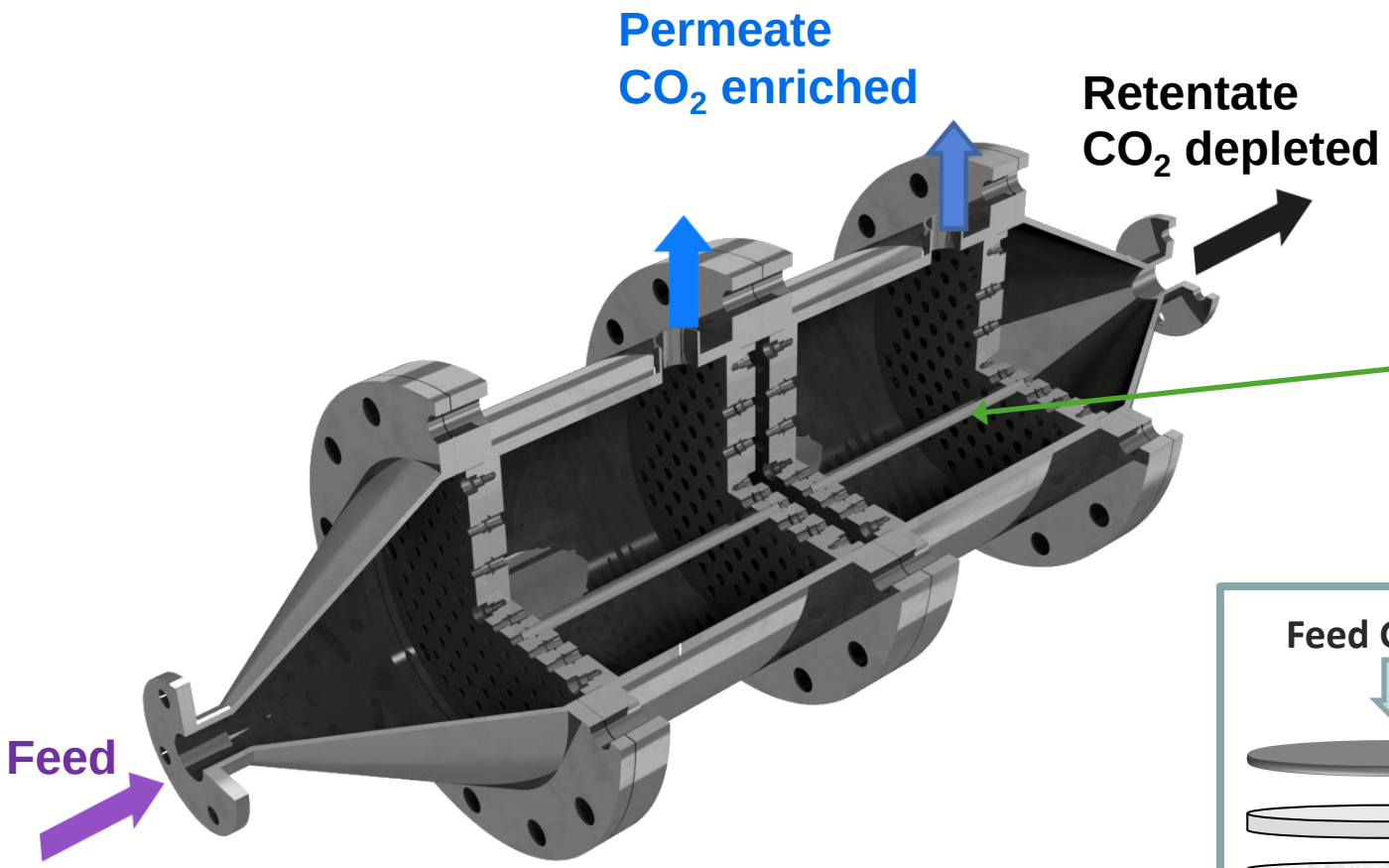
Protection layer
(δ < 150 nm)

Separation layer
(δ < 85 nm)

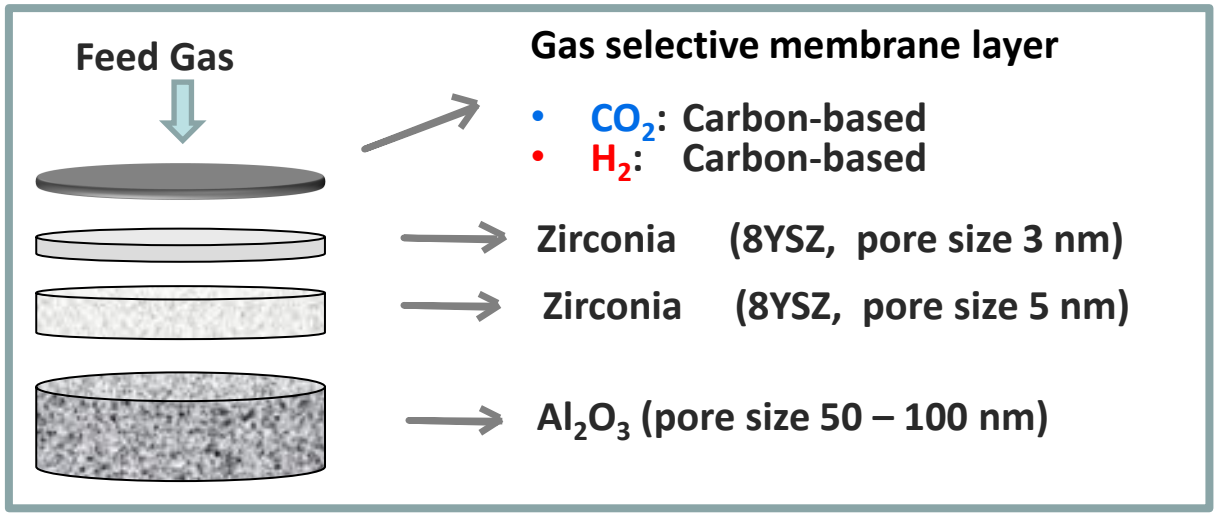
Gutter layer
(δ < 150 nm)

Porous support
(δ ~ 50 µm)

Membrane module and ceramic membrane

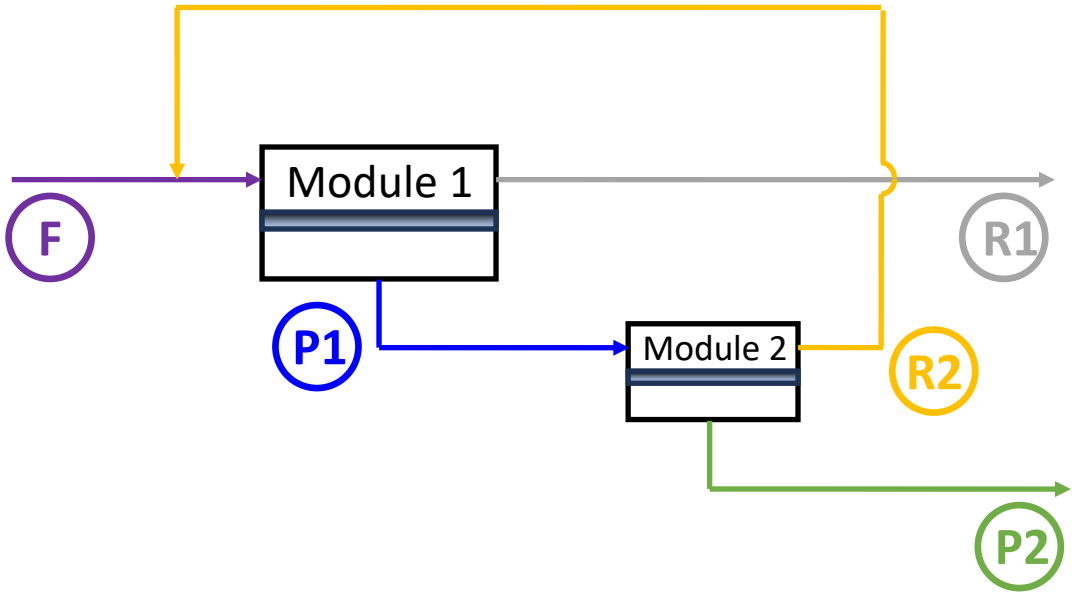


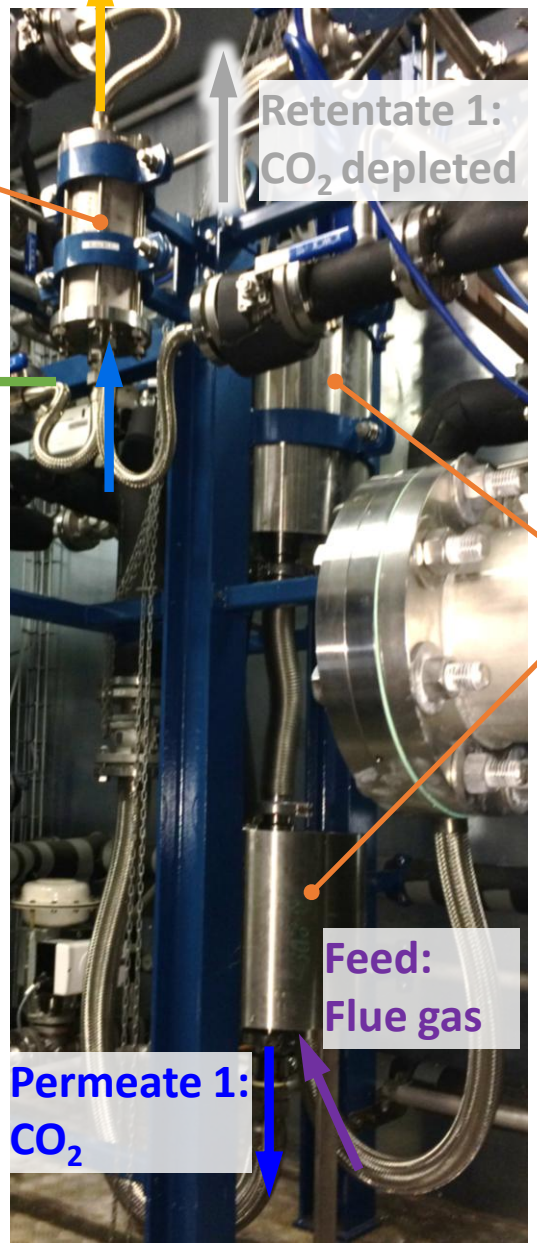
Ceramic membrane basis
Al_2O_3 -tubes



CO_2 separation from gas power plant flue gases (COG/BFG/NG)
Two stage mode – Polymer membrane

- Two stage process

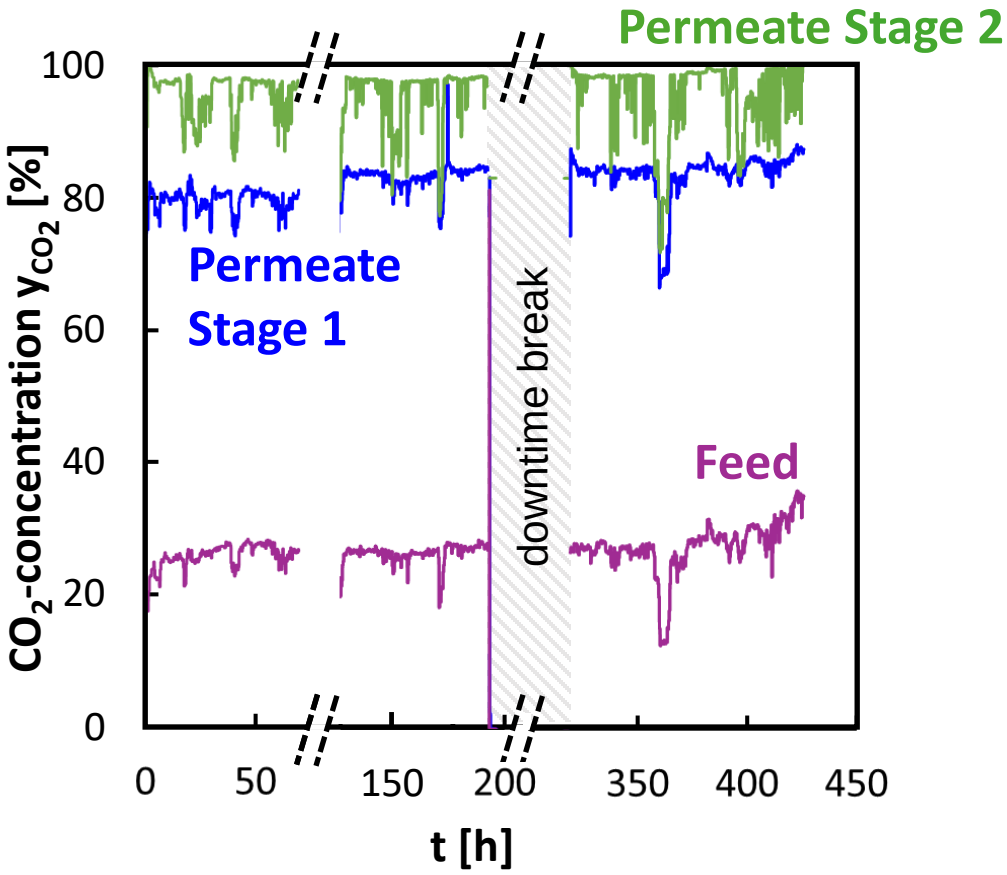


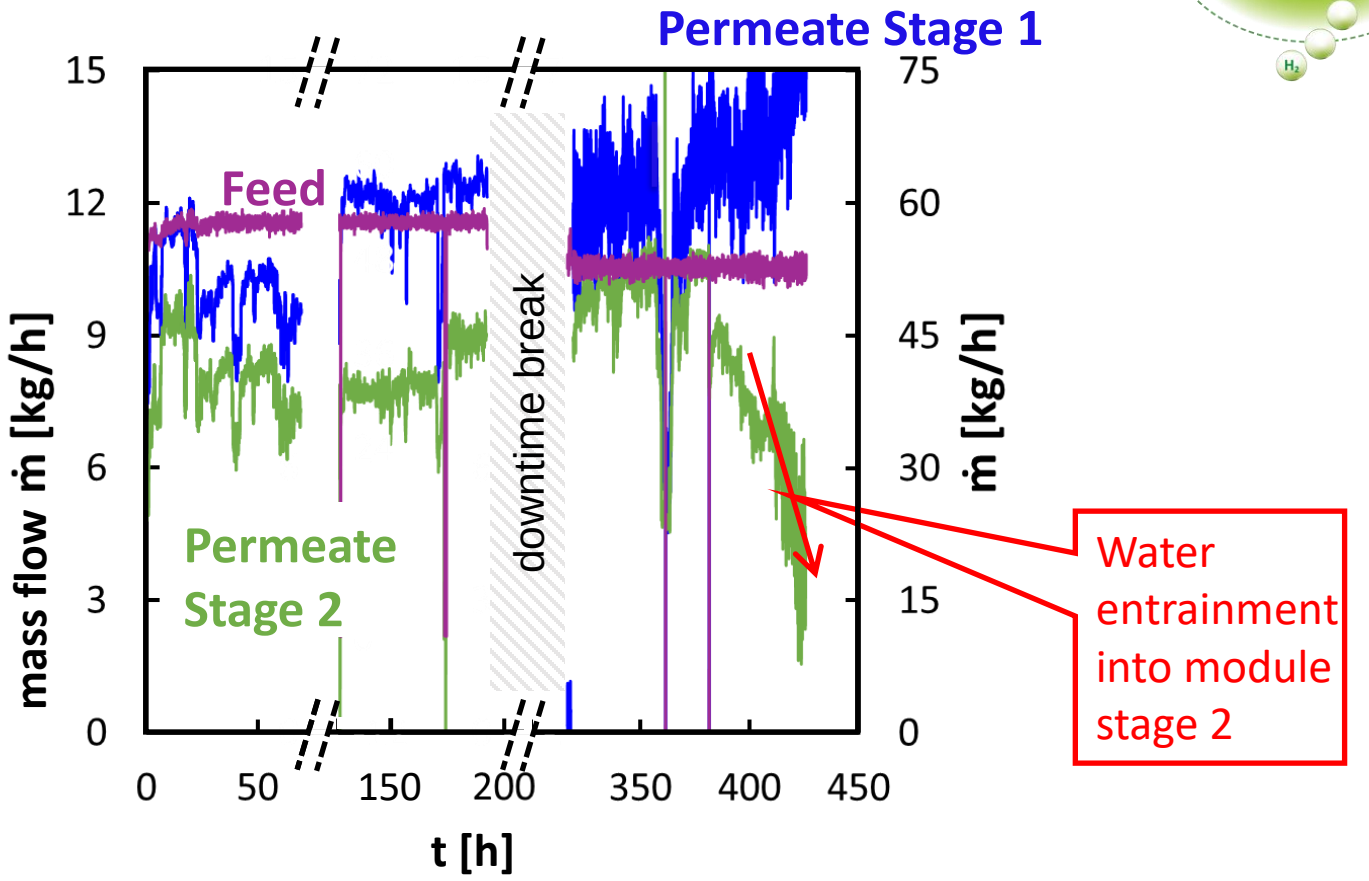


Module 1 – polymer membrane:
- CO_2 selective PolyActive™
- Area A_M=16 m^2
- Selectivity $\alpha_{CO2/N2}(\vartheta=25°C)$ = 47
- Permeance L_{CO2} (ϑ=25°C) = 3 $Nm^3/(m^2\ h\ bar)$

Module 2 – polymer membrane:
- CO_2 selective PolyActive™
- A_M=0.74 m^2
- $\alpha_{CO2/N2}(\vartheta=25°C)$ = 47
- L_{CO2} (ϑ=25°C) = 3 $Nm^3/(m^2\ h\ bar)$

Operating performance two stage mode – Polymer membrane

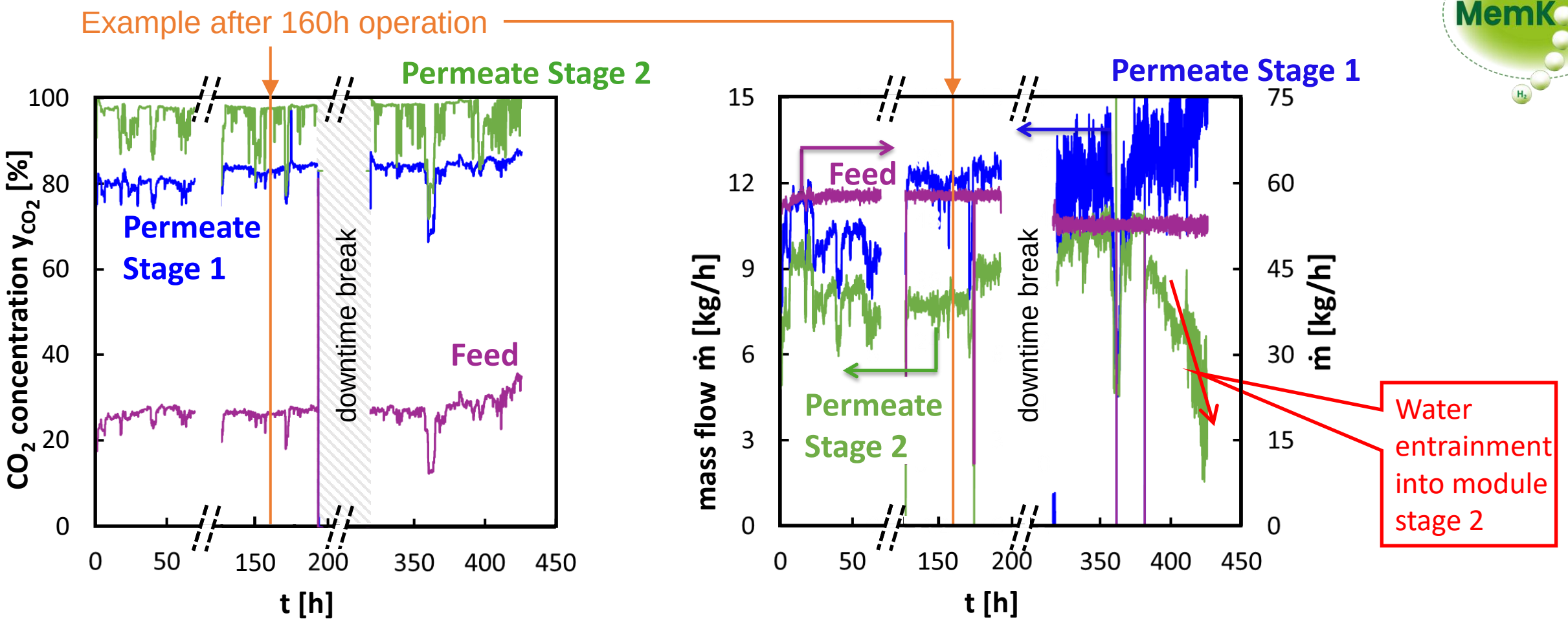




Observations:
- stable, two stage operation: CO_2 in 2nd stage permeate > 95 mol-% → fit for use ✓
- **no loss of performance** by downtime break ✓
- water entrainment severely impacts performance → risk mitigation action at feed-side

Use for up-scaling: - automated feed-gas related downtime control & gas dehumidification

Operating performance two stage mode – Polymer membrane



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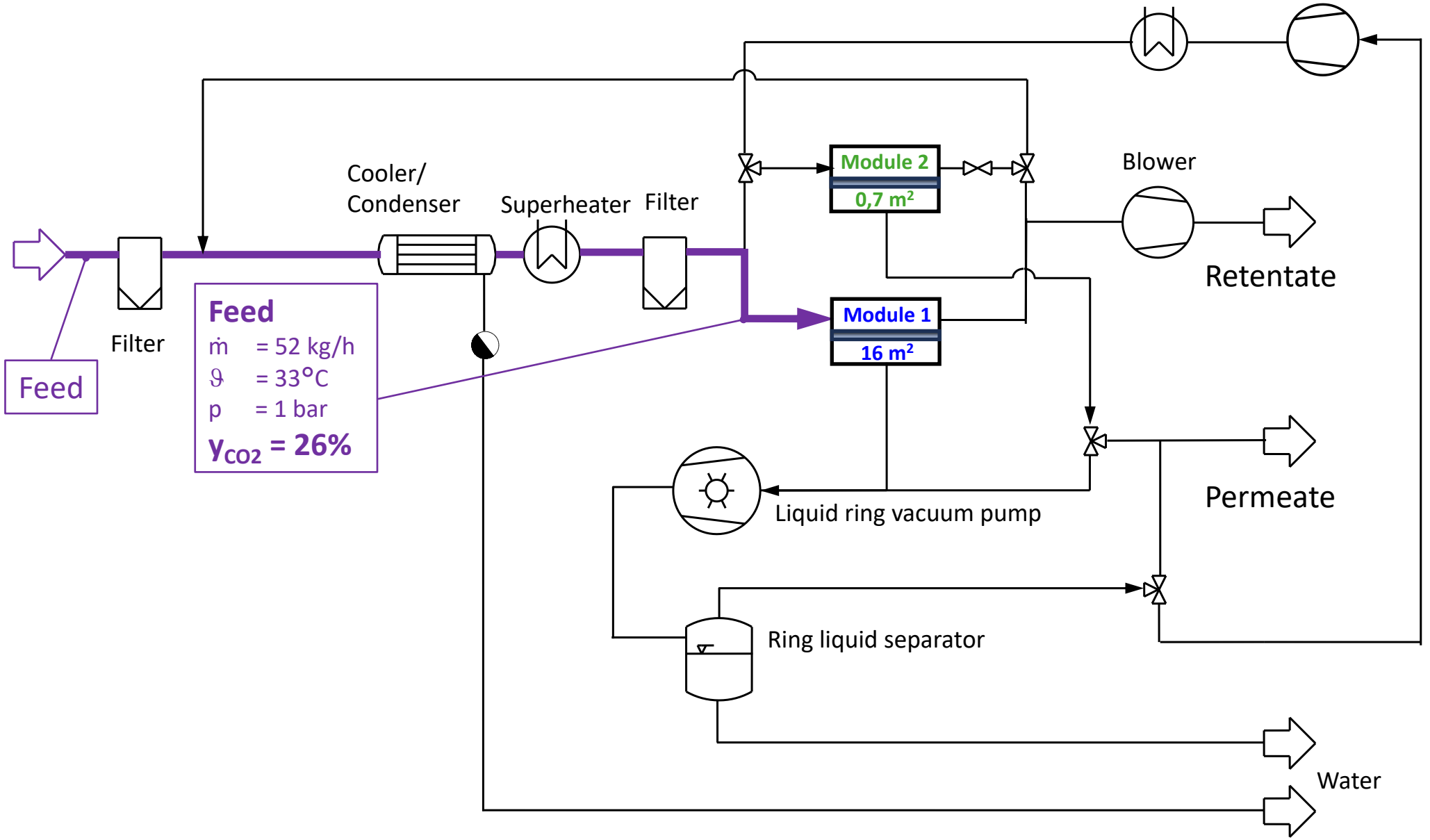
Example - Operating point after 160h (2-stage polymer membrane)



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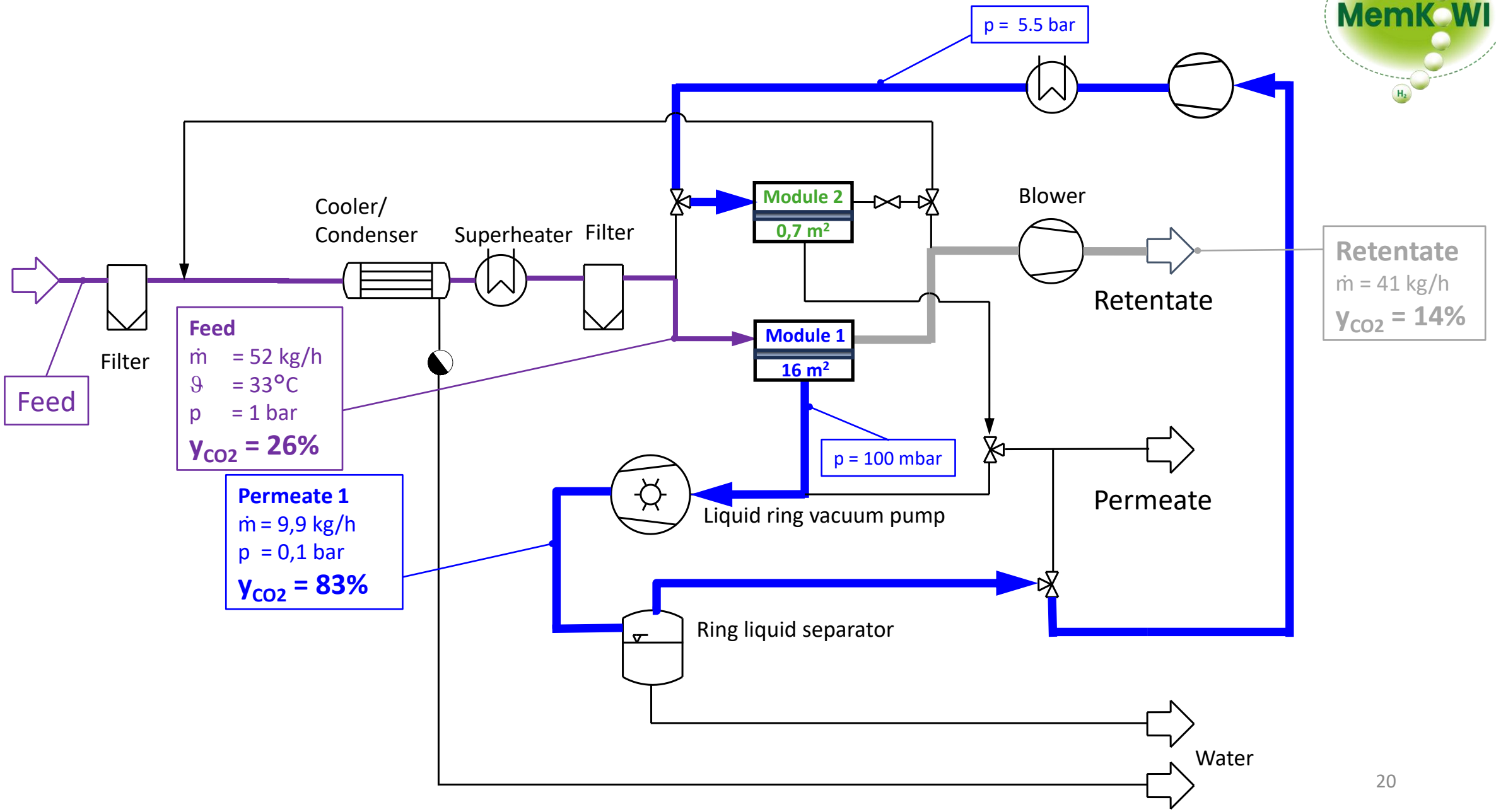

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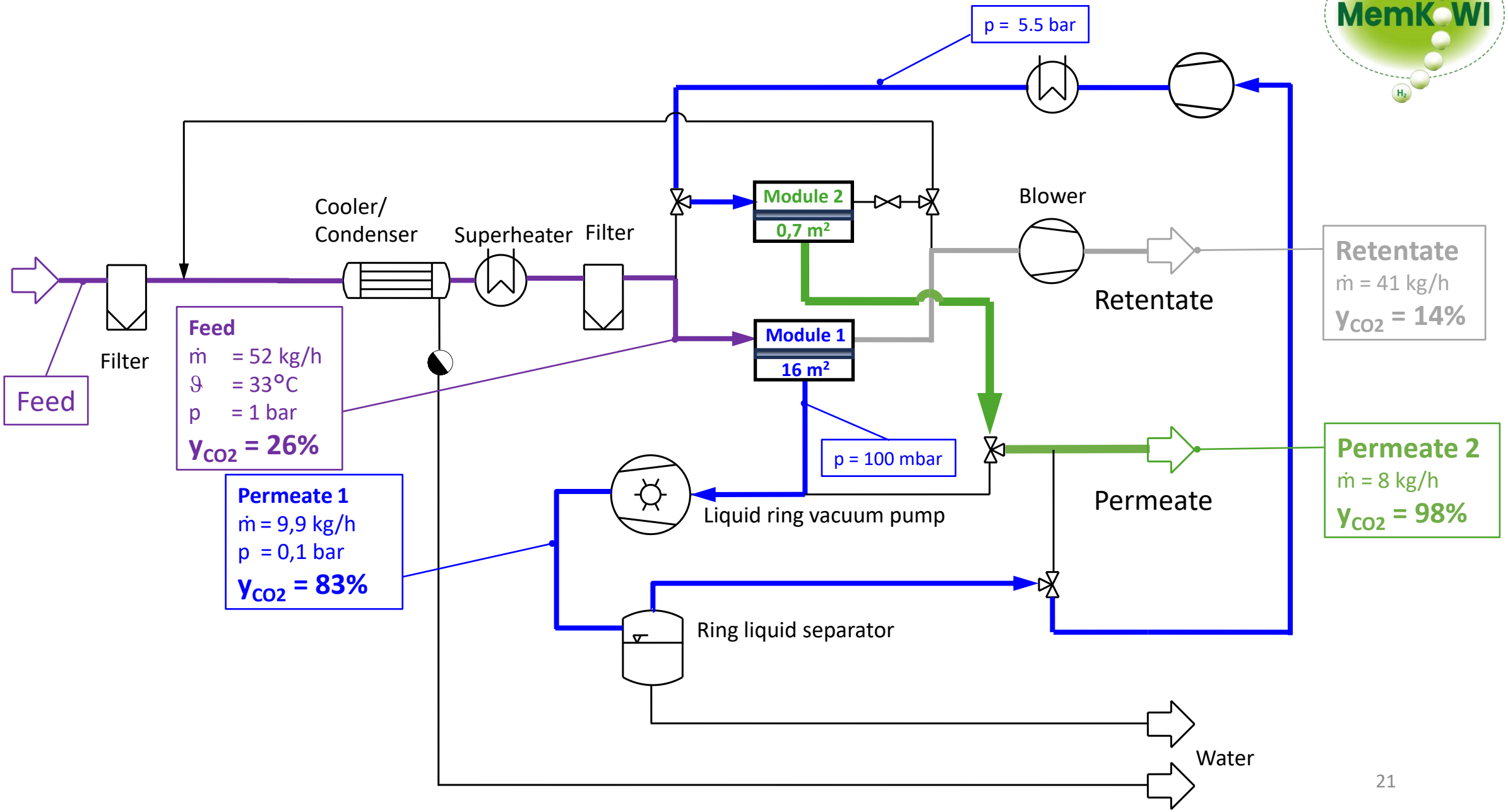

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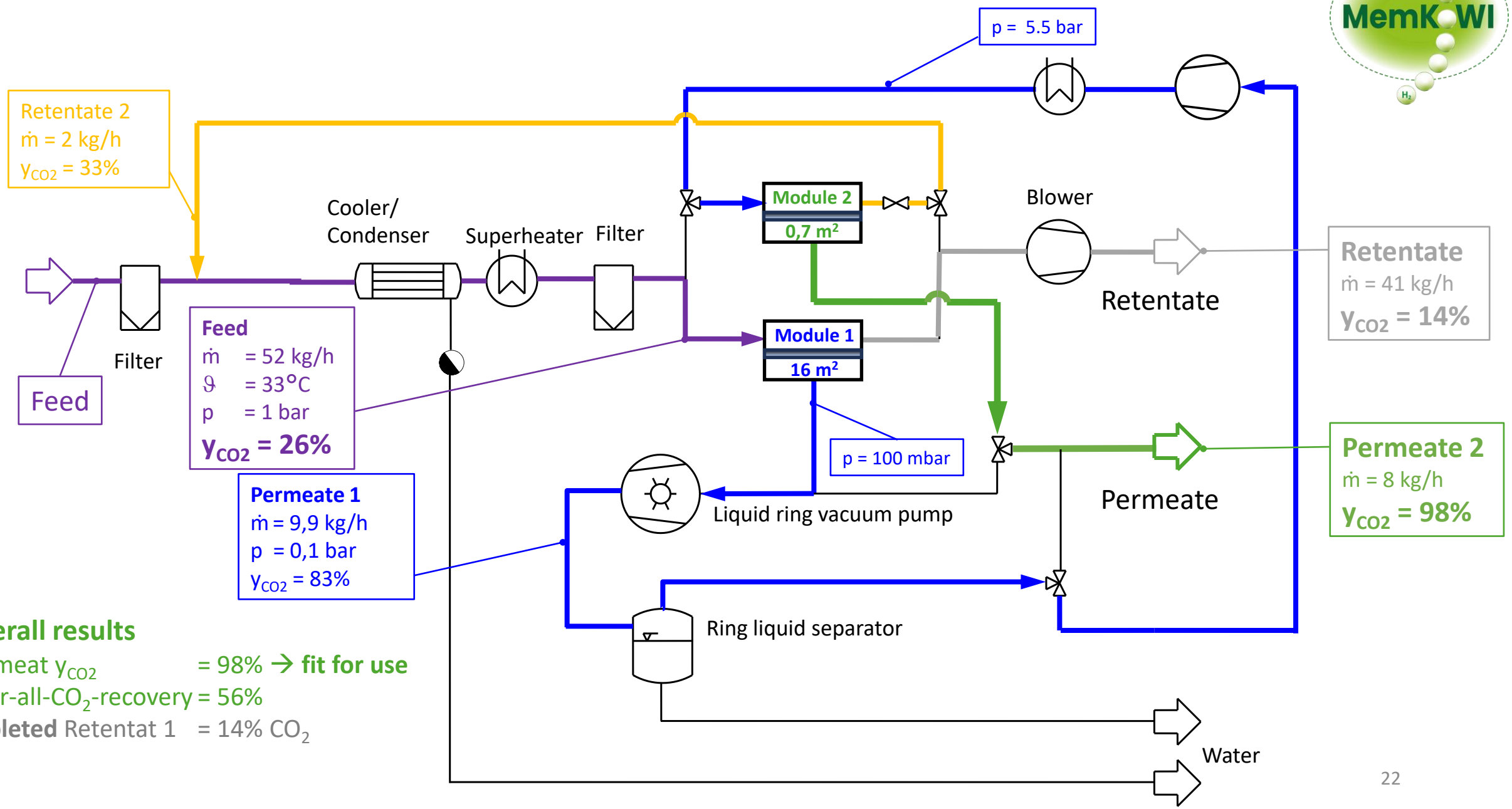


Overall results

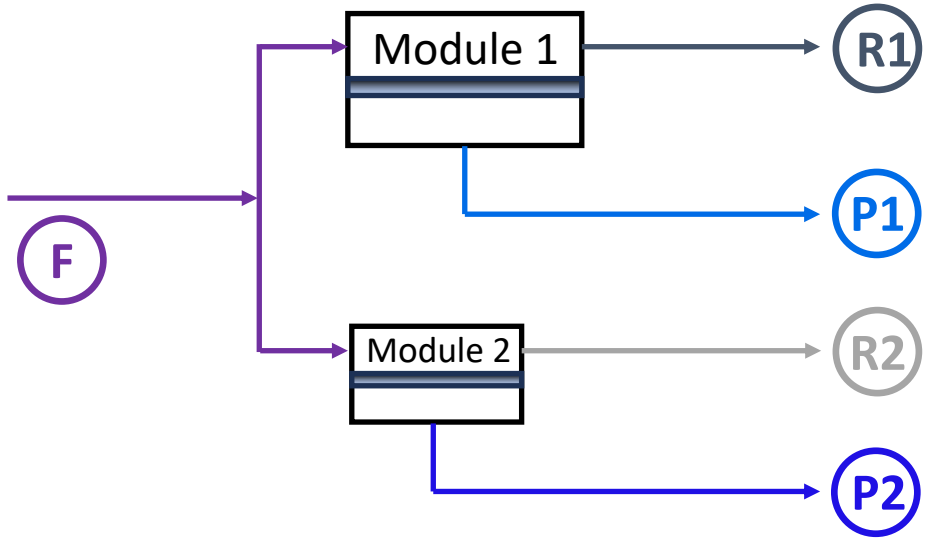
Permeat y_{CO2} = 98% → **fit for use**

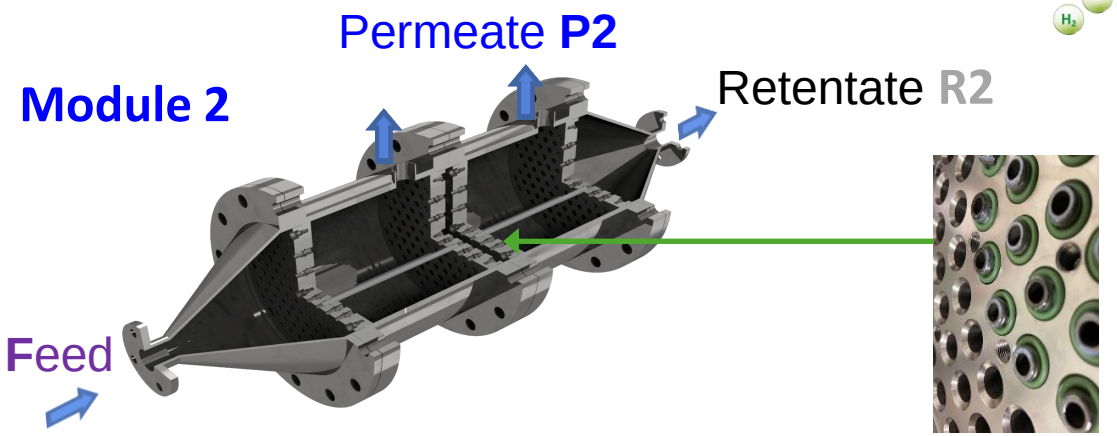
Over-all-CO_2-recovery = 56%

Depleted Retentat 1 = 14% CO_2

CO_2 separation from gas power plant flue gases (COG/BFG/NG)
One stage mode – for Ceramic and Polymer membrane

- Parallel operation





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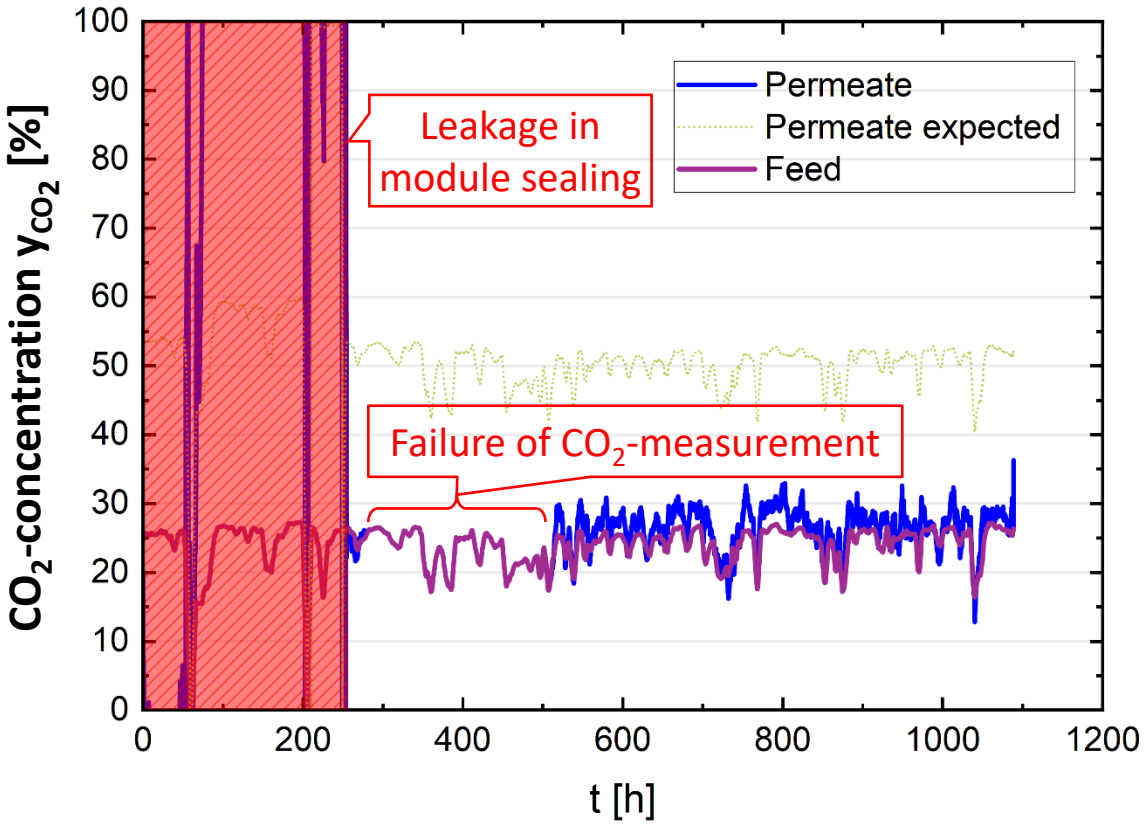
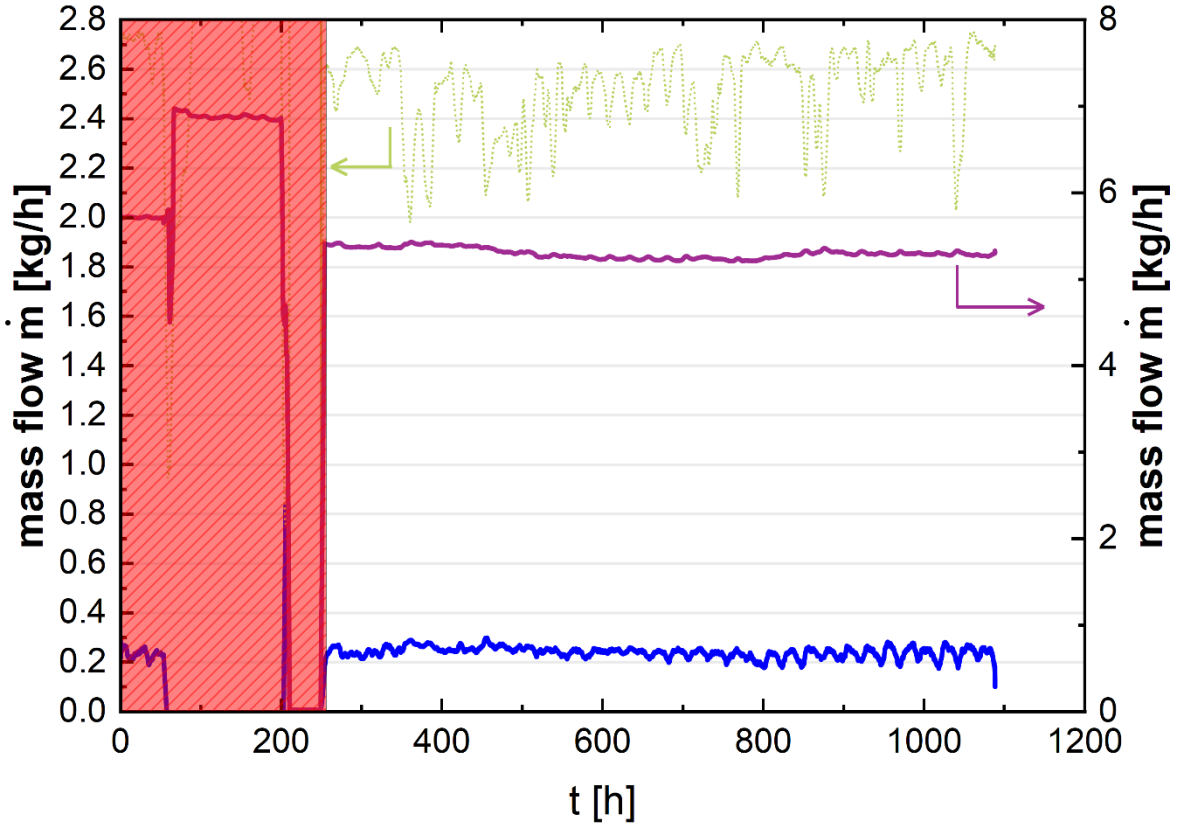
- CO_2 selective PolyActive™
- Area A_M=16 m^2
- Selectivity $\alpha_{CO2/N2}(\vartheta=25°C)$ = 47
- Permeance L_{CO2} (ϑ=25°C) = 3 $Nm^3/(m^2\ h\ bar)$
- Up to V_F = 80Nm^3/h

Module 2 – ceramic membrane:

- CO_2 selective α-Al_2O_3+8YSZ+Carbon
- A_M=0.96 m^2
- $\alpha_{CO2/N2}(\vartheta=20°C)$ = 20
- L_{CO2} (ϑ=20°C) = 1 $Nm^3/(m^2\ h\ bar)$
- Up to V_F = 8Nm^3/h

1st Operating performance single stage mode – ceramic membrane





Observations: - **stable operation** after fixing leakage **but significantly lower selectivity compared to lab-tests**

- **permeance and selectivity influenced by water and other flue gas components** (from leakage?)

- lab-tests indicate **regeneration** at ~400°C → regeneration trial is currently running

Results and next steps

- **Results**:
  - **Achieved CO_2 separation**: > 50% CO_2-off-gas depletion & >95% CO_2-Permeat for use (CCU) ✓
  - Fitting **modelling** & online **process control** ✓
  - **Long-term operation** of polymer & ceramic membranes in industrial gas:
    ⊗ sensitive to specific fluctuations (acid gases and water vapour)
    → risk mitigation possible by automated process control ✓
  - **Improved membrane** types and module-concepts:
    → New ceramic membrane & module optimization ✓
    → Improved polymeric membrane ✓
  - **Findings used for adapted concepts** and layout of the **further pilot plants** for: ✓
    → **H_2** separation from COG & BFG *(under construction – fit for 180°C)*
    → **CO_2** separation from BFG, cement plant- and biomass power plant-flue gases *(under construction)*

- **Next steps**:
  - **Long-term-testing** other gas-membrane-combination with modelling & optimization & potentials for TRL9
  - **Membrane type- & module-upscaling** based on pilot trial experiences
  - **New pilot plants** commissioning, testing and optimisation under industrial conditions
  - **Develop upscaling concepts** with cost and potential for CCU & CCUS

Power4Steel with MemKoWI

Thank you!

MemKoWI-meeting in Dillingen - plant tour with Power4Steel

Commissioning MemKoWI-pilot plant at Dillinger

Project coordination
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torsten.brinkmann@hereon.de
+49 (0) 175 238 2232

Research	Steel industry	Cement industry / Plant design
Membranes/Polymer: hereon; Steel industry: BFI Angewandte Spitzenforschung	DILLINGER	thyssenkrupp Polysius
Membranes/Ceramic: JÜLICH Forschungszentrum; Gas technologies: DVGW, ebi		
Membrane production	**Regenerative energies**	**Engineering**
atech innovations gmbh	iqony	Linde

Projektträger Jülich Forschungszentrum Jülich

Supported by:

Federal Ministry for Economic Affairs and Climate Action

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on the basis of a decision by the German Bundestag