ESTEP 2025 Annual Event
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Udine (ITALY)

How decarbonisation, digitisation and circular solutions forge the sustainable European steel future?

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steel plant EAF-Project

MemKoWI & Sector coupling with Power4Steel:

New findings with pilot-scale CO_2- and H_2-separation by membrane technology from industrial gases of steel-, cement- and biomass-plants

Power4Steel supported by:
Ministerium für Wirtschaft, Innovation, Digitales und Energie SAARLAND
Federal Ministry for Economic Affairs and Energy

MemKoWI supported by:
(FKZ: 03EE5115)
Federal Ministry for Economic Affairs and Energy

Conventional ore-based steel production route at DILLINGER:

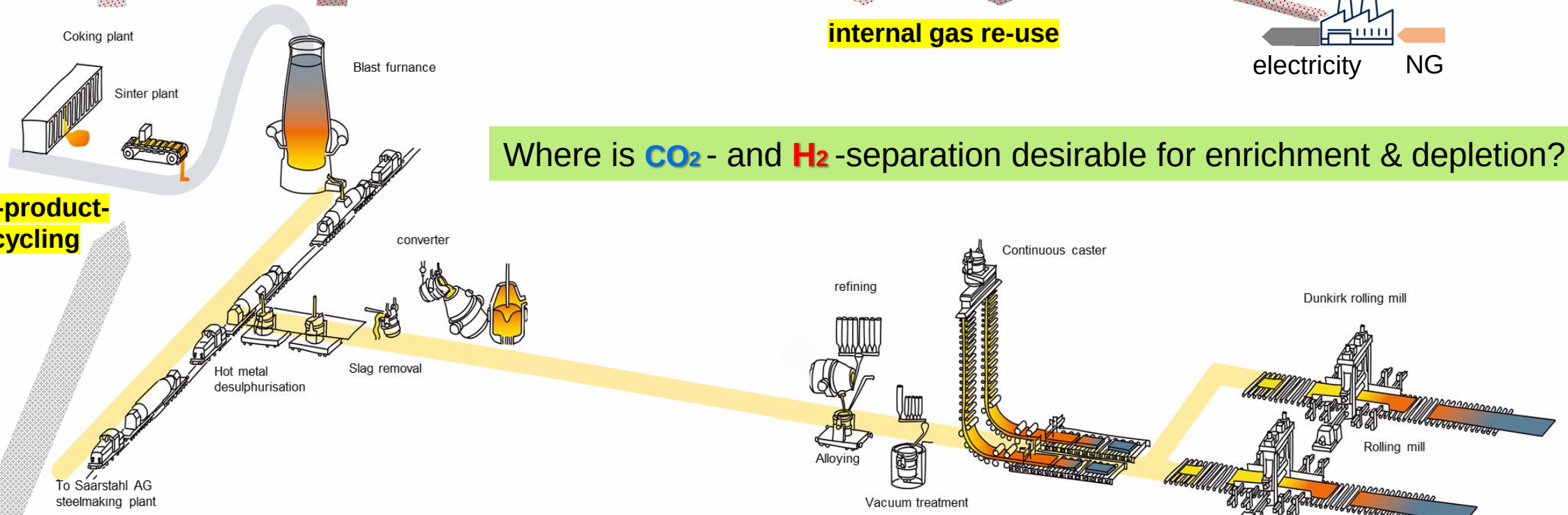
Efficient steel production with internal gas reuse and high internal recycling-rates

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

internal gas re-use

electricity NG

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

Power4Steel

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

H_2 → MemKoWI ← H_2 | MemKoWI → CO_2 → CCU

internal gas re-use

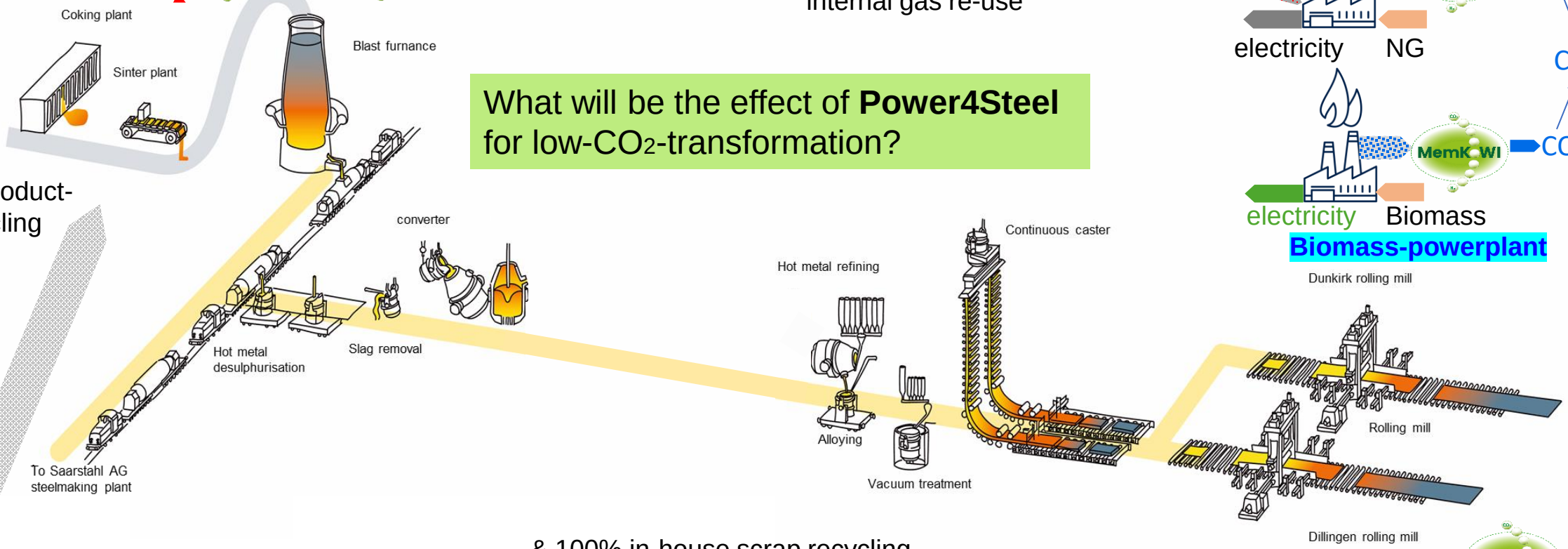
MemKoWI → CO_2 → CCU/S

electricity NG

MemKoWI → CO_2 → CCU/S

electricity Biomass

Biomass-powerplant



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

~95% by-product-recycling

& 100% in-house scrap recycling

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

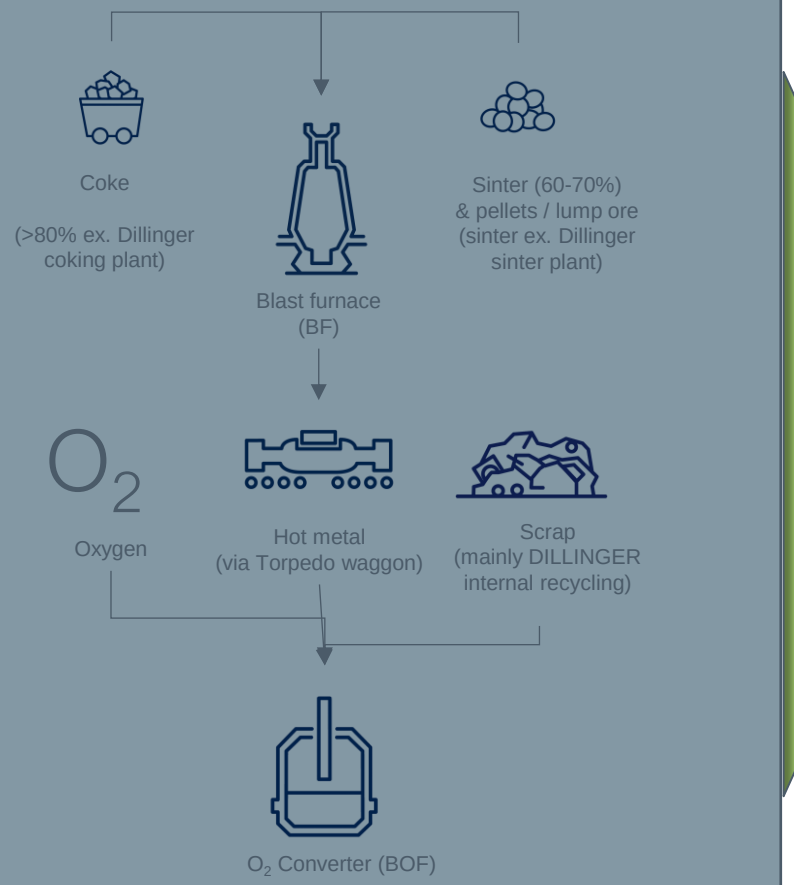
~5% landfill from by-products

MemKoWI → CO_2 → CCU/S

Slag for **cement industry**, road construction,…

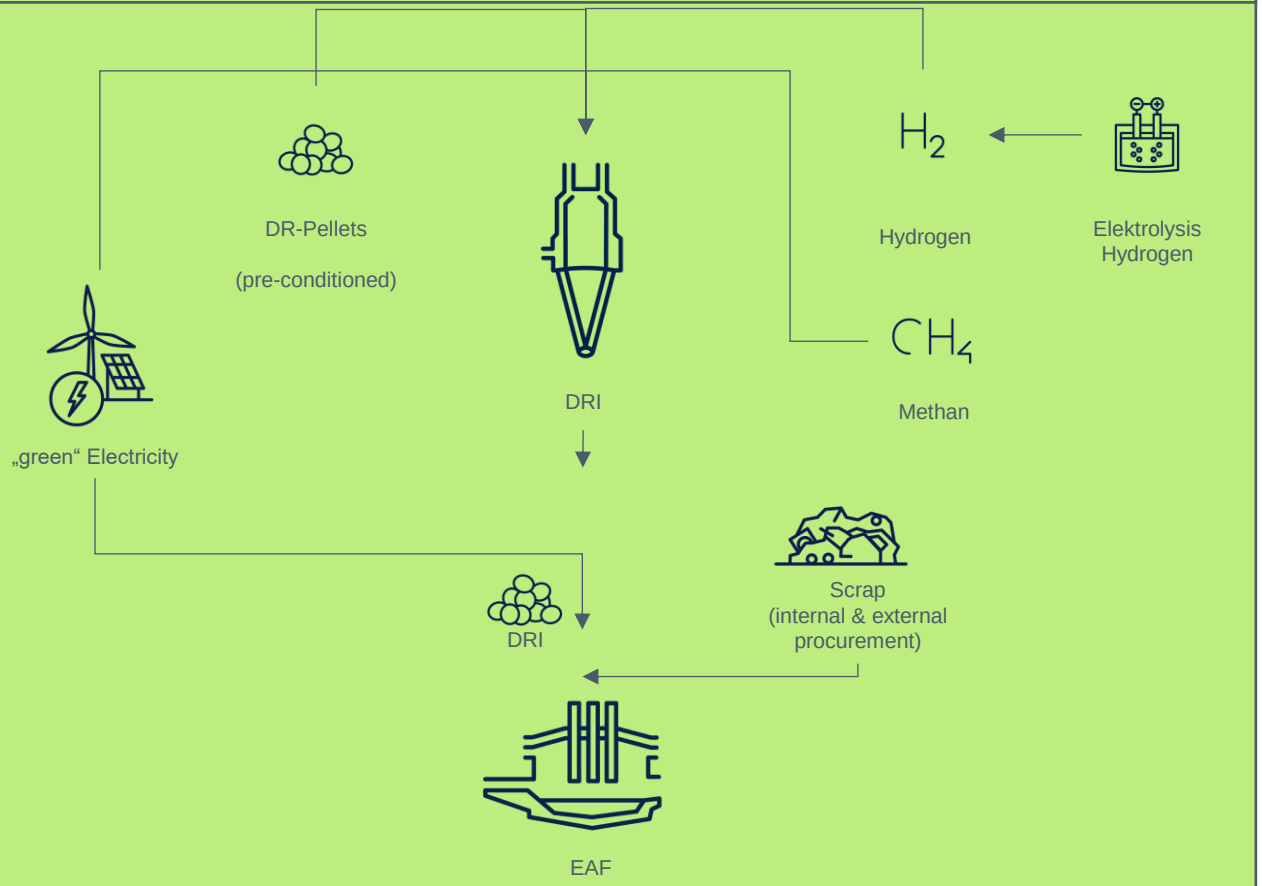
Steel production from „conventional“ to „green" (= low CO_2)

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)

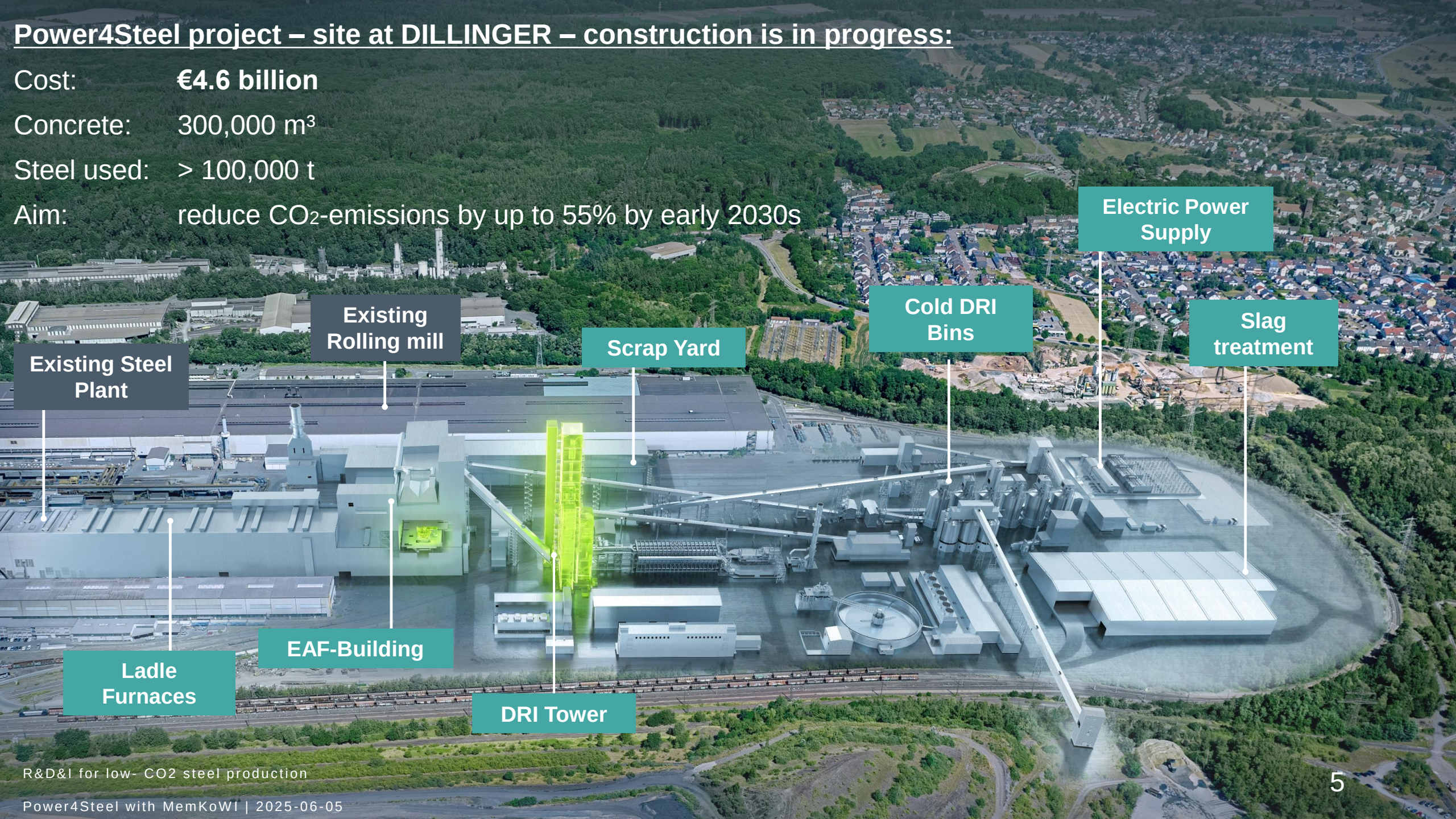
Power4Steel project – site at DILLINGER – construction is in progress:

Cost: **€4.6 billion**

Concrete: 300,000 m³

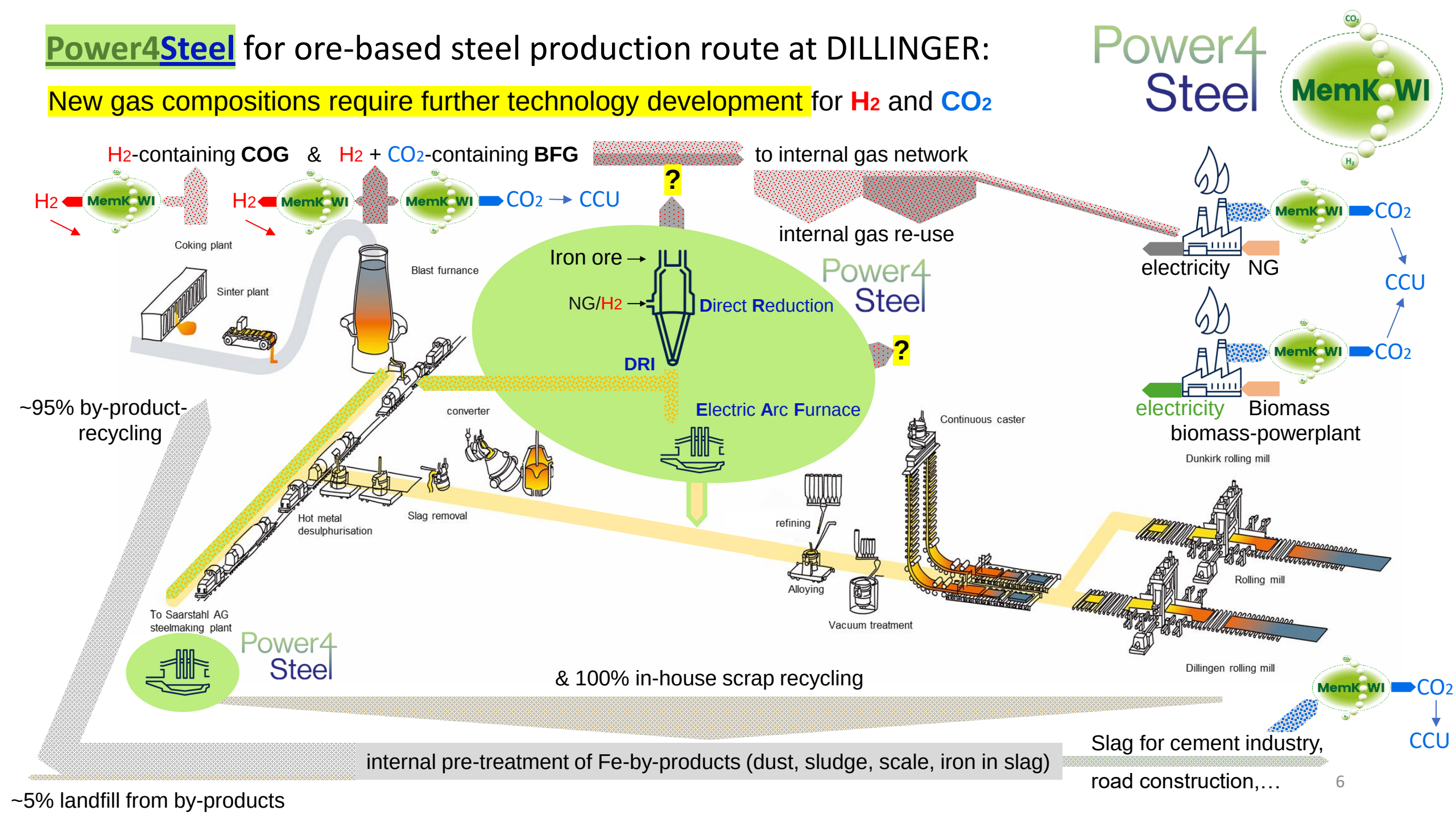
Steel used: > 100,000 t

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



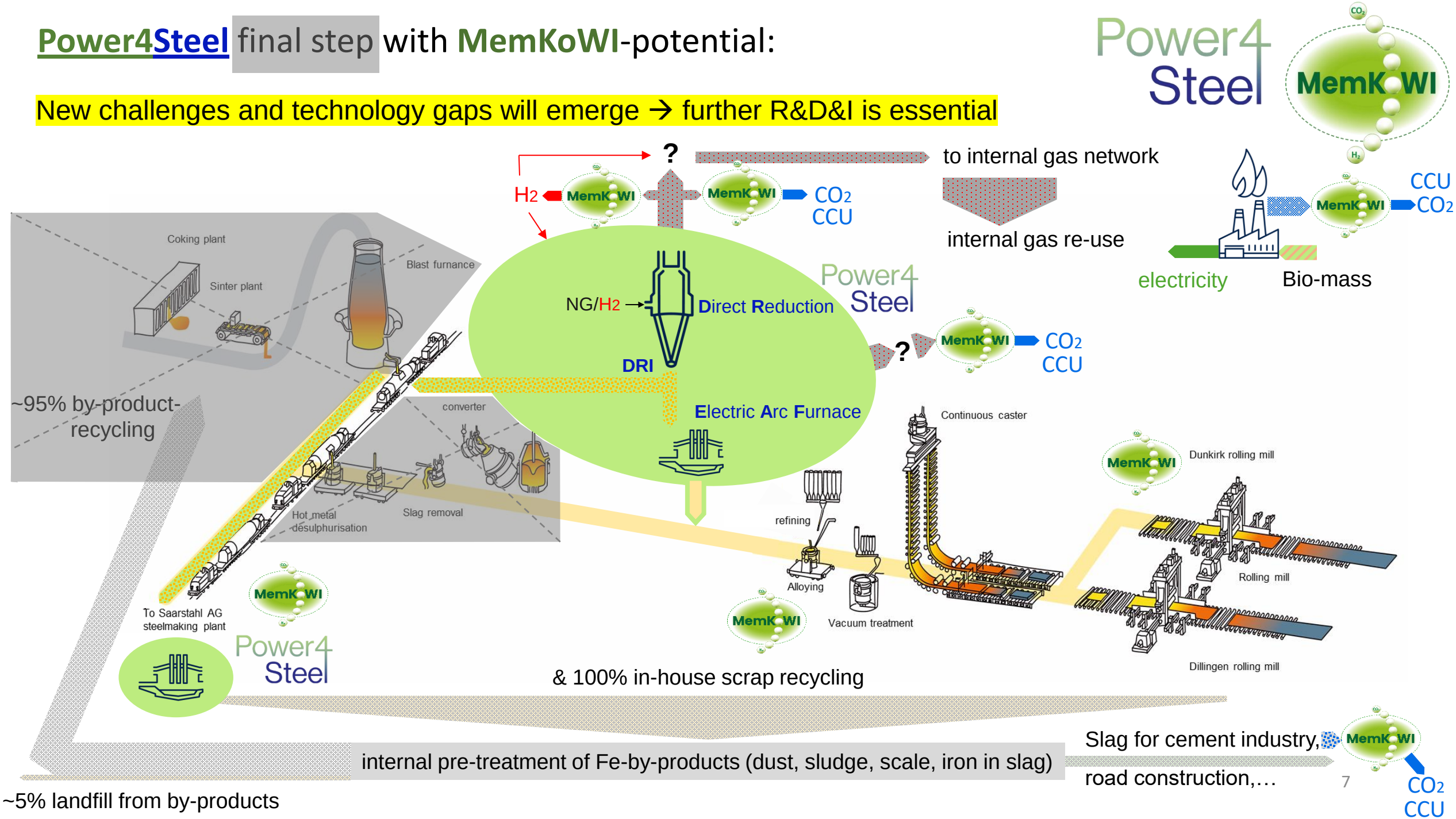
Power4Steel for ore-based steel production route at DILLINGER:

New gas compositions require further technology development for H_2 and CO_2



Power4Steel final step with MemKoWI-potential:

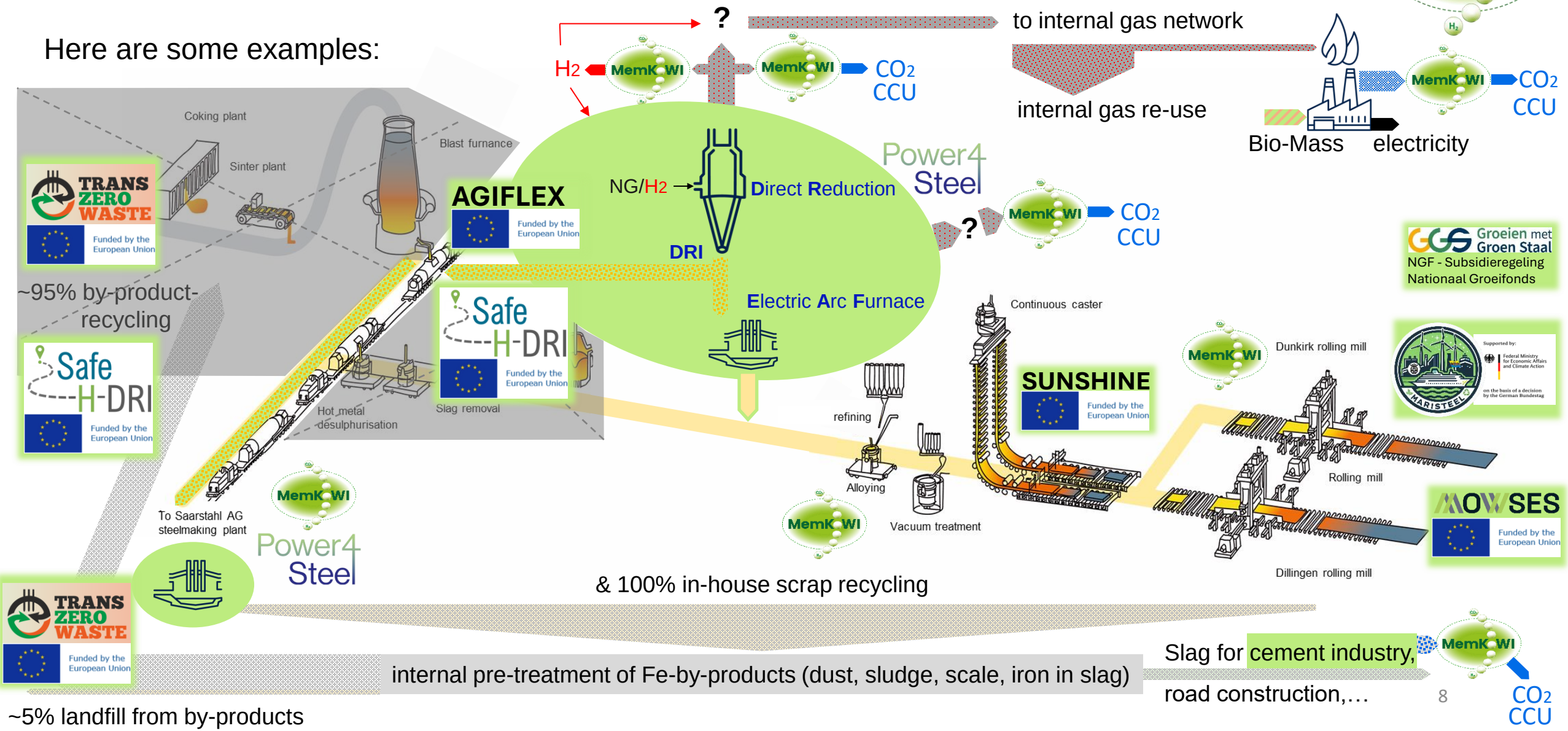
New challenges and technology gaps will emerge → further R&D&I is essential



Power4Steel final step 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

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**
  - Steel, CO_2 and H_2
  - Cement , CO_2
  - Biomass power plant, CO_2

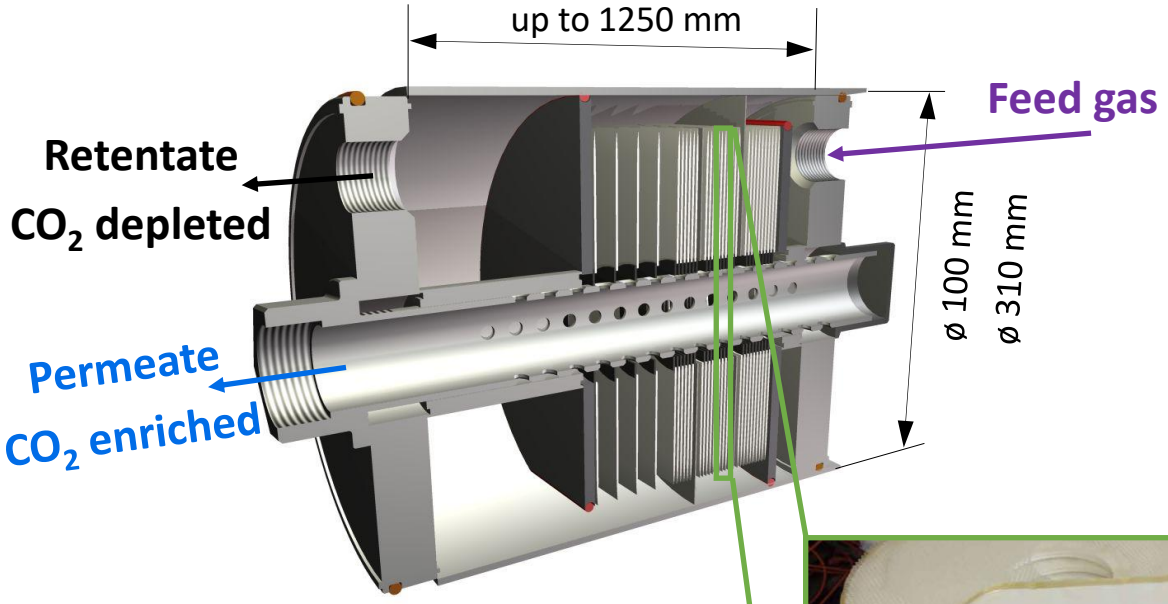
- **Optimized membranes and membrane modules**
  - Polymers
  - Ceramics

- **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

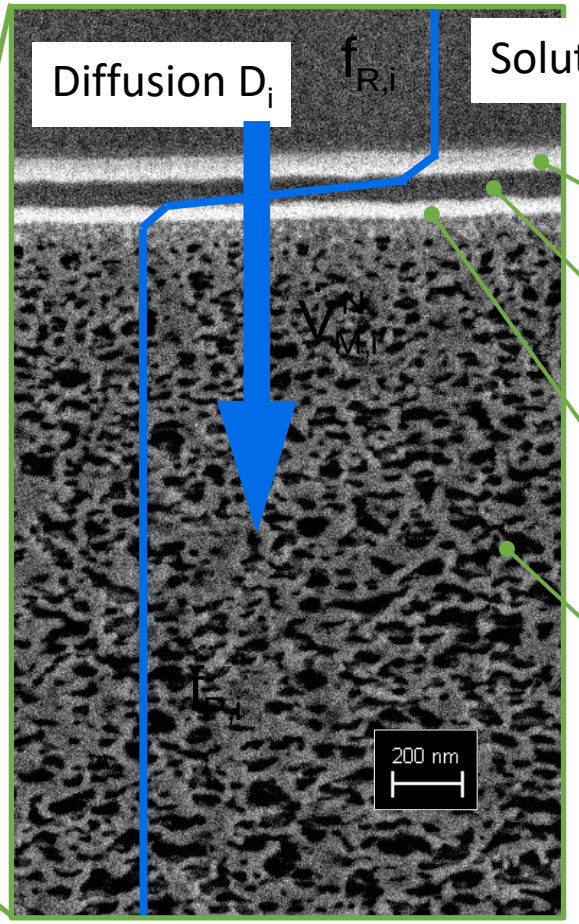
Membrane module and membrane – polymeric membranes

Envelope type membrane module



Membrane envelopes

Cross section of thin film composite membrane



Protection layer
(δ < 150 nm)

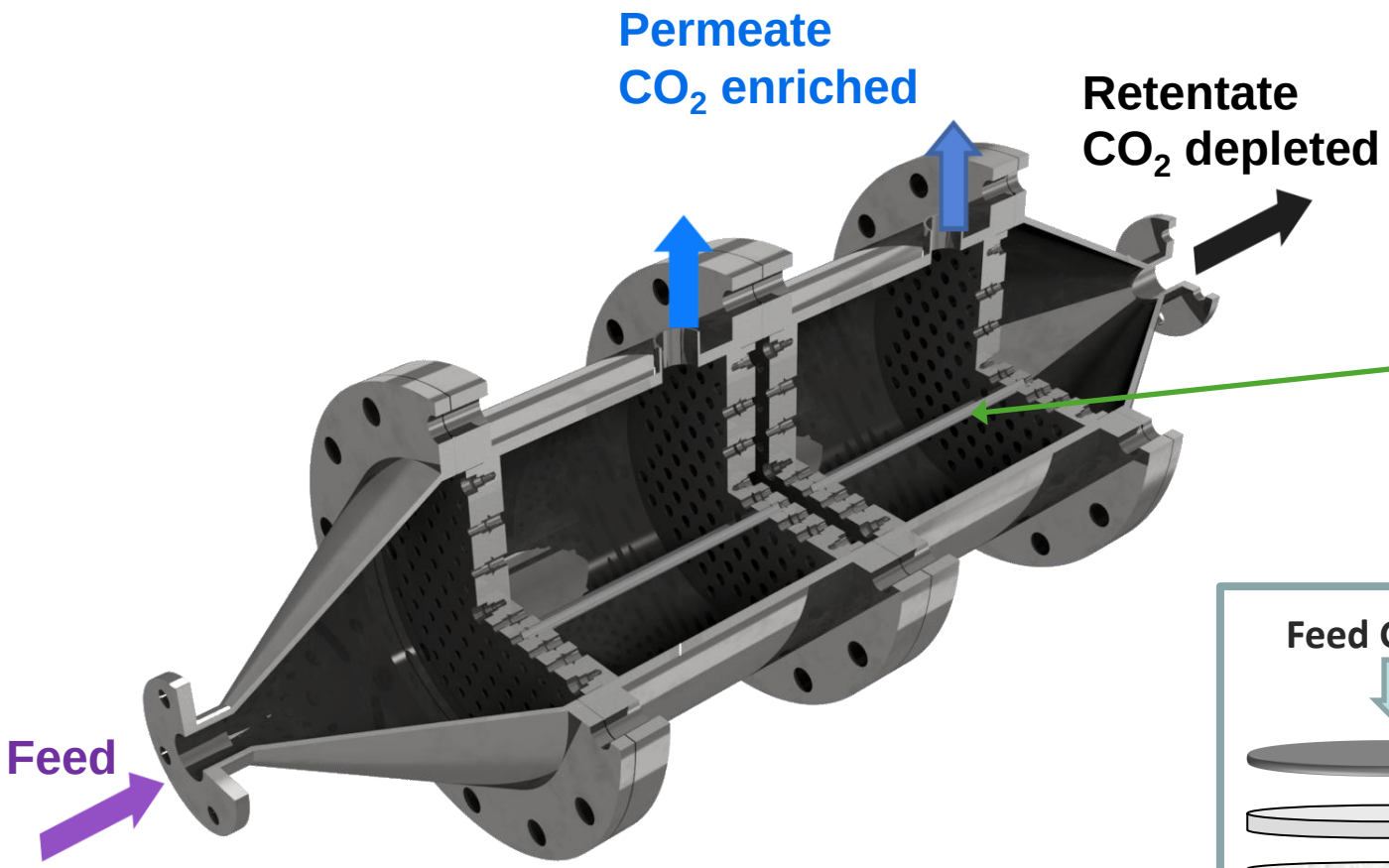
Separation layer
(δ < 85 nm)

Gutter layer
(δ < 150 nm)

Porous support
(δ ~ 50 µm)

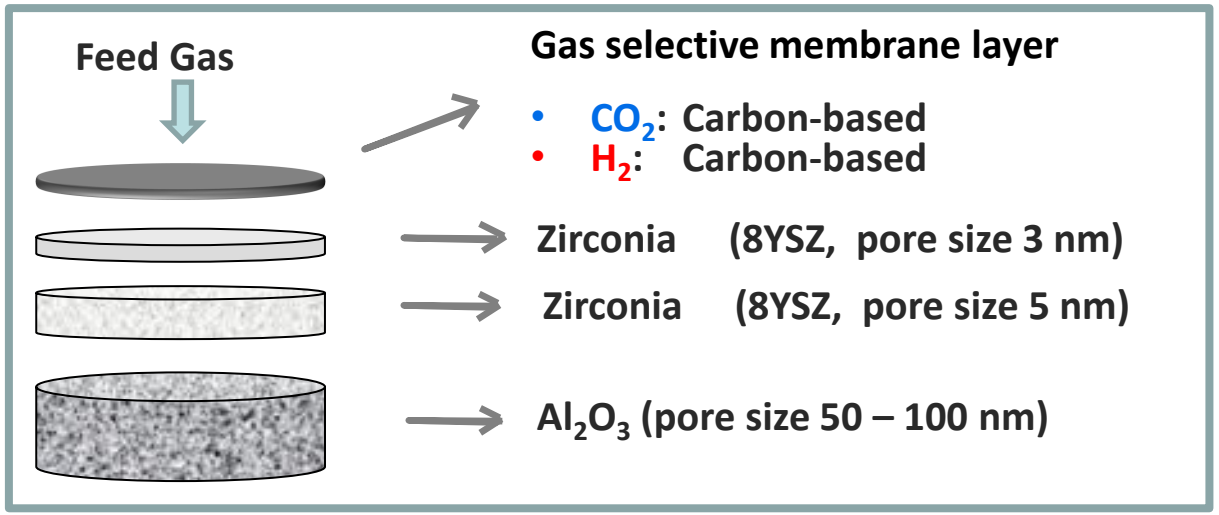
- Rubbery polymers: selective for CO_2
- Glassy polymers: selective for H_2

Membrane module and ceramic membrane



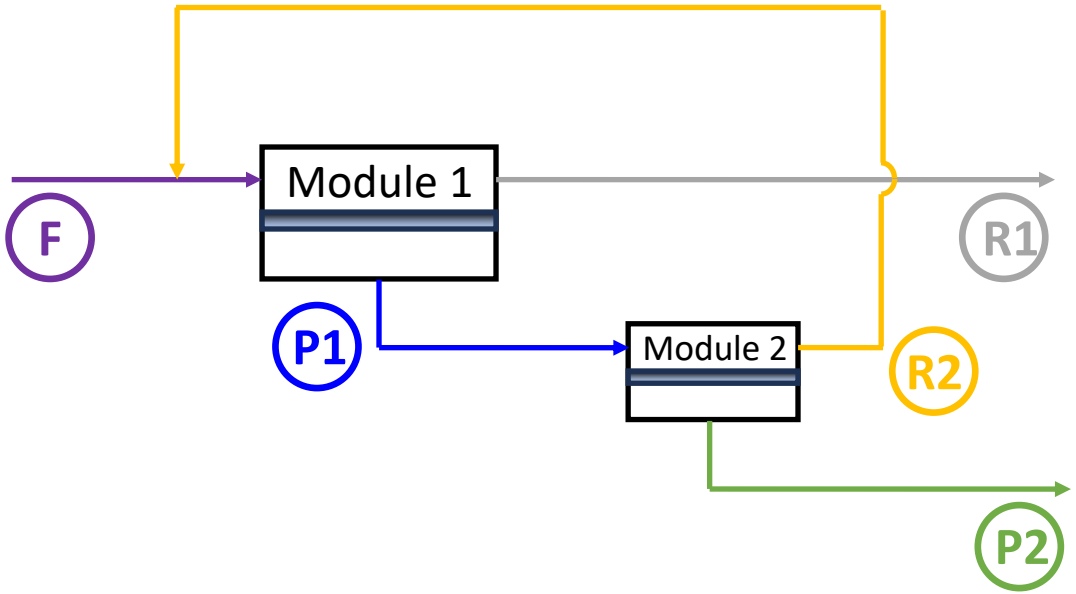
Ceramic membrane basis
Al_2O_3 -tubes

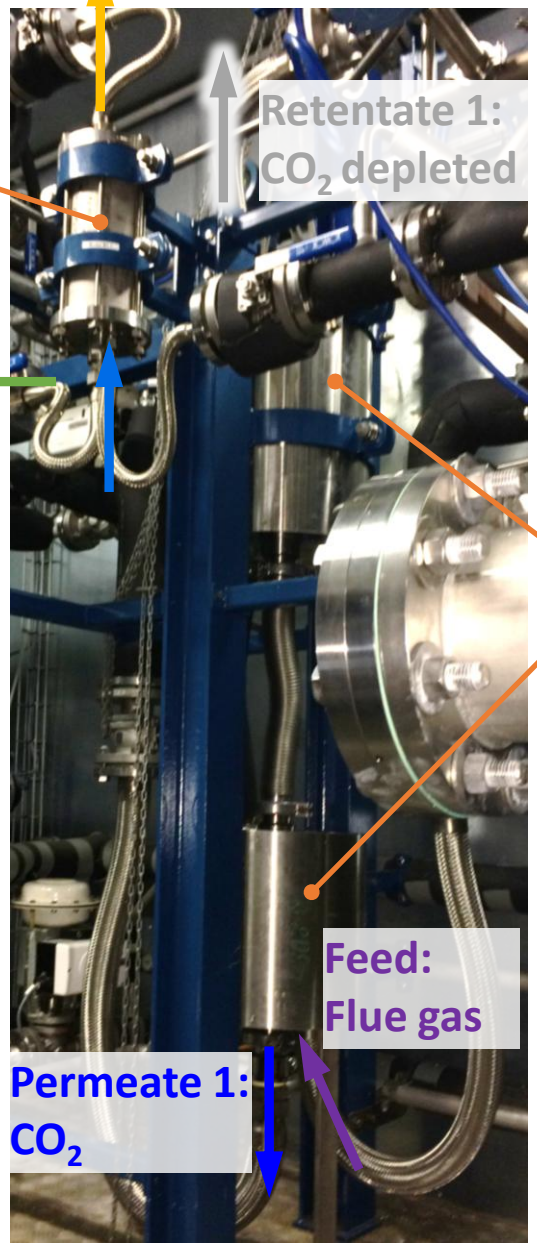
- < 1 nm : Surface diffusion via adsorption and desorption, selective for CO_2
- < 0.5 nm : Molecular sieving, selective for H_2



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

- Two stage process

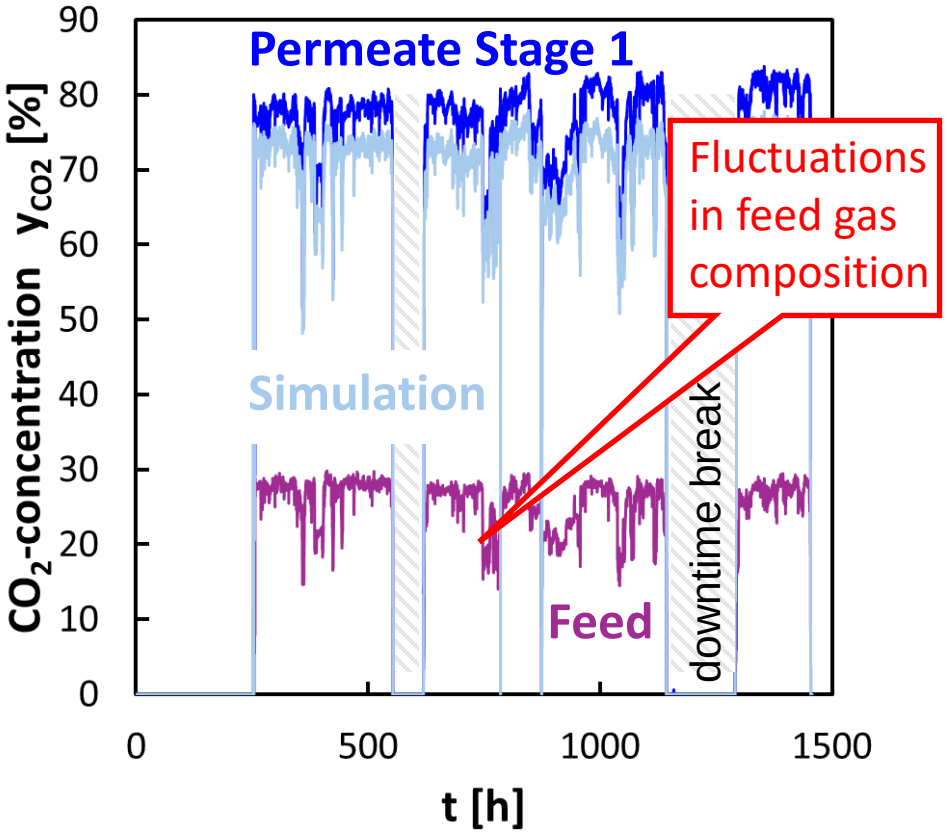


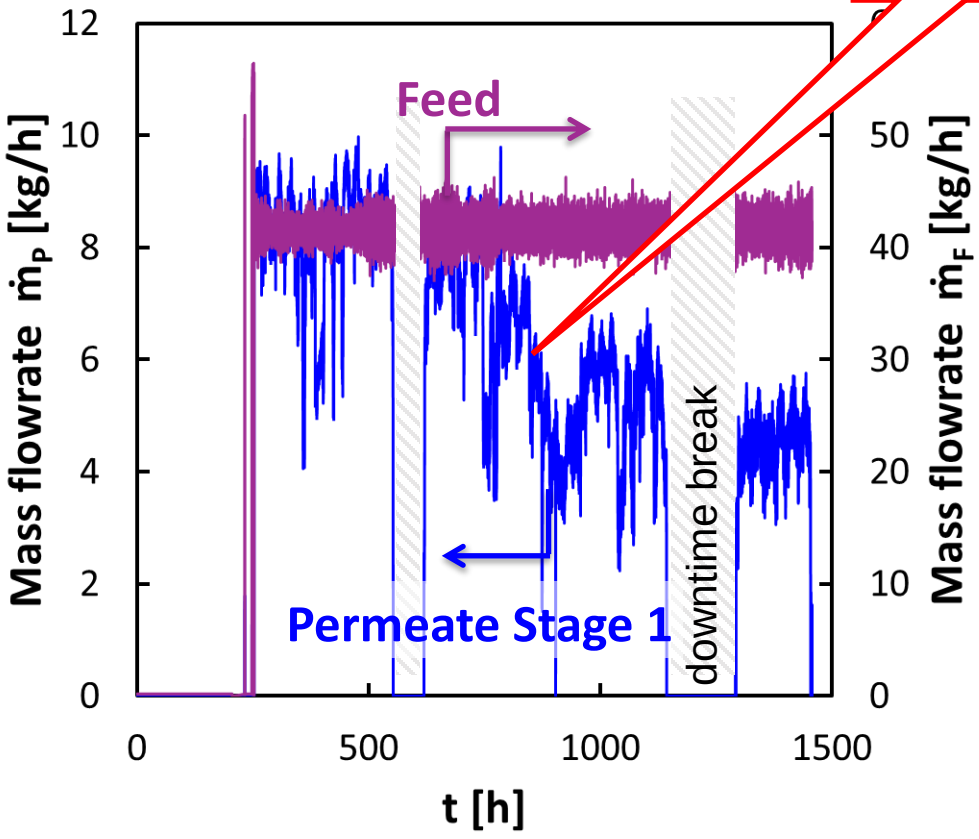


Module 1 – polymer membrane:
- CO_2 selective PolyActive™
- Area A_M=16 m^2
- Selectivity $\alpha_{CO2/N2}(\vartheta=25°C)$ = 47
- Permeance L_{CO2} (ϑ=25°C) = 3 $Nm^3/(m^2\ h\ bar)$

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 one stage mode – Polymer membrane

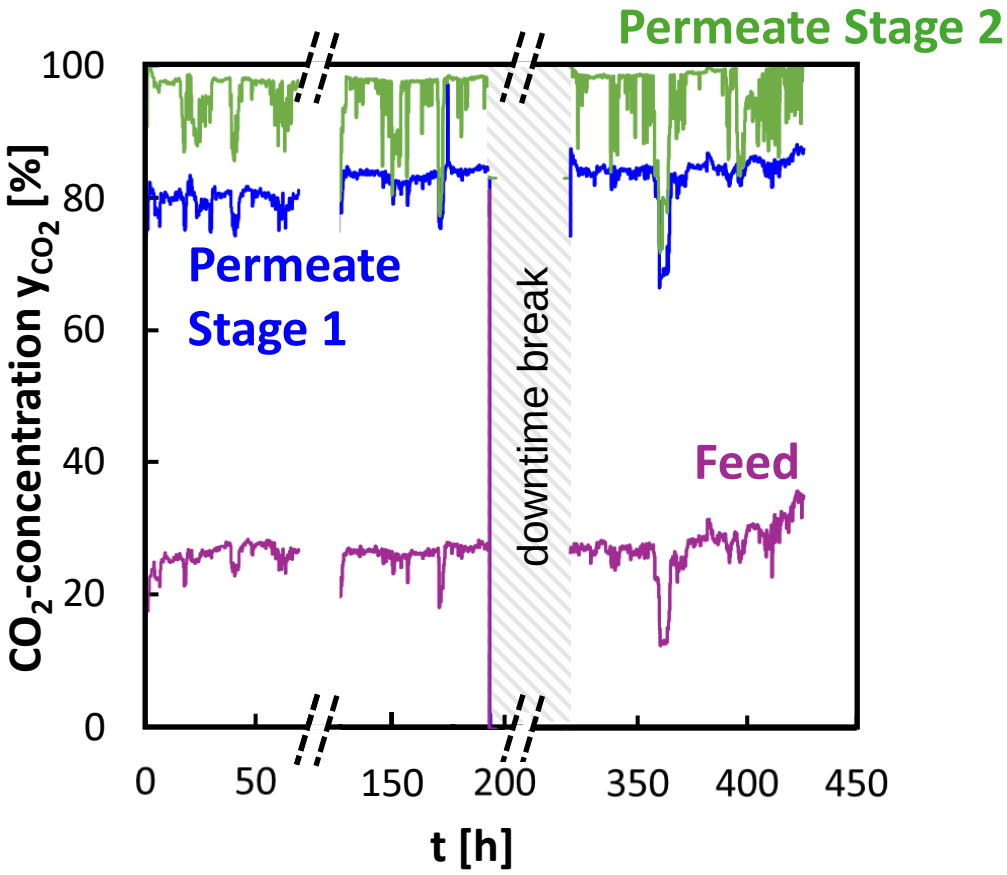


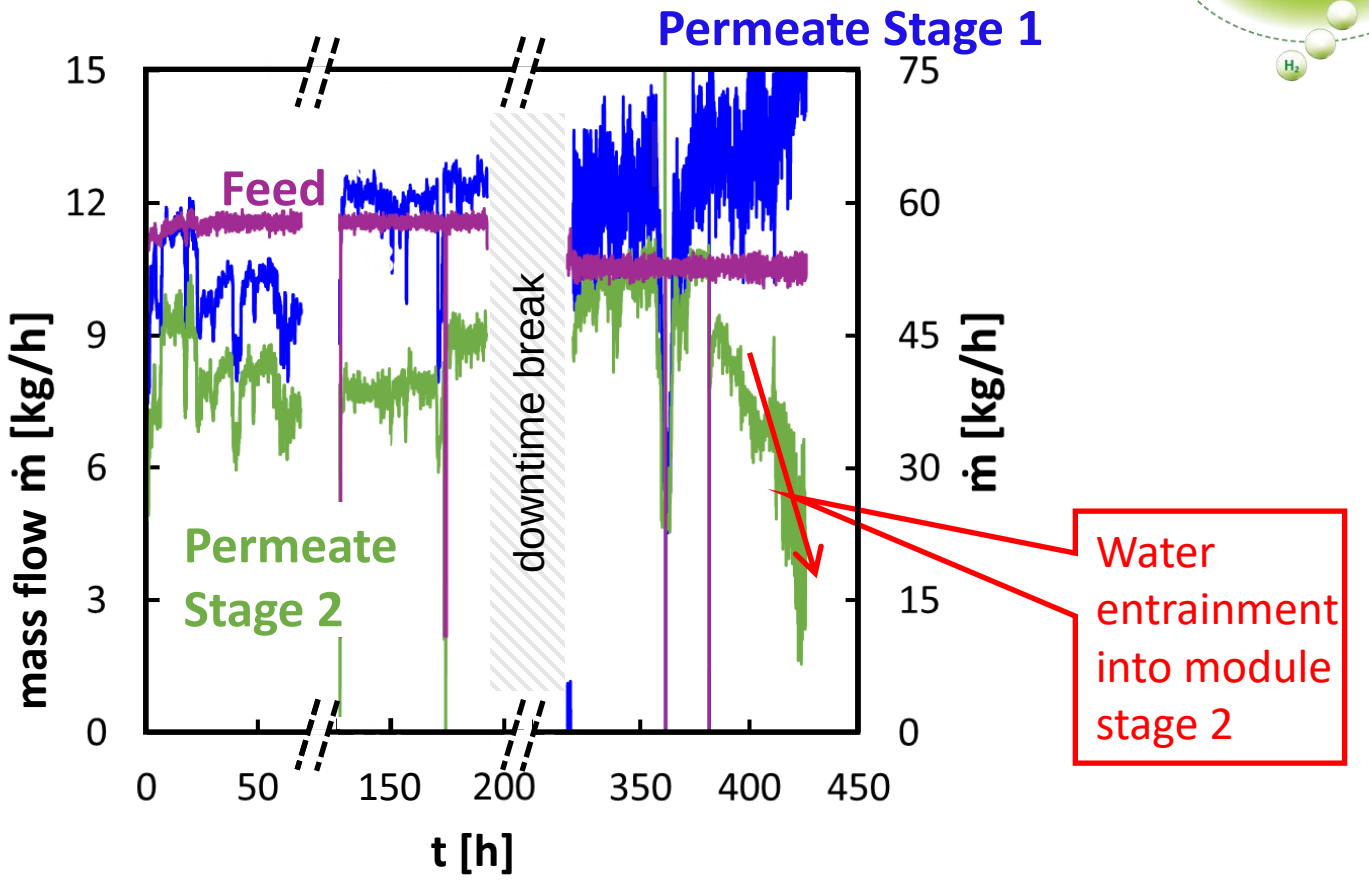


Observations:
- stable, two stage operation: CO_2 in 1st stage permeate > 80 mol-% ✓
- **no loss of performance** by downtime break ✓
- fluctuations in feed gas composition → drop in membrane performance

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

Operating performance two stage mode – Polymer membrane

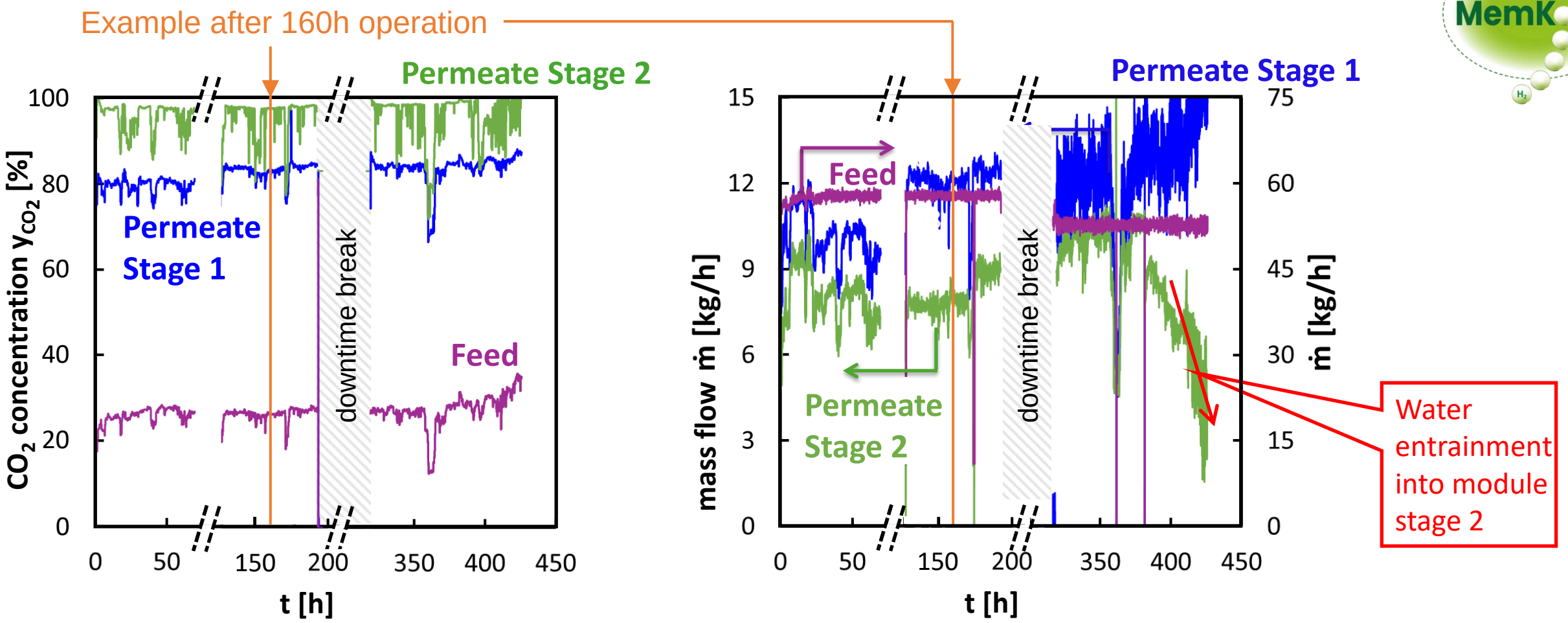




Observations:
- stable, two stage operation: CO_2 in 2nd stage permeate > 95 mol-% → fit for use ✓
- **no loss of performance** by downtime break ✓
- water entrainment severely impacts performance → risk mitigation action at feed-side

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

Operating performance two stage mode – Polymer membrane



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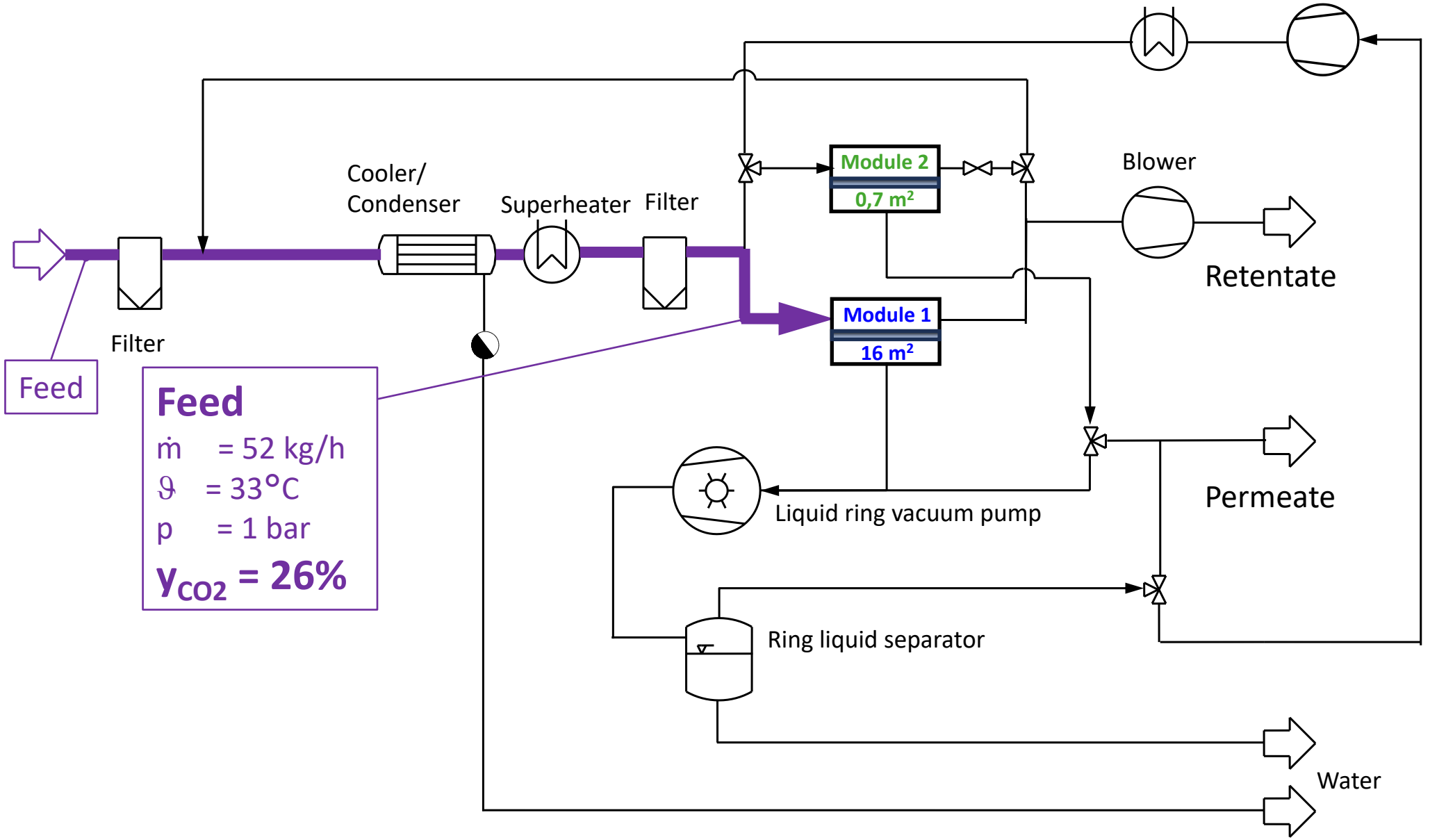
Example - Operating point after 160h (2-stage polymer membrane)



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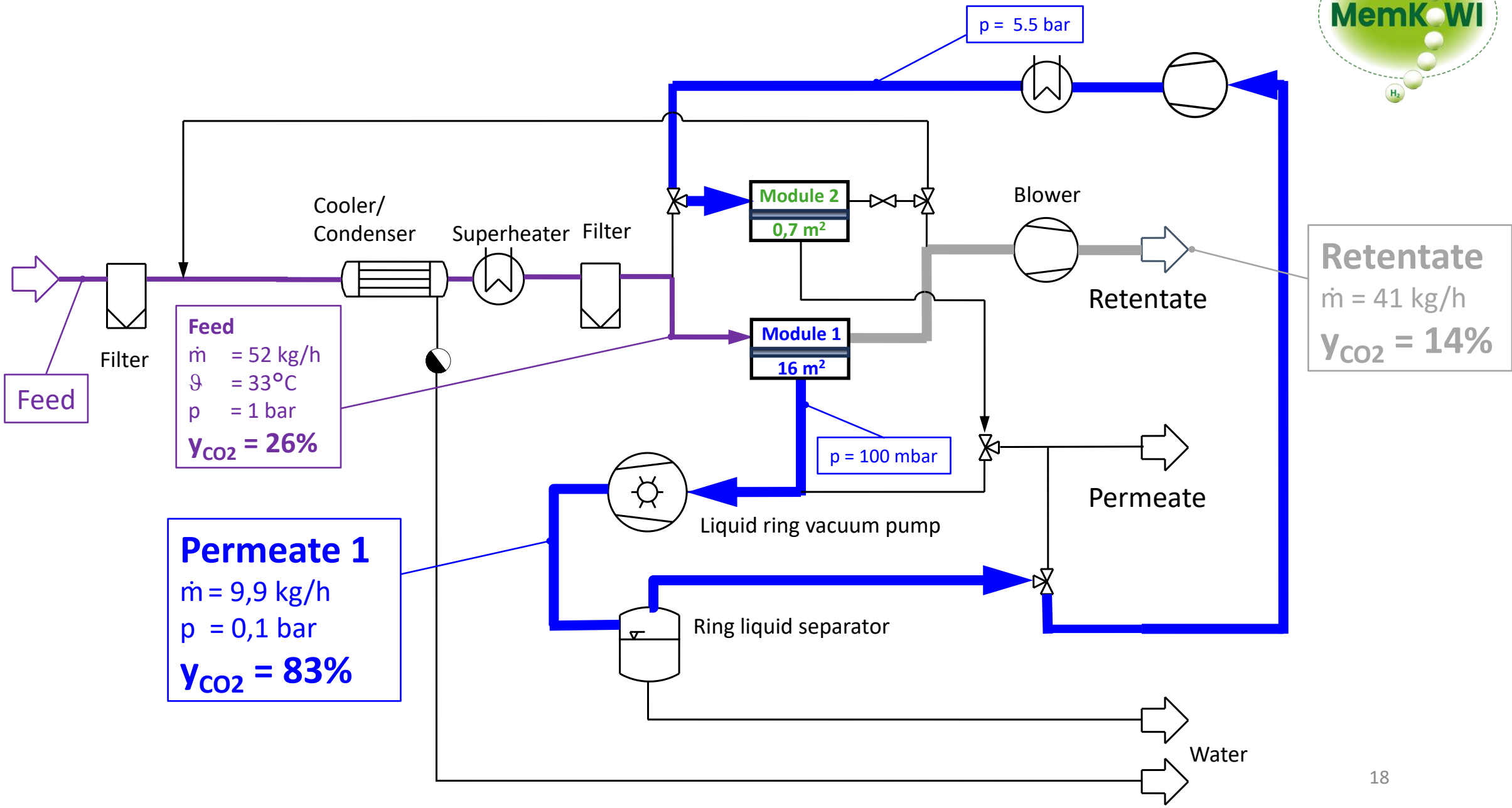

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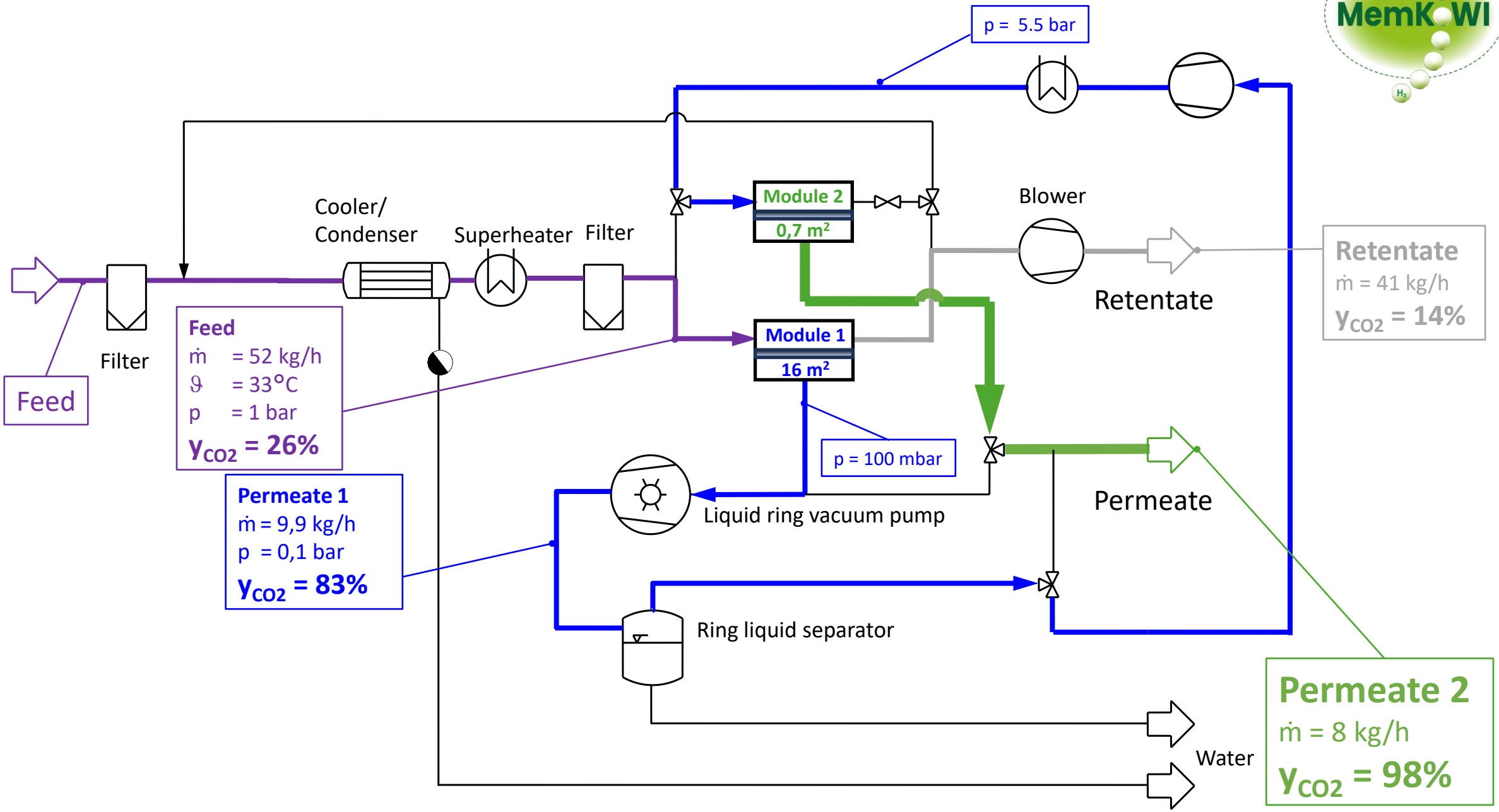

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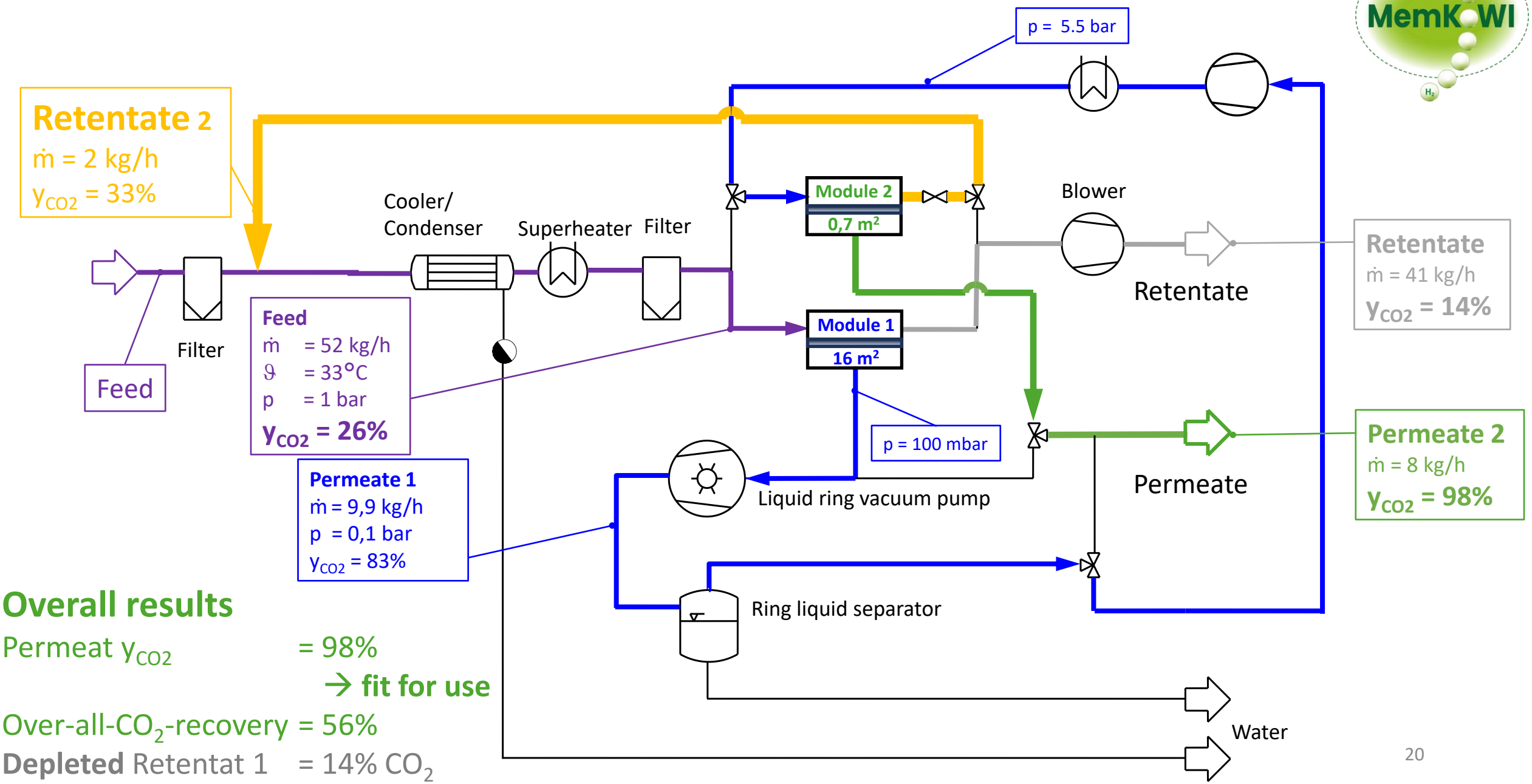


Overall results

Permeat y_{CO2} = 98%

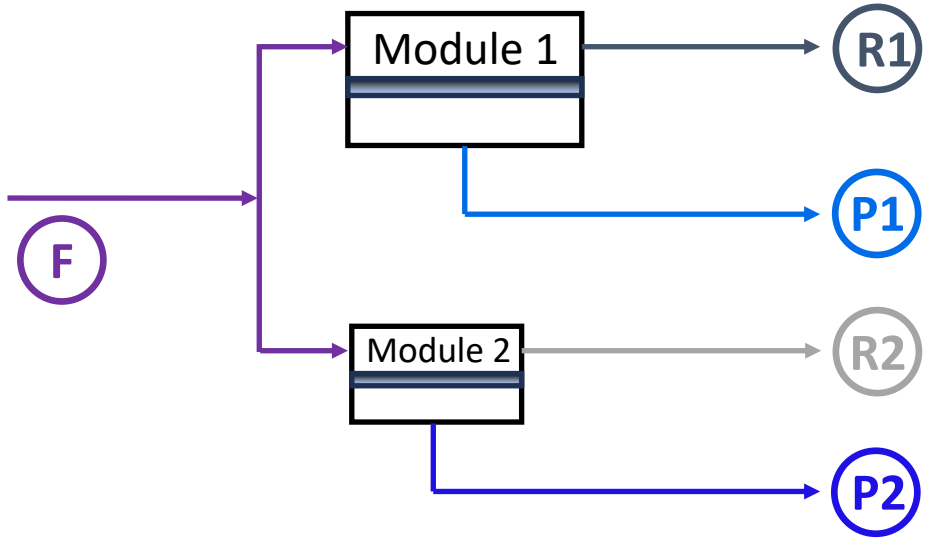
→ **fit for use**

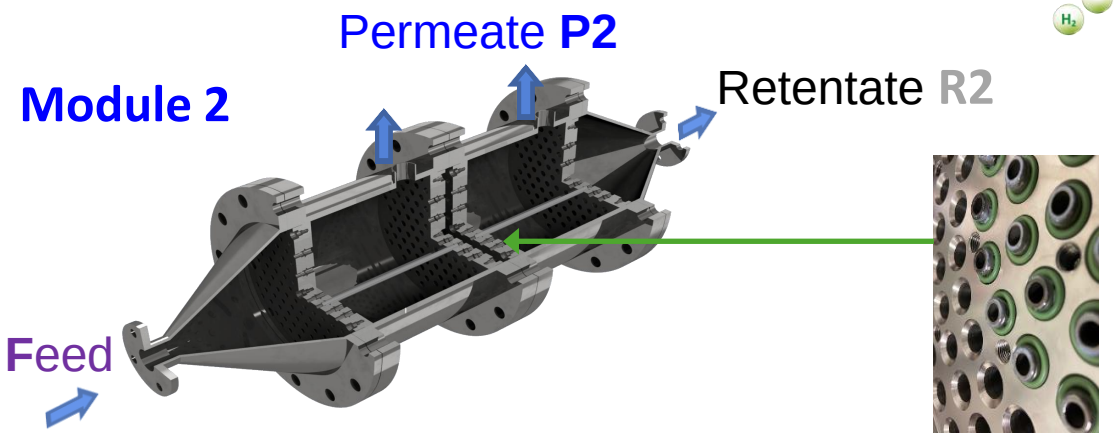
Over-all-CO_2-recovery = 56%

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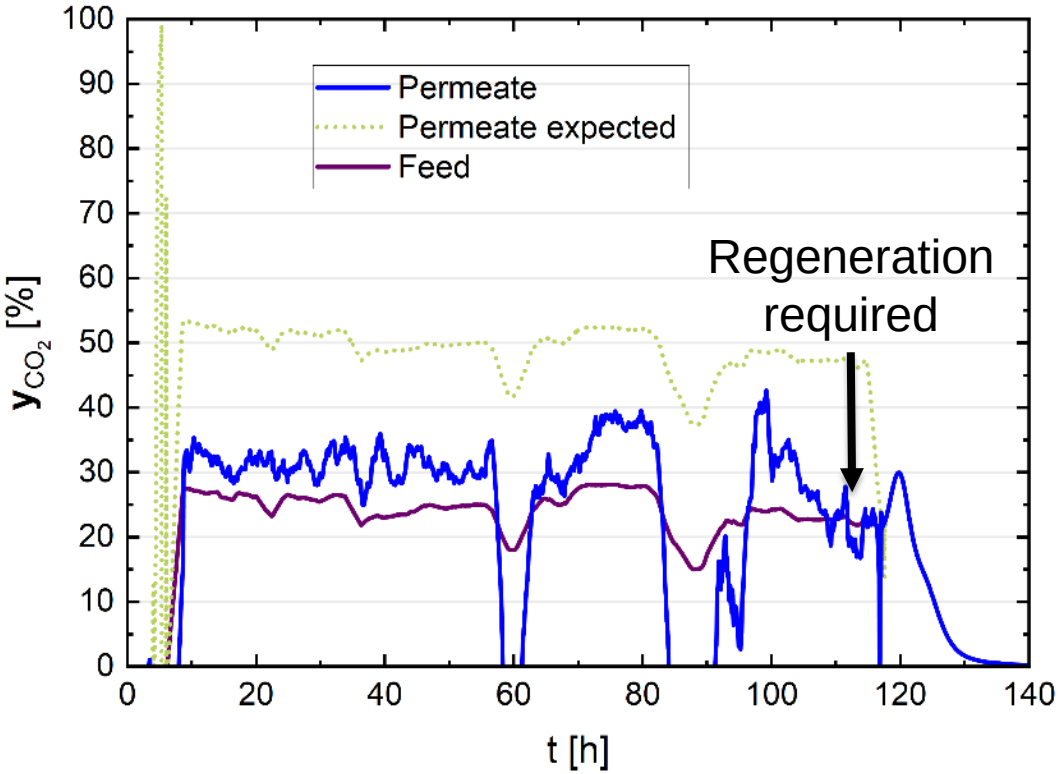
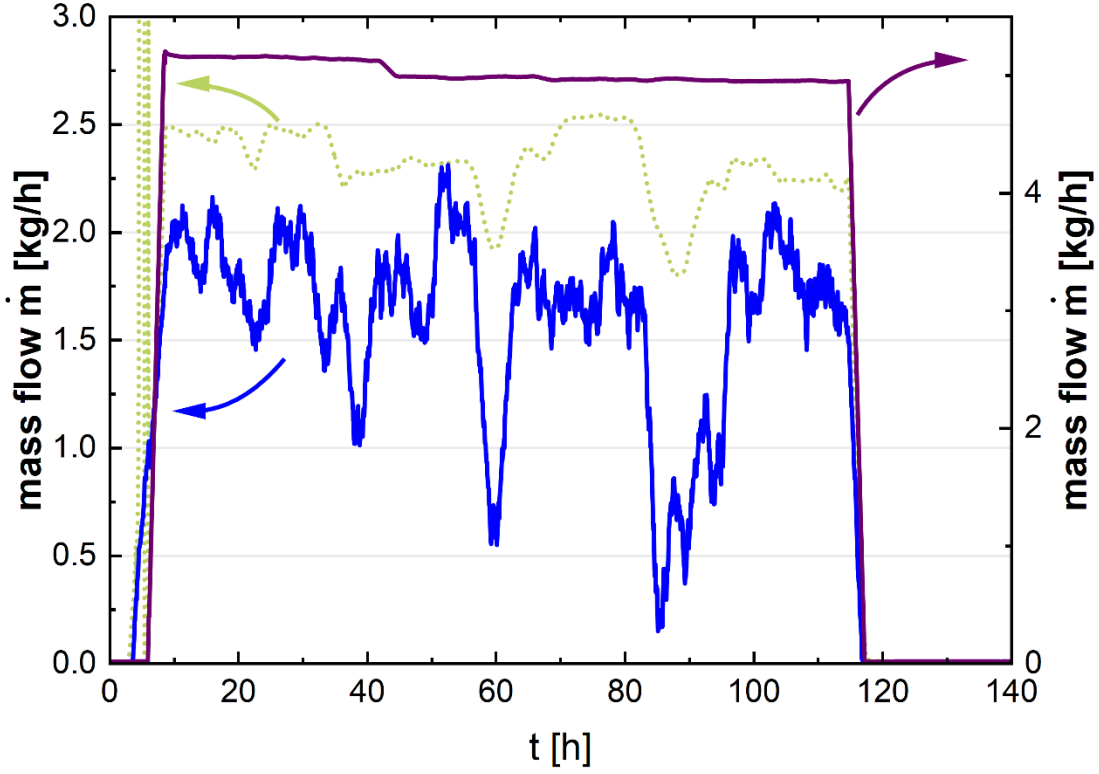
- CO_2 selective PolyActive™
- Area A_M=16 m^2
- Selectivity $\alpha_{CO2/N2}(\vartheta=25°C)$ = 47
- Permeance L_{CO2} (ϑ=25°C) = 3 $Nm^3/(m^2\ h\ bar)$
- Up to V_F = 80Nm^3/h

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:

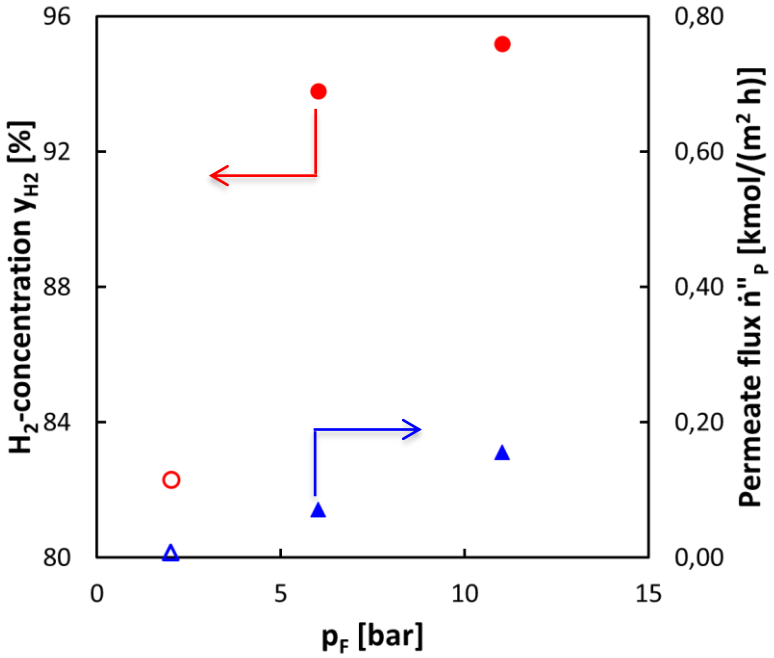
- ceramic module performance degrades fast in flue gas
- permeance and selectivity influenced by water and flue gas components
- lab-regeneration at ~400°C successful …→ again fast degradation in industrial environment

→ **Ceramic membrane less successful for CO_2-separation compared to polymer membrane**

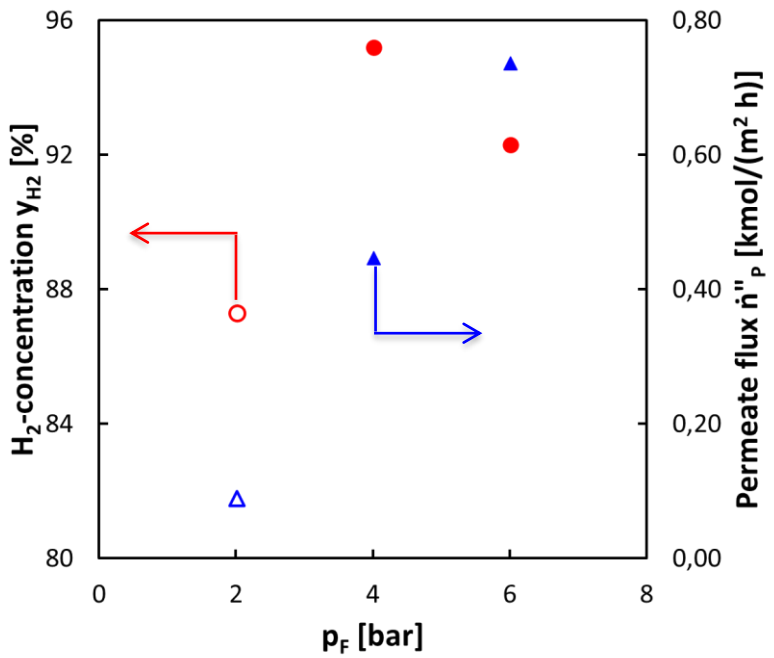
H_2 separation

- **H_2 separation from COG & BFG** *(finalizing construction for commissioning in Dec. 2025 – fit for 180°C)*
- COG with $y_{F,H2}$ = 56 % (synthetic gas mixture, ideal conditions)
- **Lab-scale trials** with MemKoWI-membranes at BFI

Polymer membrane (Hereon)



Ceramic membrane (FZ Jülich)



Observations:

→ Membranes well suited for H_2 separation from COG

→ **Ceramic membrane clearly outperforms polymer membrane**:

→ Higher fluxes at lower pressures with nearly identical H_2 purity

Results and next steps

- **Results**:
  - **Achieved CO_2 separation**: > 50% CO_2-off-gas depletion & >95% CO_2-Permeat for use (**CCU**) ✓
  - **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 with Polymer membrane ✓
    → regeneration possible for ceramic membranes ✓
    → stable high long-term performance with polymer membrane for CO_2-separation ✓ → for further upscaling & CCU
    simulation tool: operating performance predicted ✓
  - **Findings used for adapted concepts** and layout of the **further pilot plants** for: ✓
    → H_2 separation from COG & BFG (*finalizing construction for commissioning in Dec. 2025 – fit for 180°C)*
    → CO_2 separation from BFG, cement plant- and biomass power plant-flue gases (*finalizing optimized constructions*)
- **Next steps**:
  - **Long-term-testing** other gas-membrane-combination with modelling & optimization & evaluation of potential 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! → Questions?

Commissioning MemKoWI-pilot plant at Dillinger

MemKoWI-meeting in Dillingen - plant tour with Power4Steel

MemKoWI-Project coordination
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MemKoWI supported by:

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

Federal Ministry for Economic Affairs and Energy

ptj projektträger jülich

Power4Steel-Project of Dillinger-SHS-Saarstahl

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Power4Steel our journey – **Pure Steel+** our destination

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