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E-methanol production with electrified purification using heat pump assisted distillation

Lucas Poker – L.a.t.poker@tudelft.nl

PhD candidate Process Systems Engineering

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TU Delft

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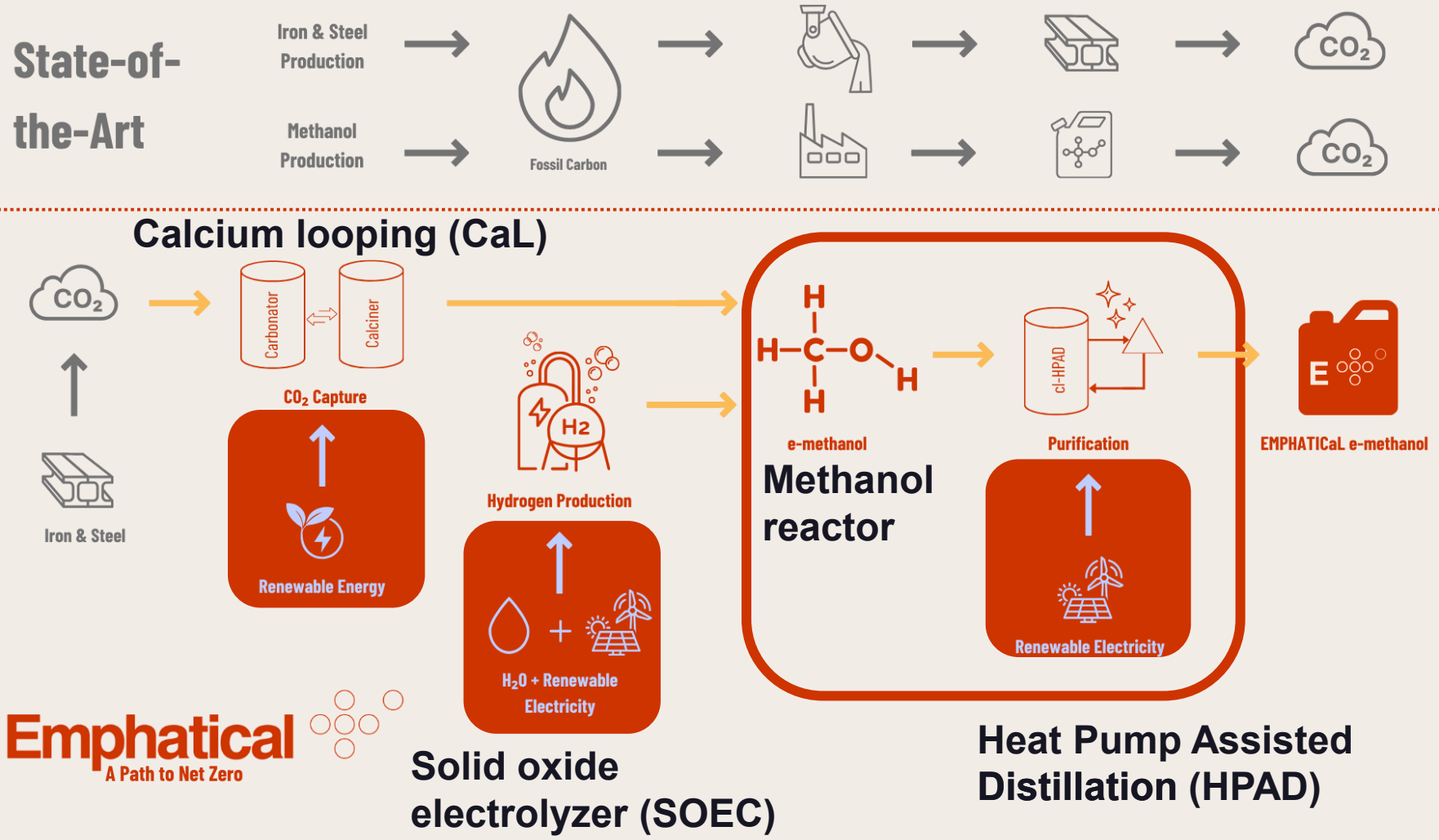
EMPHATICaL

- Reduce overall energy costs by 25%
- Fully renewable energy driven



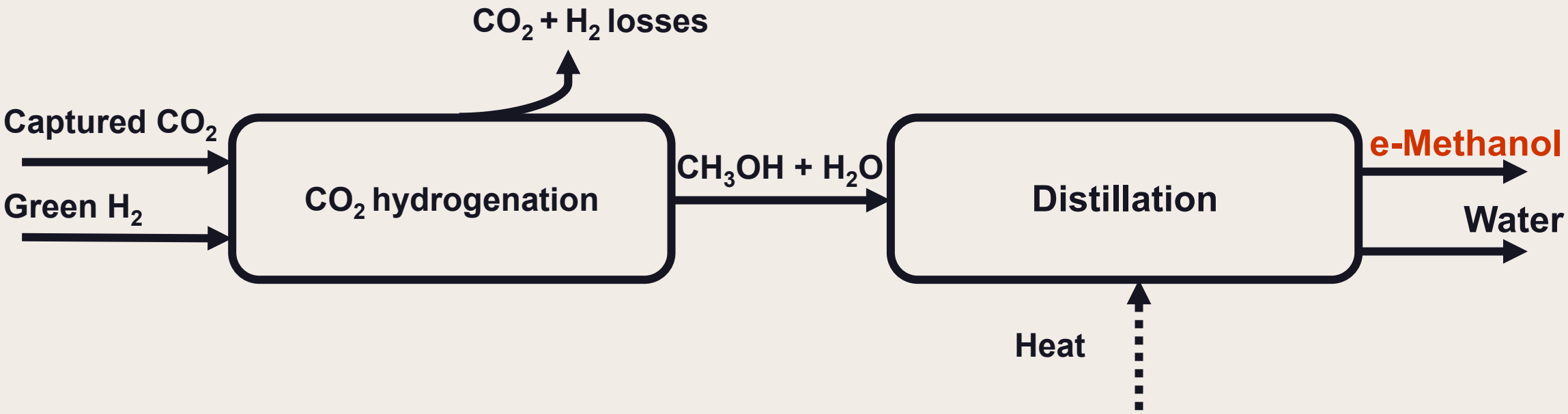
E-methanol production with electrified purification using heat pump assisted distillation

Methanol production & purification overview

Challenge: reduce overall e-methanol energy costs by 25%

Objectives:

1. High efficiency methanol production through CO_2 hydrogenation
2. High efficiency for methanol purification

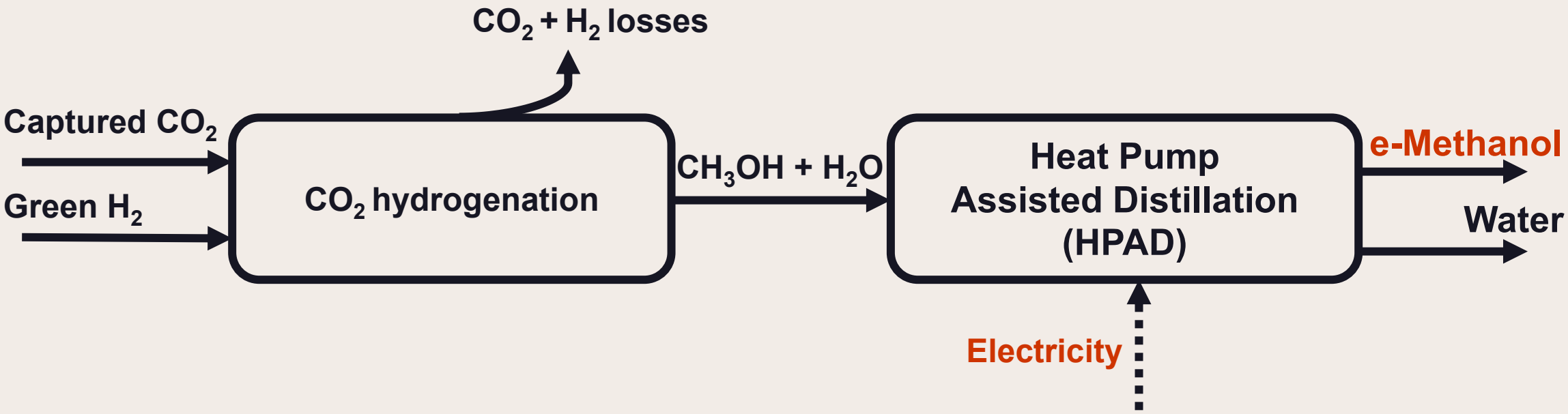


Methanol production & purification overview

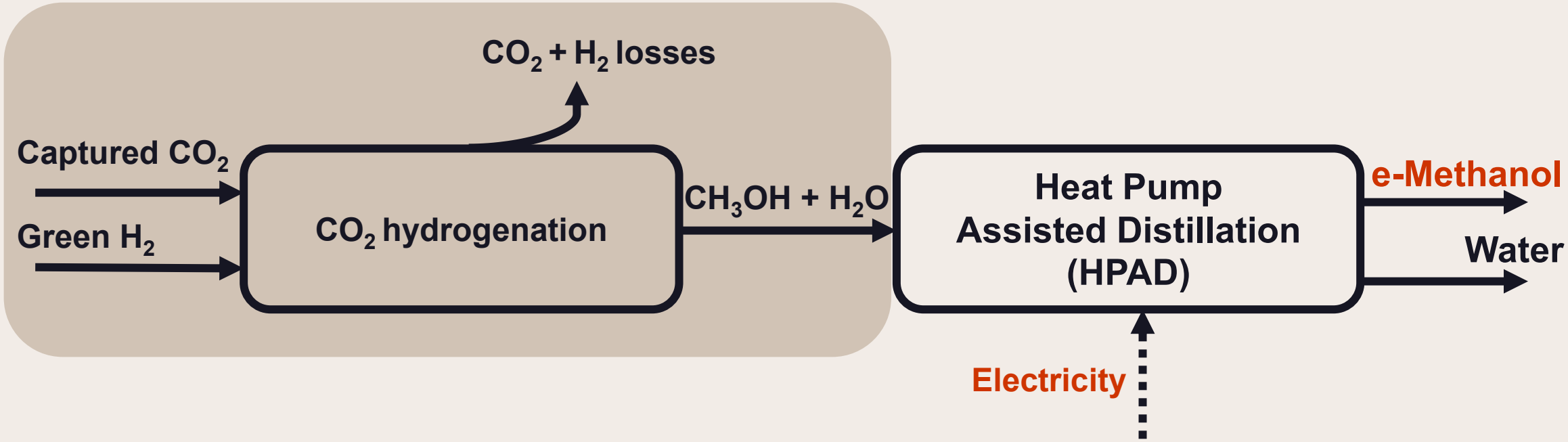
Challenge: reduce overall e-methanol energy costs by 25%

Objectives:

1. High efficiency methanol production through CO_2 hydrogenation
2. High efficiency, fully electrified methanol purification through Heat Pump Assisted Distillation (HPAD)



02: Methanol production



Methanol synthesis through CO_2 hydrogenation

1) $\mathbf{CO_2 + 3H_2 \leftrightarrows CH_3OH + H_2O,\ \ \Delta H_{298K} = -49.16\ kJ/mol}$

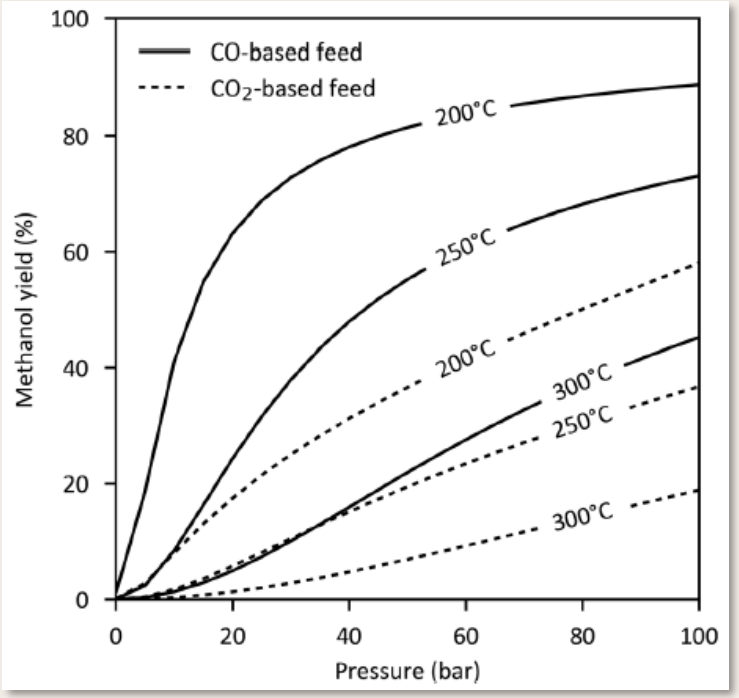
2) $\mathbf{CO_2 + H_2 \leftrightarrows CO + H_2O,\ \ \Delta H_{298K} = 41.21\ kJ/mol,\ Reverse\ water\ gas\ shift\ (WGS)}$

3) $\mathbf{CO + 2H_2 \leftrightarrows CH_3OH,\ \ \Delta H_{298K} = -90.77\ kJ/mol}$

$$\text{Stoichiometric number} = \frac{y_{H_2} - y_{CO_2}}{y_{CO} + y_{CO_2}} = 2$$

CO_2:H_2 = 3:1

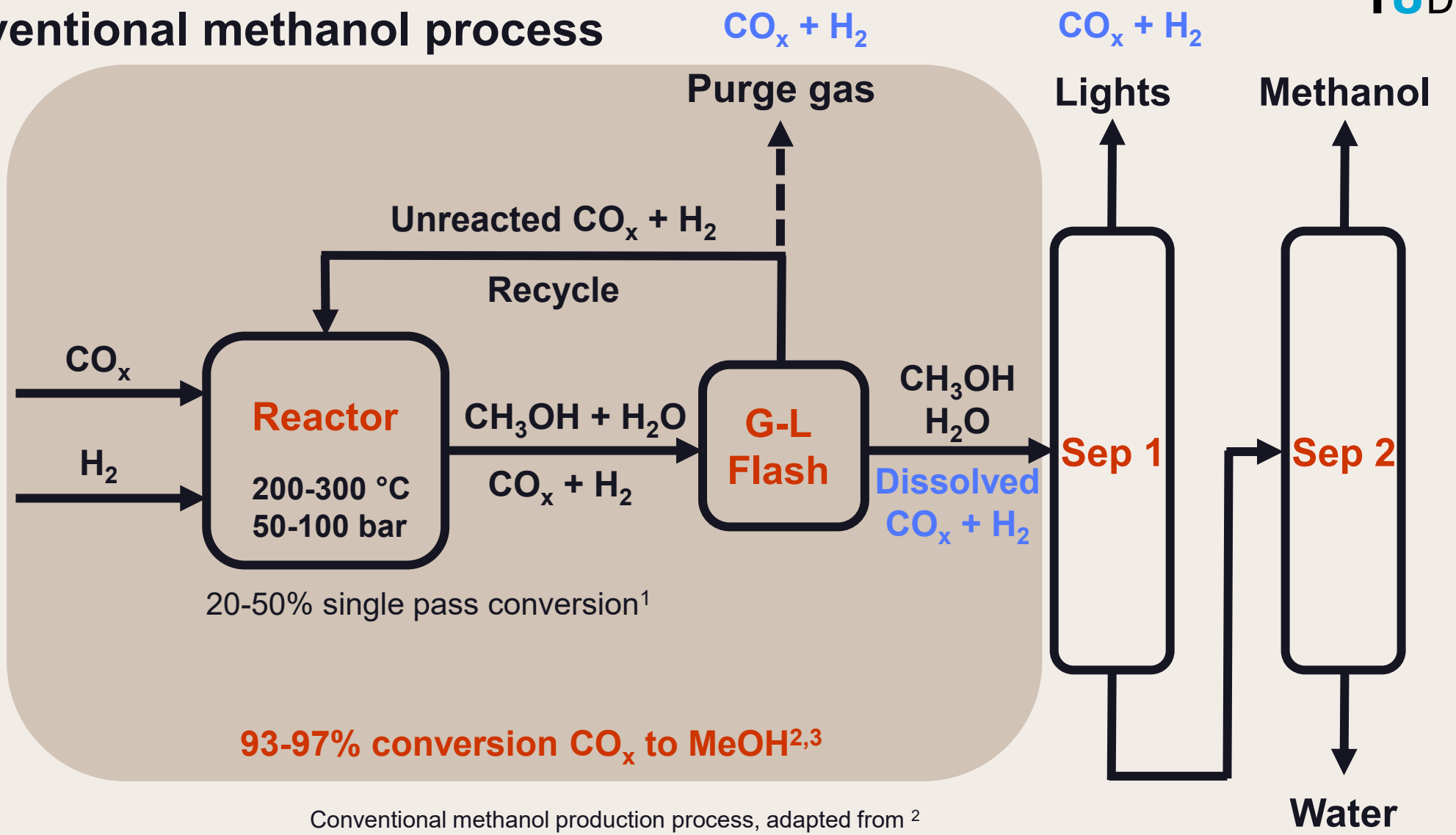
- Exothermic, decrease in total number of moles
- Low temperature, high pressure
- 200 °C: kinetically limited
- 250+ °C: equilibrium limited
- Water formation limits equilibrium conversion
- Trade-off between feed gas compression & recycle compression costs



Equilibrium conversion of CO- or CO_2-based feed gas to methanol[1]

[1] Dieterich et al. (2020), Power to liquid via synthesis of methanol, DME or Fisher Tropsch fuels a review

Conventional methanol process

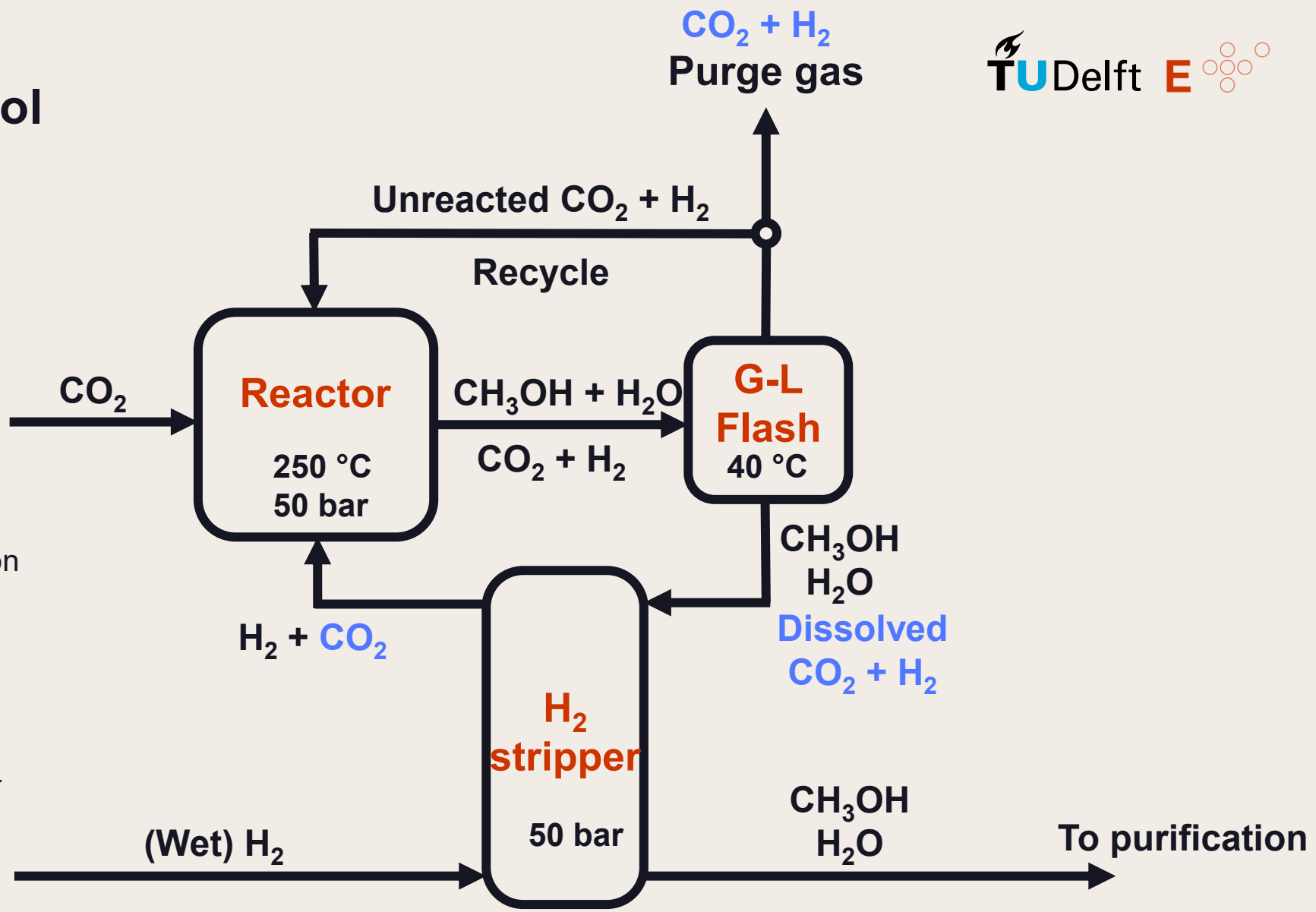


Conventional methanol production process, adapted from [2]

[1] Dieterich et al. (2020), Power to liquid via synthesis of methanol, DME or Fisher Tropsch fuels a review
[2] Kiss & Pragt (2016), Novel efficient process for methanol synthesis by CO2 hydrogenation

EMPHATICaL e-methanol production process

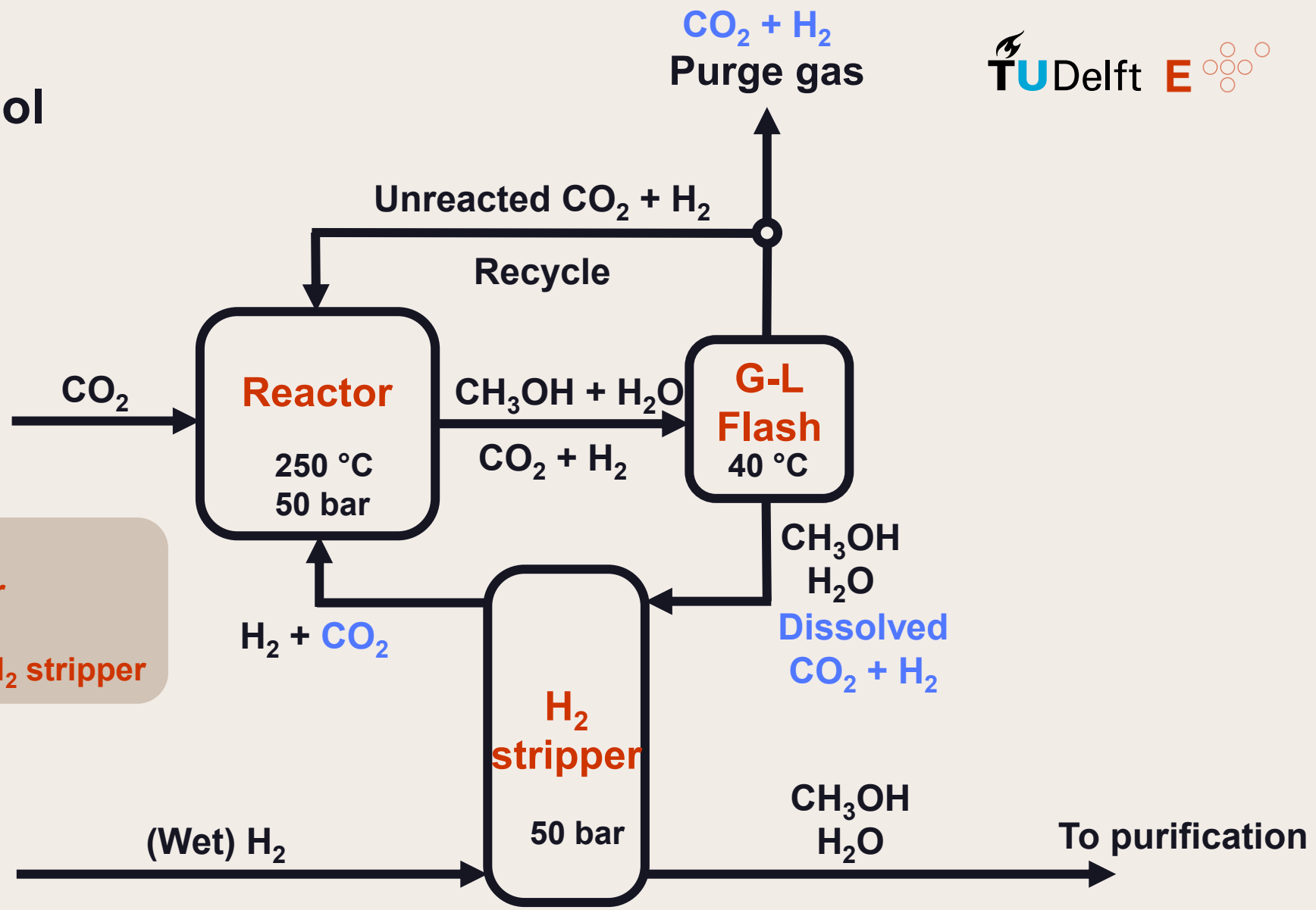
- Modeled in Aspen Plus
- 18.6% reactor single pass conversion
- H_2 stripper recycles nearly all dissolved CO_2
- Water of wet H_2 gets removed, increasing conversion in reactor
- Overall less CO_2 and H_2 needed per unit of MeOH
- Extra equipment cost: stripper



Methanol production process through CO2 hydrogenation with hydrogen stripper, based on [2,3]

[2] Kiss & Pragt (2016), Novel efficient process for methanol synthesis by CO2 hydrogenation
[3] Vaquerizo & Kiss (2023), Thermally self-sufficient process for cleaner production of e-methanol by CO2 hydrogenation

EMPHATICaL e-methanol production process



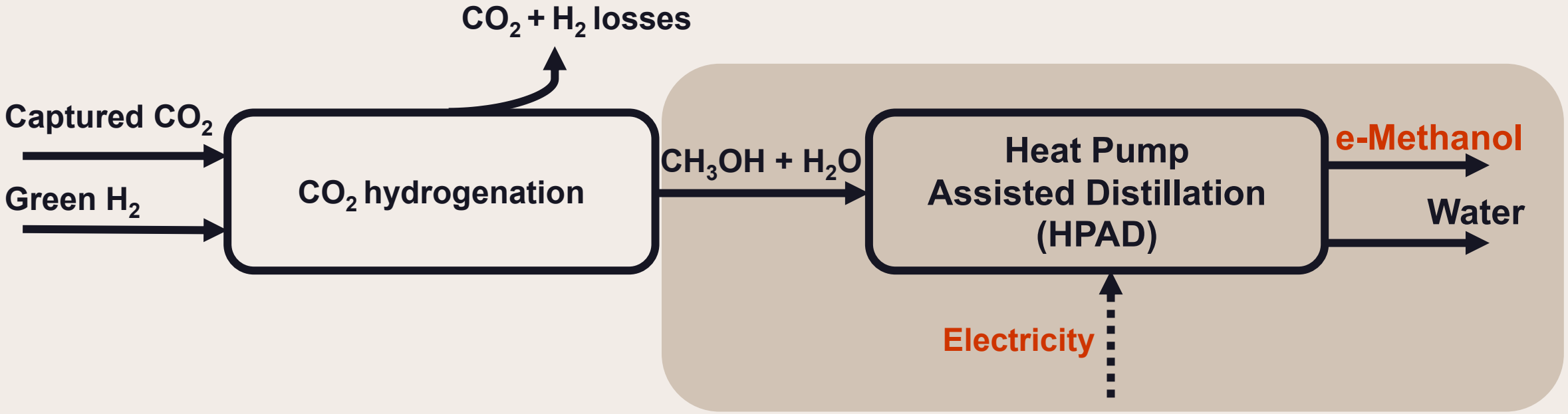
99.5% overall conversion
CO_2 to MeOH with H_2 stripper
vs
93-97% overall conversion without H_2 stripper

0.189 kg H_2/ kg MeOH
vs. conventional[4]
0.20 kg H_2/ kg MeOH
5.1% reduction

Methanol production process through CO2 hydrogenation with hydrogen stripper, based on [2,3]

[2] Kiss & Pragt (2016), Novel efficient process for methanol synthesis by CO2 hydrogenation
[3] Vaquerizo & Kiss (2023), Thermally self-sufficient process for cleaner production of e-methanol by CO2 hydrogenation

03: Heat Pump Assisted Distillation



Heat pump assisted distillation (HPAD)

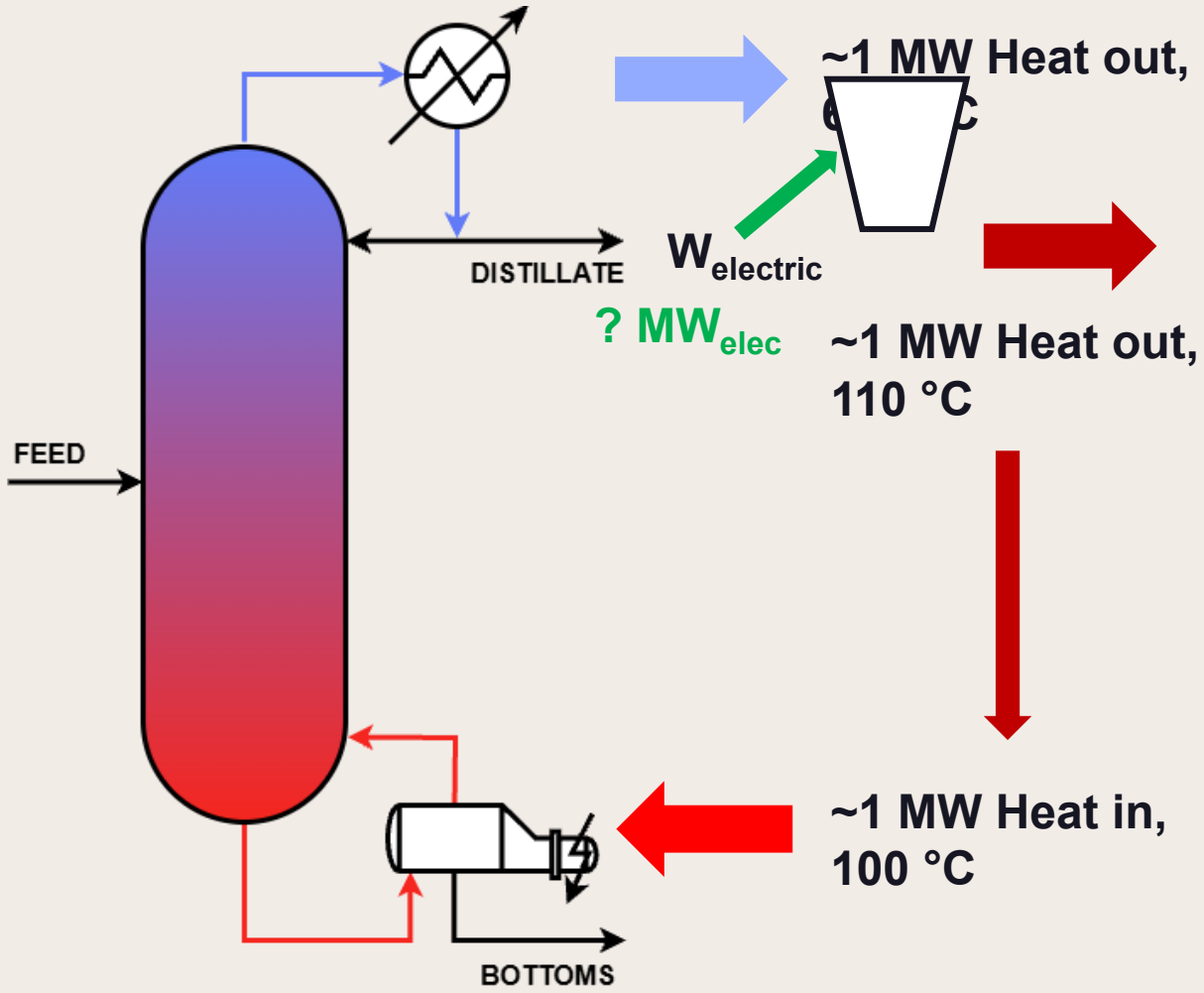
- $CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$
- Methanol – water separation, side products
- Distillation energy inefficient

- Upgrade heat with compressor

- Drive reboiler with latent heat condenser

- What compressor power is required?

- Highly dependend on ΔT_{lift}



Methanol-water distillation column

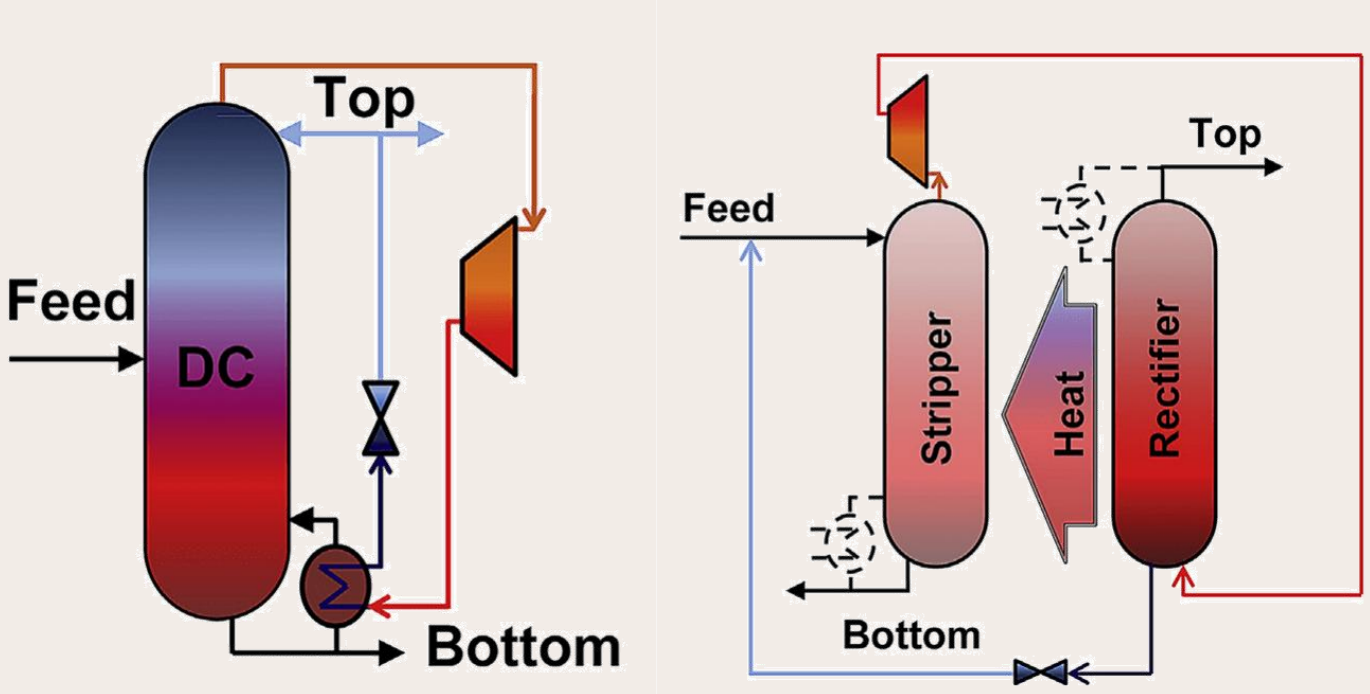
Heat Pump Assisted Distillation technologies

- Mechanical vapor recompression (MVR)
- Directly compress overhead vapor to use latent heat to drive reboiler

Or, more complex:

- Heat Integrated Distillation Column (HIDiC)
- Potential 80% energy savings vs conventional column

- MVR commercially applied
- Goal EMPHATICaL to de-risk HIDiC, TRL7 pilot



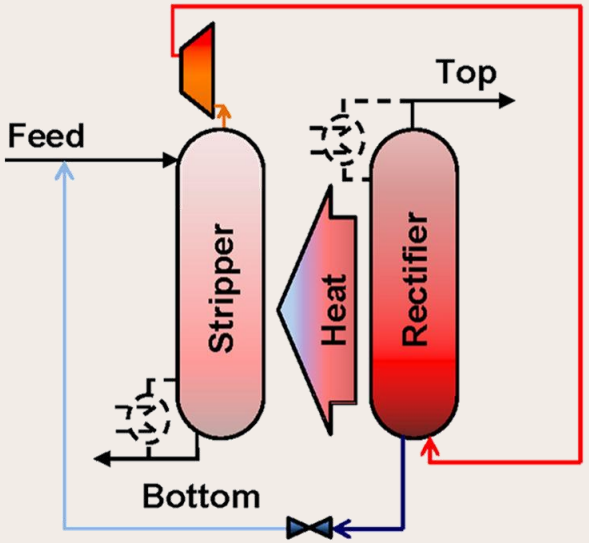
Mechanical vapor recompression (MVR) system (left) and HIDiC configuration (right)[4]

[4] Kiss & Olujić (2014), A review on process intensification in internally heat integrated distillation columns

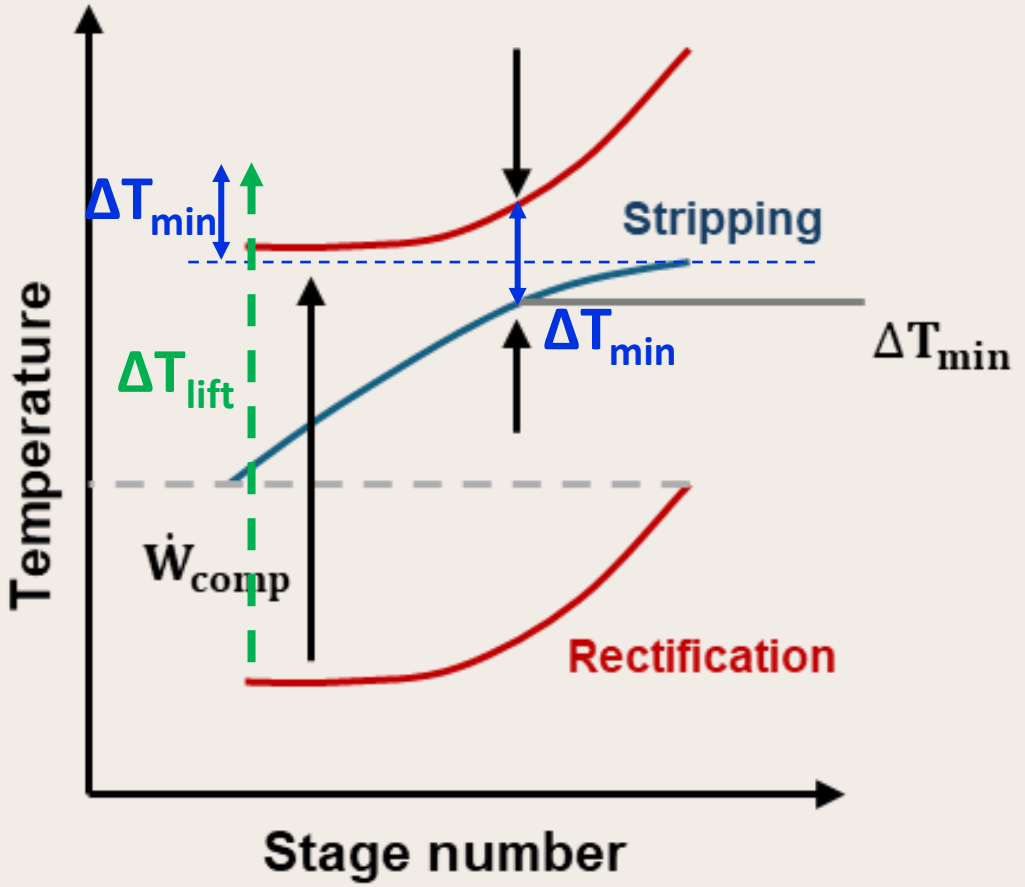
Heat integrated distillation column (HIDiC)

- Rectifying section operated at higher pressure
- Heat transfer from rectifier to stripper

- Reduced ΔT_{lift}, reduced pressure ratio, higher energy savings

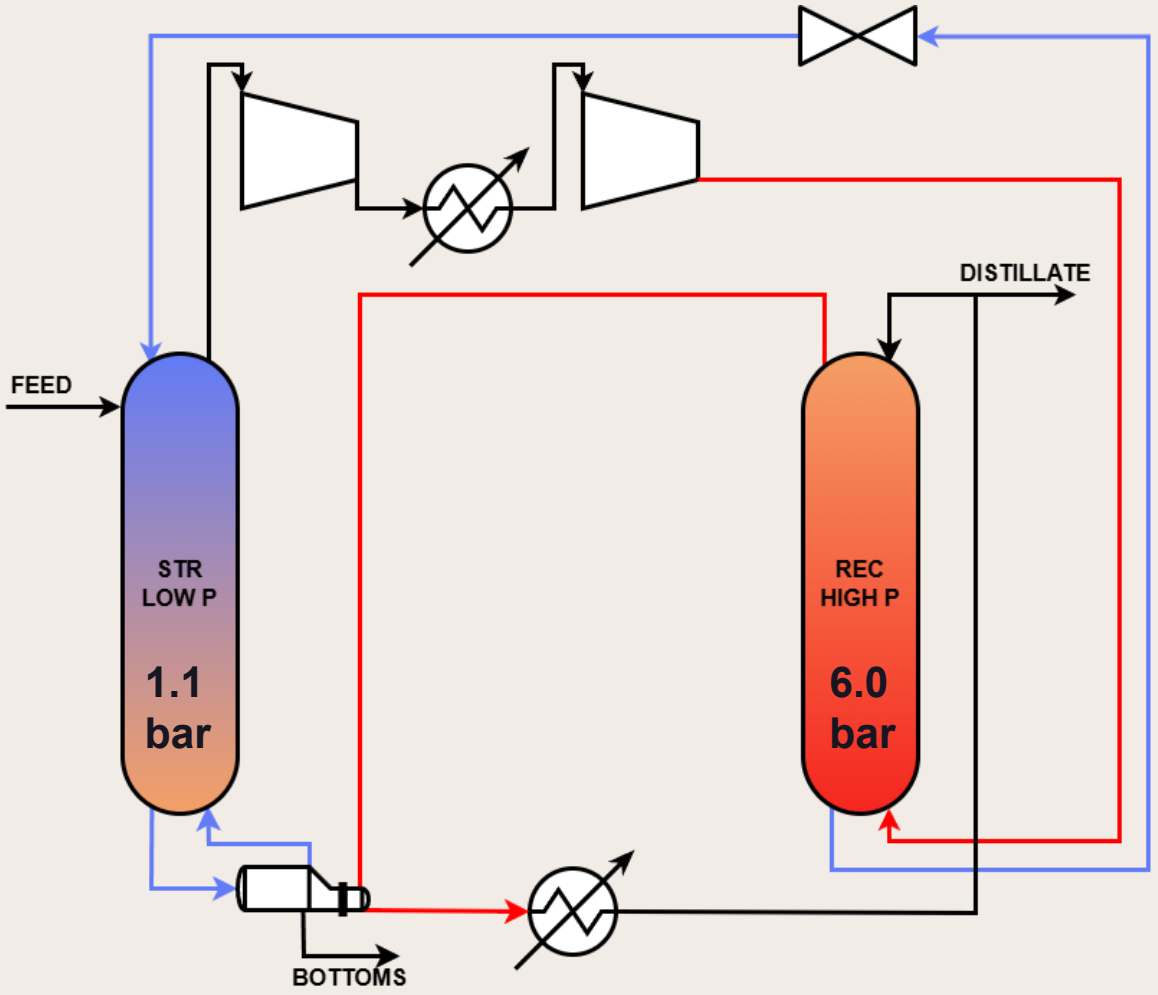


Heat Integrated Distillation Column (HIDiC)

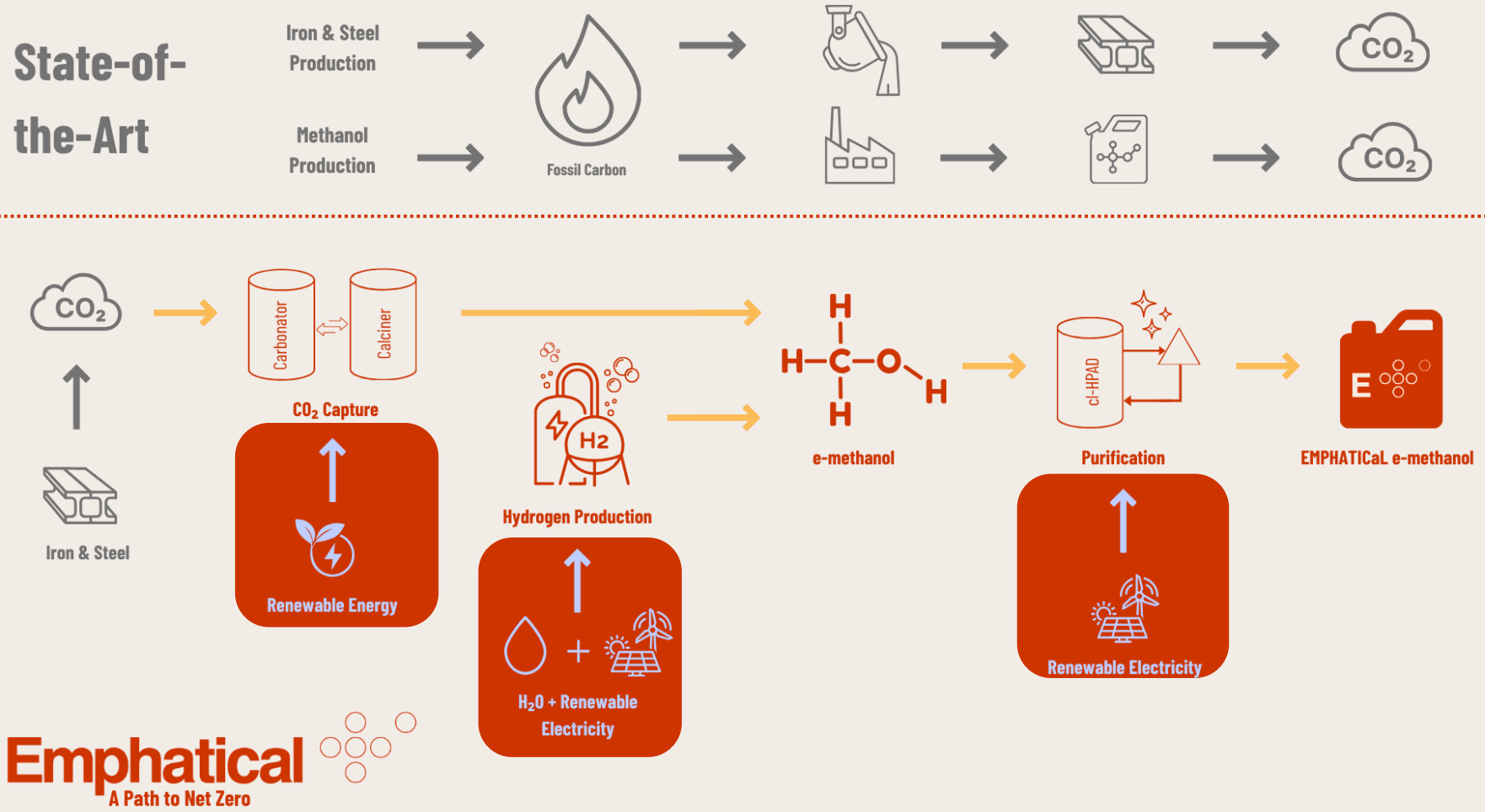


Closed-loop heat pump assisted distillation (cl-HPAD)

- Configuration of pilot plant to advance cl-HPAD to TRL-7
- Overhead vapor rectifier coupled with reboiler stripper
- 2-stage compression with intercooling to deal with methanol superheating & enhance efficiency
- Modeled in Aspen Plus
- $COP = \frac{Heat\ output}{Electric\ power\ input} = \frac{Q_{conventional\ column}}{W_{elec}} = 5.06$
- 80.2% energy savings versus conventional single distillation column for same separation task



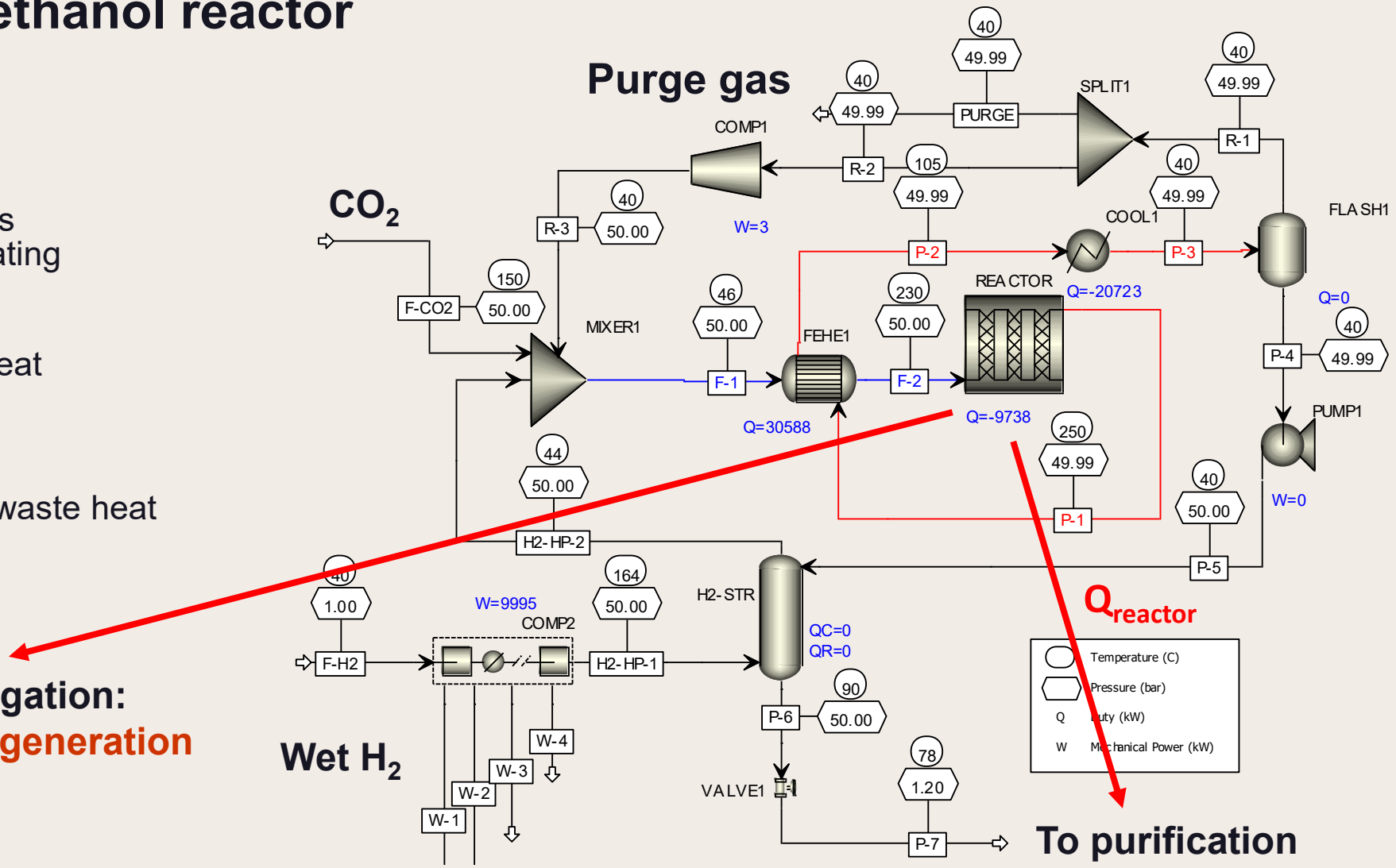
04: Heat integration & flexibility



E-methanol production with electrified purification using heat pump assisted distillation

Heat integration methanol reactor

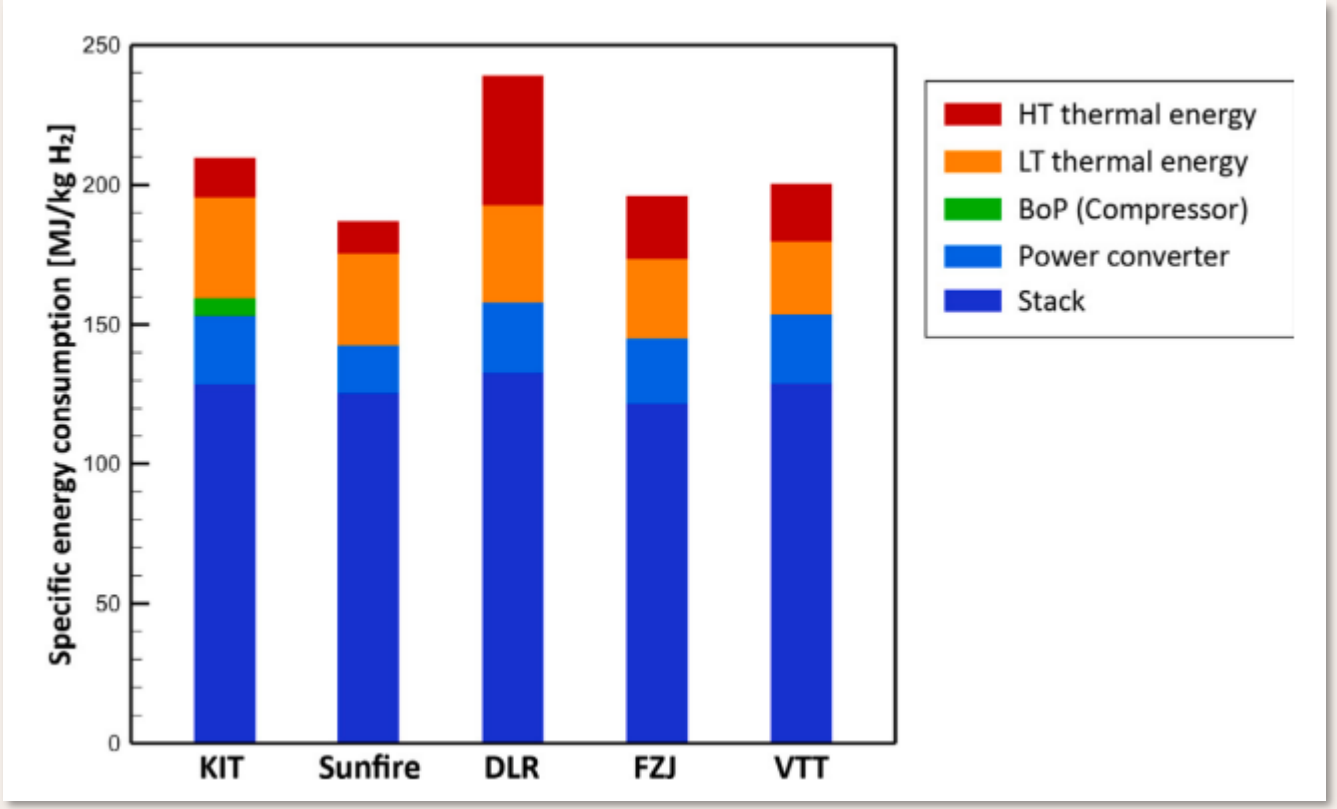
- Exothermic reaction
- After startup, reactor provides enough heat for feed pre-heating
- Heat from reactor ~60% of heat demand of distillation
- But: HPAD does not require waste heat



SOEC energy costs

- ~20 % of total energy demand used for heating
- LT thermal energy through heat integration
- HT thermal energy generated with electric heating for these cases[6]

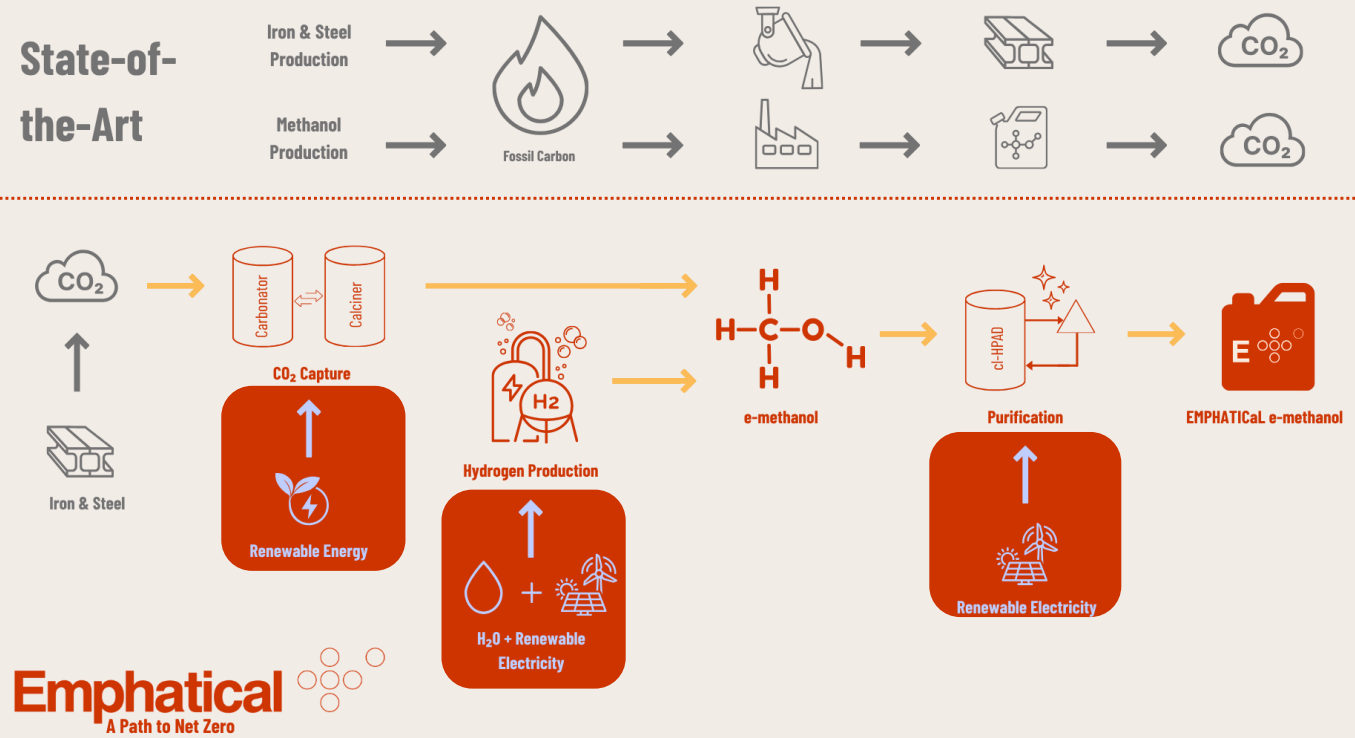
- Use of high temperature (>800 °C) CaL waste heat for HT thermal energy
- Use of reactor waste heat for LT thermal energy

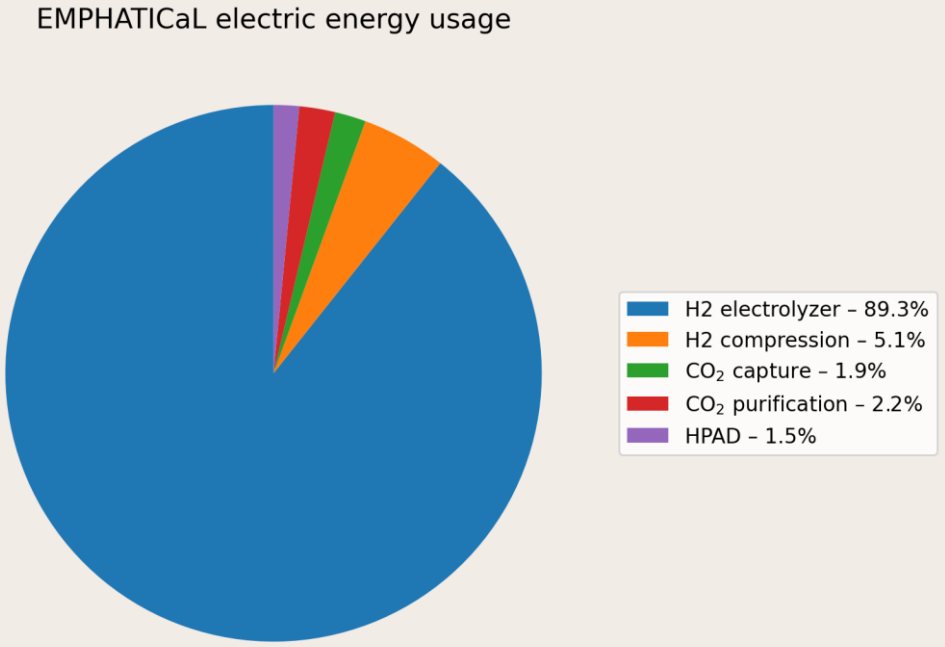


Specific energy consumption for verified SOEC systems[6]

[5] Min et al. (2022), A review of solid oxide steam-electrolysis cell systems: Thermodynamics and thermal integration

Electric energy usage distribution

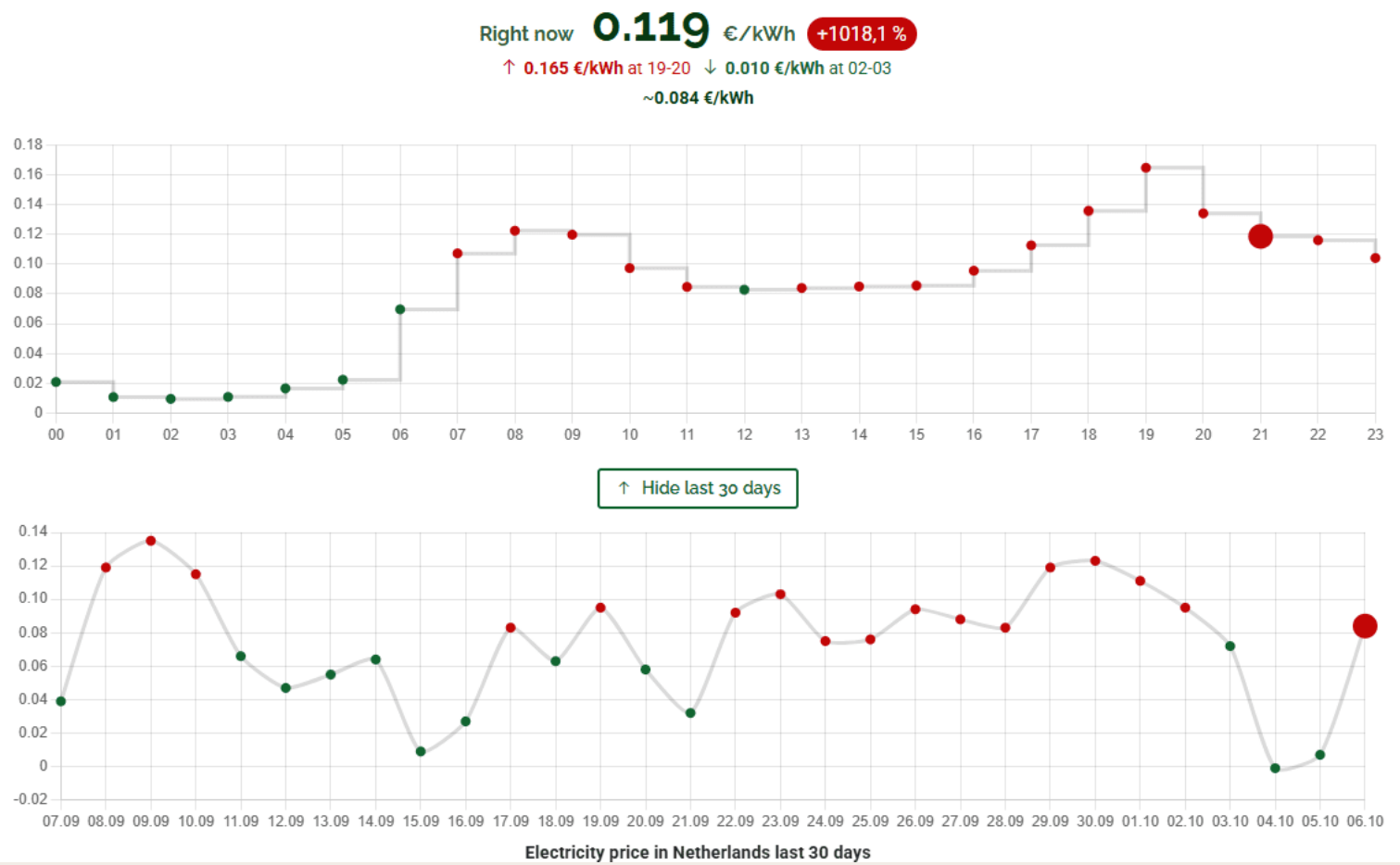




Preliminary result EMPHATICaL electricity usage per unit of methanol

Potential of 8.4% reduction in SOEC hydrogen production cost using reactor waste heat

Variable electricity costs

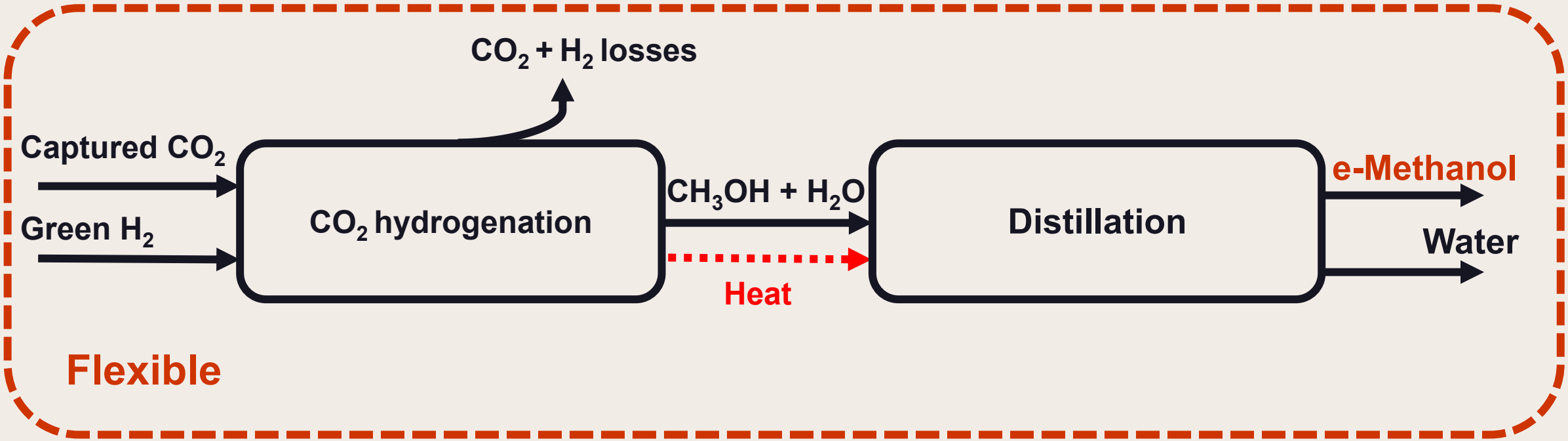


Hourly (top) and daily (bottom) energy prices in the Netherlands[5]

[5]www.energyprices.eu, checked at 06/10/2025

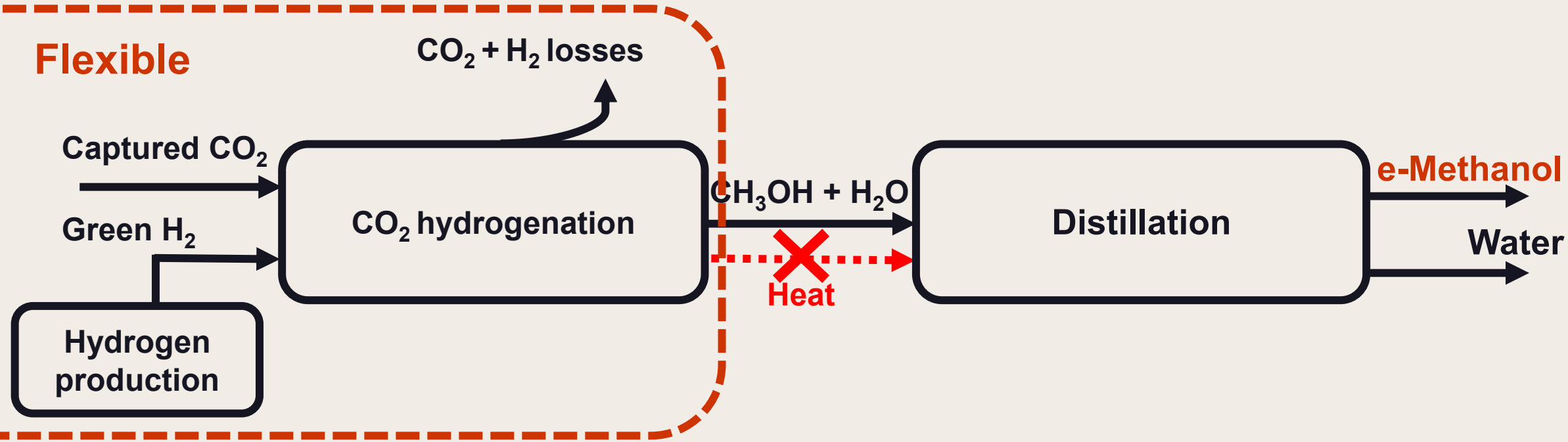
Conventional flexible e-methanol production

- Flexible operation based on electricity price enables potential energy costs reduction
- But: distillation less flexible than methanol reactor



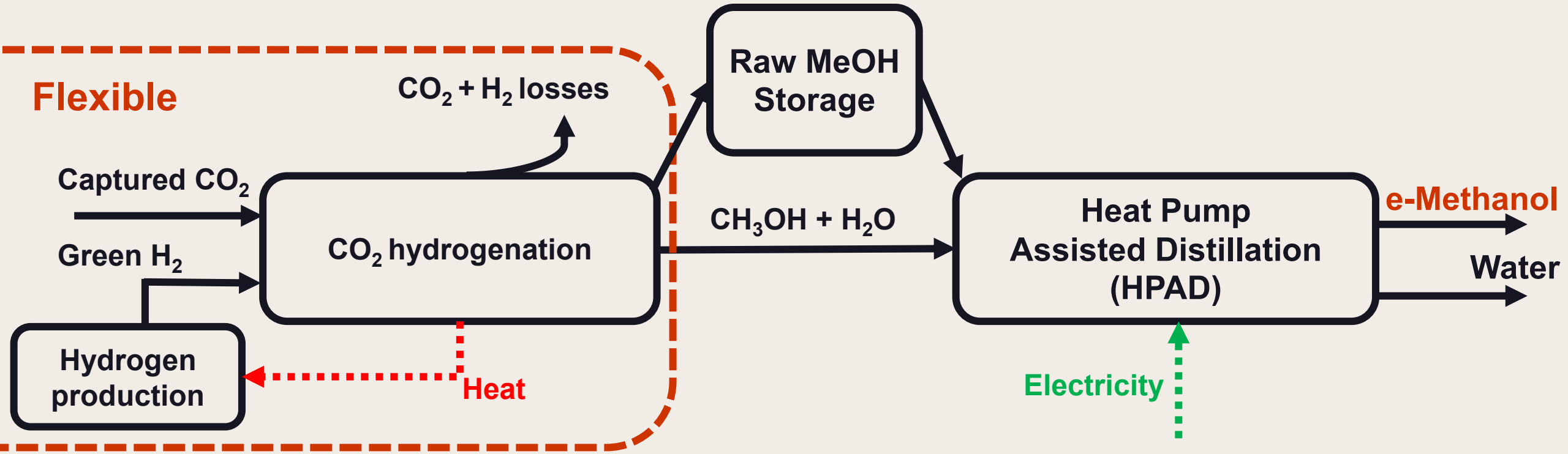
Conventional e-methanol production

- Flexible operation based on electricity price enables energy costs reduction
- Distillation less flexible than methanol reactor
- Heat integration methanol reactor & distillation insufficient during periods of load difference



Possible EMPHATICaL e-methanol production

- High process inertia of distillation
- Decoupling of methanol synthesis and purification



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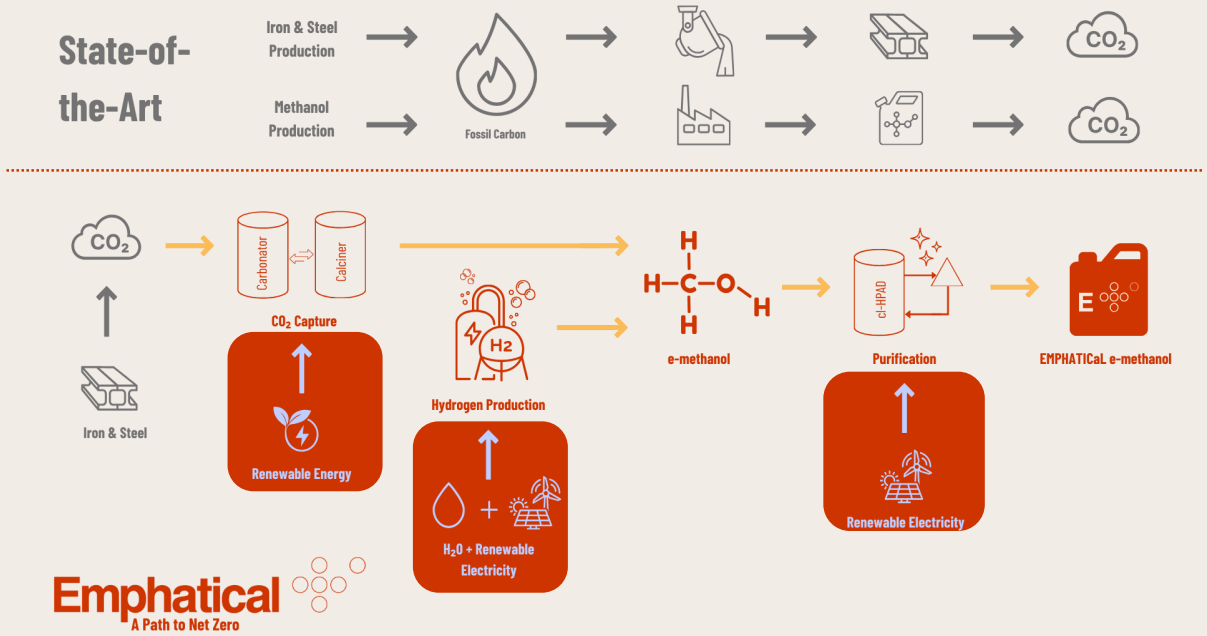
05: Conclusion & outlook

Conclusion

Challenge: reduction of e-methanol production energy costs by 25%

- Efficient reactor design using hydrogen stripper reduces hydrogen costs by 5%
- cl-HPAD enables 80% energy savings versus conventional distillation & allows fully electric operation
- Using cl-HPAD allows the use of reactor heat elsewhere, e.g. hydrogen production using SOEC



Outlook

- Investigate energy savings of heat integration methanol reactor with SOEC
- Investigate flexibility cl-HPAD through dynamic modelling and pilot run
- Quantify benefits of flexible methanol production
  - Thermal decoupling methanol reactor and purification
  - Investigate sizing of intermediate storage to enable flexible operation

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Thank you for your attention!

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