



WEBINAR · 21 OCTOBER 2026

*Advanced Biofuels and Biomethanol:
From Production, Applications to the End-Use*

Electrified Biogas-to-Methanol Production: Balancing Carbon Efficiency, Hydrogen Demand, and Electricity Consumption

Muhammad Zulkefal

PhD Scholar, Department of Energy and Process Engineering
Norwegian University of Science and Technology (NTNU), Trondheim

Organised by NextFuel, FUEL-UP and REFOLUTION





What a good marine fuel requires from its production

Environmental performance
over the whole life cycle



How much of the biogas carbon ends up in methanol, and how clean the process is

Fuel quality



Fuel-grade methanol, at least 99.85 wt %, to be considered as fuel

Cost



Electricity per tonne of methanol, the plant's main energy input, including hydrogen from electrolysis

Engine compatibility

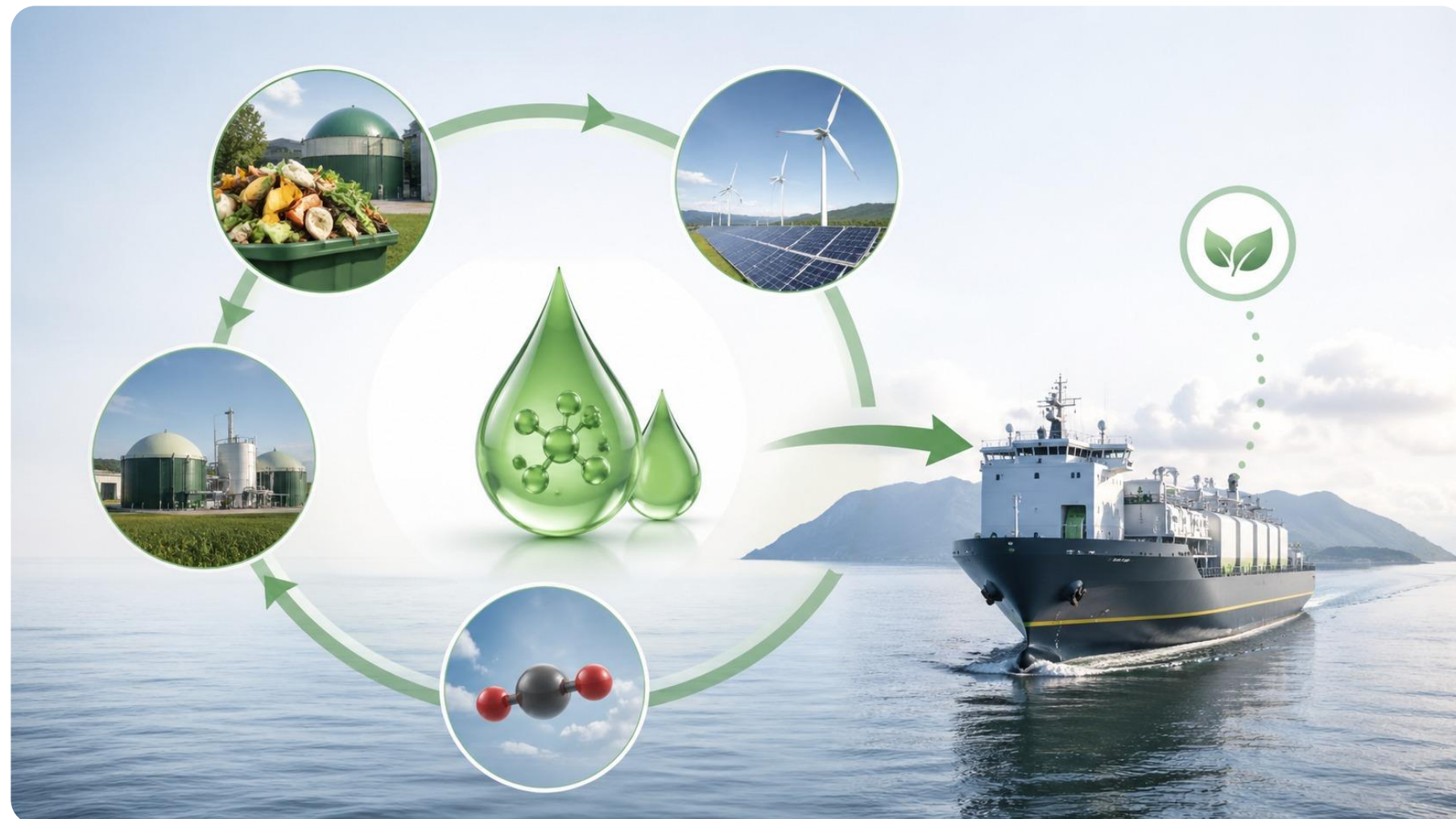


Decided on board, so outside this talk. Methanol is liquid at ambient conditions and fits existing infrastructure [1].

This talk: methanol from biogas and renewable electricity, and how the plant balances carbon, hydrogen and electricity

[1] Brynolf et al., *J. Clean. Prod.* (2014).

My route: biomethanol from biogas and renewable electricity



Carbon source

Biogas

CH₄ and CO₂ from organic waste and residues are waste-derived feedstocks. The carbon in the fuel is biogenic.

+

Heat and extra hydrogen

Electricity

An electric reformer (eSMR) gives 20-50 % lower CO₂ than a conventional one, with fast start-up [2], and is about 100 times more compact [3]. Extra hydrogen comes from electrolysis.

=

Product

Methanol

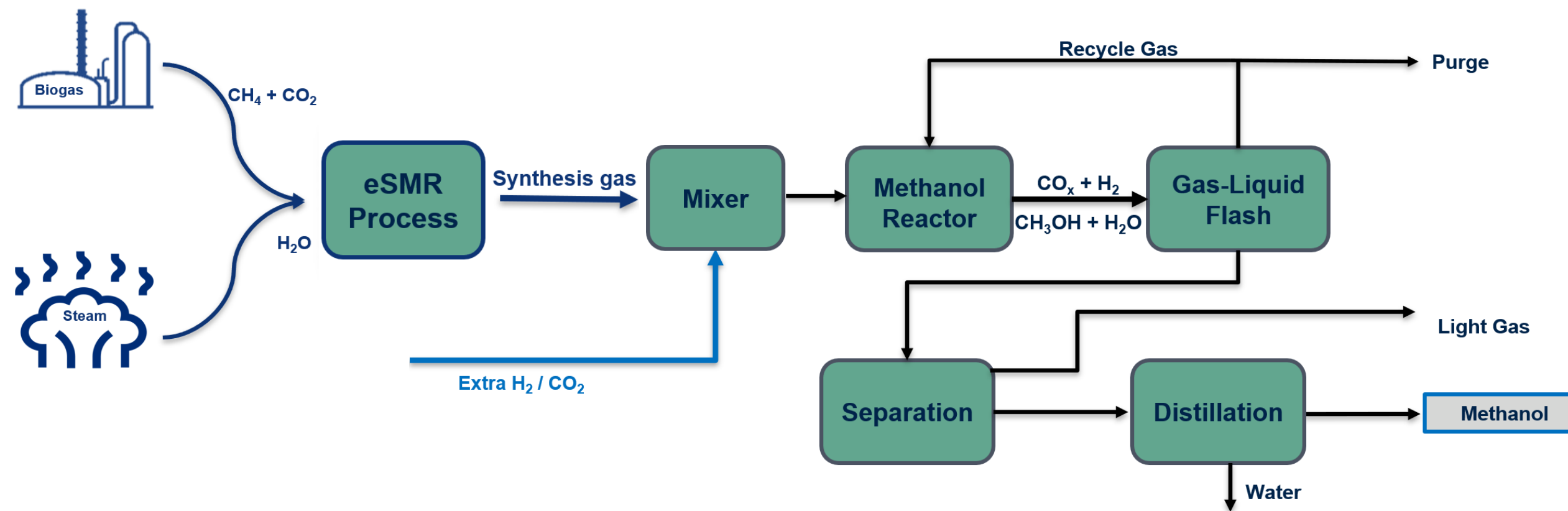
Fuel-grade and liquid at ambient conditions. With renewable feedstocks, its life-cycle emissions can be close to zero [4].

Core idea: turn biogas and renewable electricity into methanol, a cleaner fuel for ships

[2] Wismann et al., *Science* (2019); [3] Song et al., *Energy Convers. Manag.* (2022); [4] Olah et al., *J. Org. Chem.* (2009).



Base case: fuel-grade methanol, but the gas is short of hydrogen



145 t/day

biogas in, 60 % CH₄ and 40 % CO₂

950 °C, 25 bar

eSMR; converts 96.2 % of the methane

SN 1.36

after reforming; methanol needs 2.01

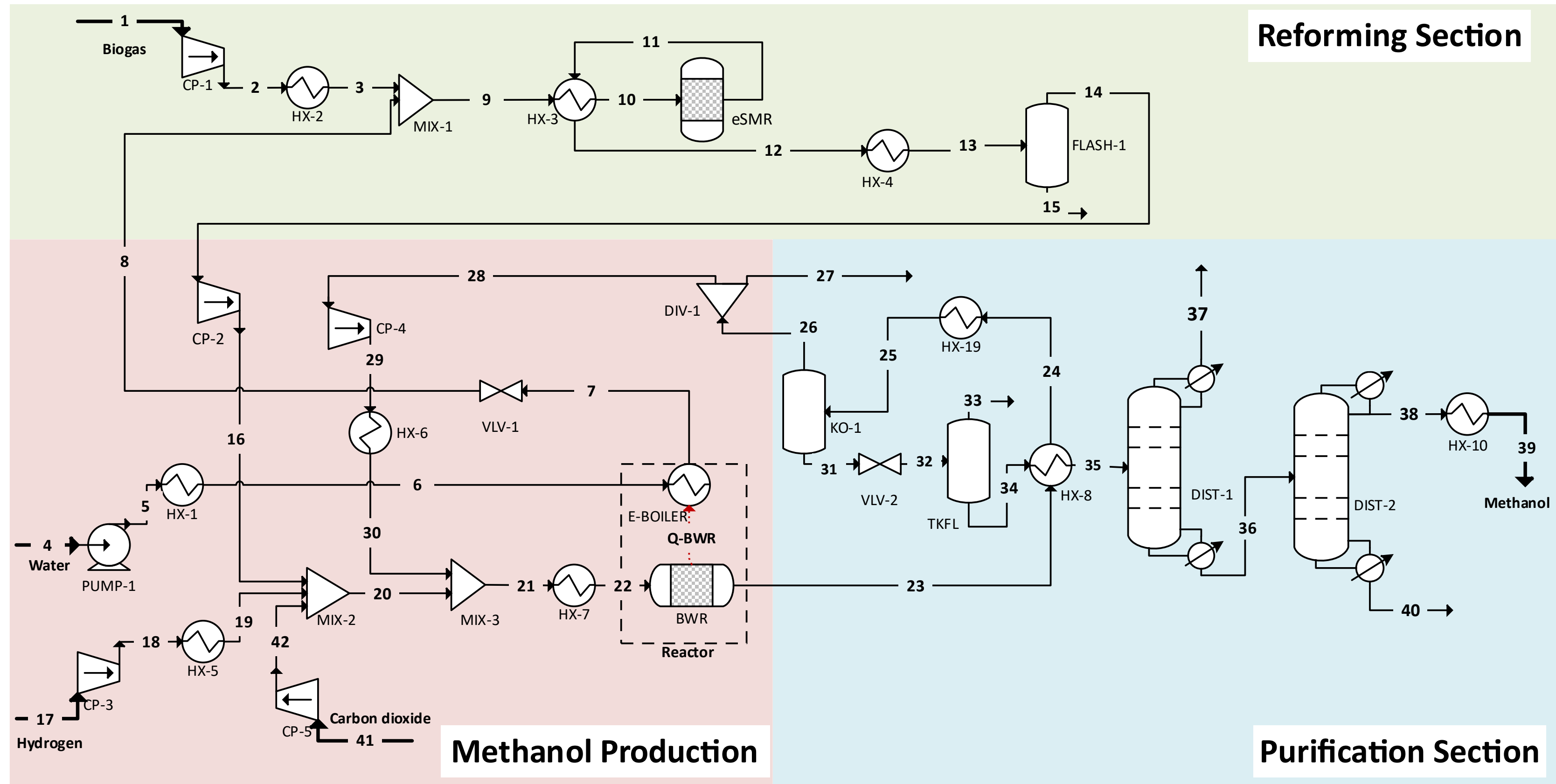
≈ 150 t/day

methanol at 99.85 wt % purity

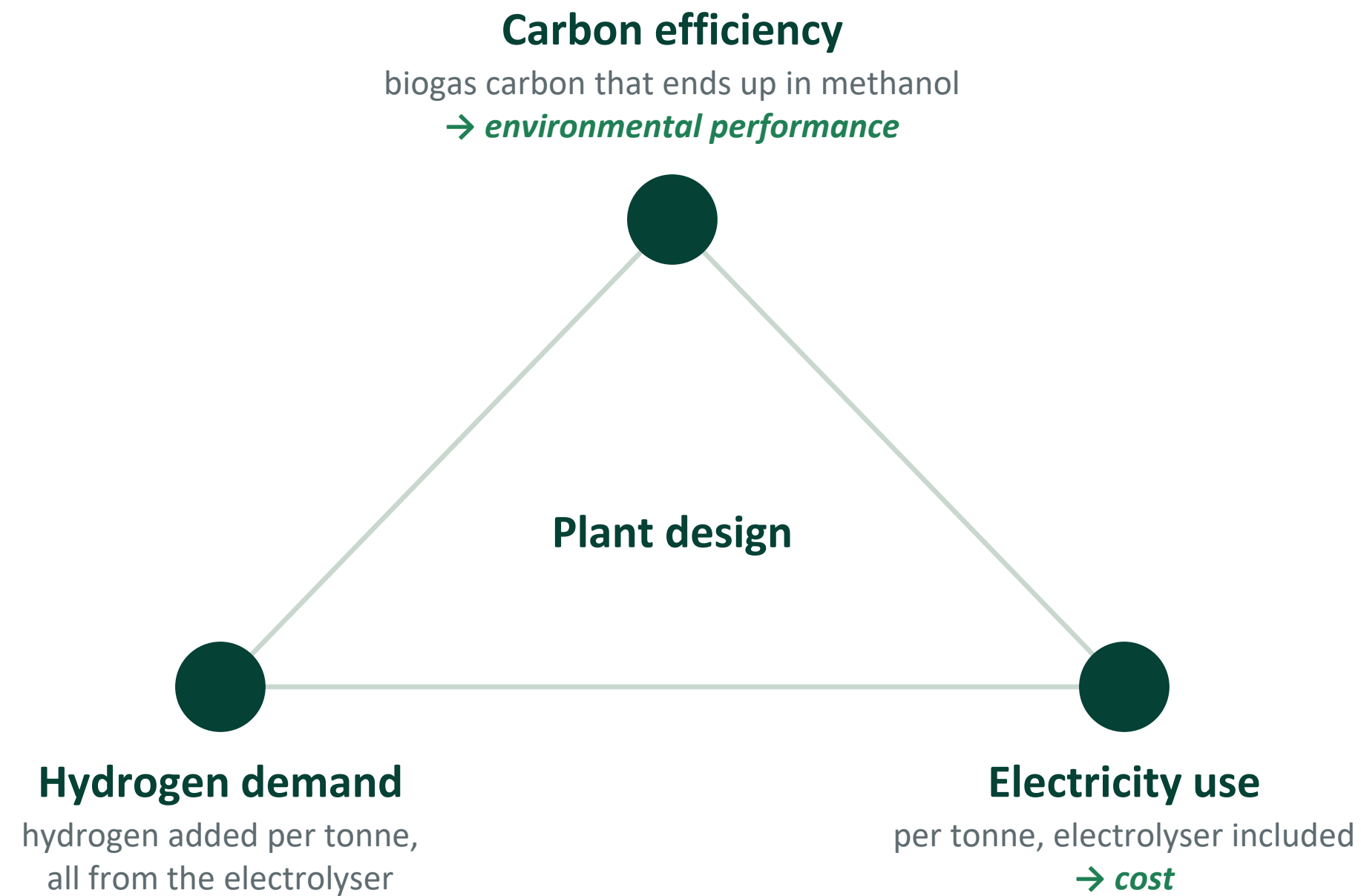
Methanol reactor: a boiling-water reactor (Lurgi type). We can use the produced steam from this reactor for our prior reforming process

The gas is short of hydrogen, so ≈ 6.8 t/day of H₂ is added before the methanol reactor. That is where the trade-offs start.

Base case of the steady-state Aspen Plus model; methanol synthesis at 75 bar. $SN = (H_2 - CO_2) / (CO + CO_2)$.



In the plant: three targets that pull against each other



Why they pull against each other

CO₂-rich biogas gives hydrogen-short gas.
SN $\approx$ 1.36 instead of the 2 that methanol needs.

Hydrogen from the electrolyser costs power.
38 kWh per kilogram in this study.

A hotter reformer helps, but at a cost.
It makes more hydrogen itself, but needs more electrical heat.

Fixed in every optimisation: fuel-grade methanol (≥ 99.85 wt %) and at least 150 t/day. Which design balances these three?



One process model, three studies

1 Stoichiometric study

Question

How much extra hydrogen or CO₂ does the synthesis gas need, and what determines that amount?

Method

Reformer temperature, pressure, steam-to-carbon ratio and biogas composition varied in the model

Published · ESCAPE 36 (2026)



2 Exergy assessment

Question

Where in the plant is useful energy lost?

Method

Exergy balance of every unit in the base case, followed by a parametric study of reactors to check for trade-offs, i.e., conversion vs. exergy destruction

Accepted · PRES'26



3 Process optimisation

Question

Which operating conditions use the least electricity per tonne of methanol?

Method

Particle swarm optimisation (PSO) coupled to the Aspen Plus model

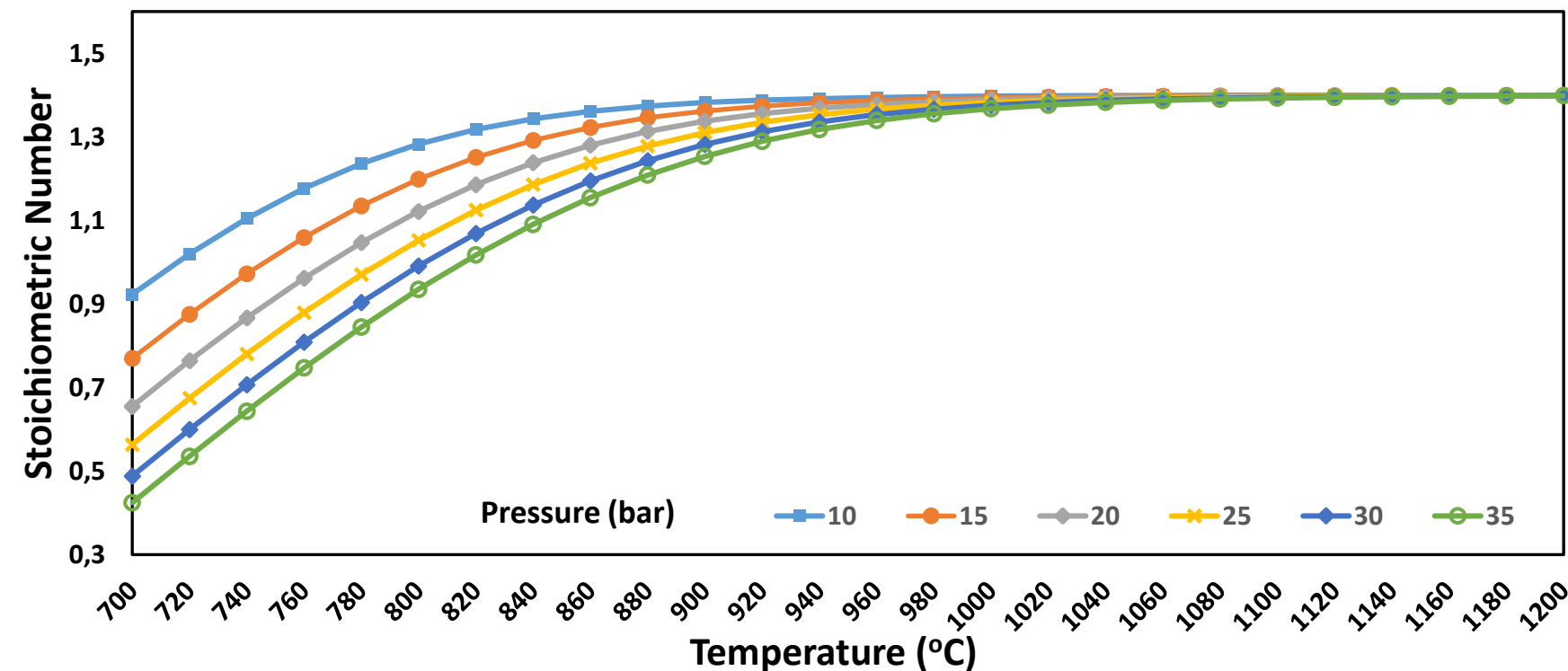
Manuscript in preparation

All three studies use the same steady-state Aspen Plus model of the full plant, from biogas to fuel-grade methanol.

Results: What Controls the Stoichiometric Number?

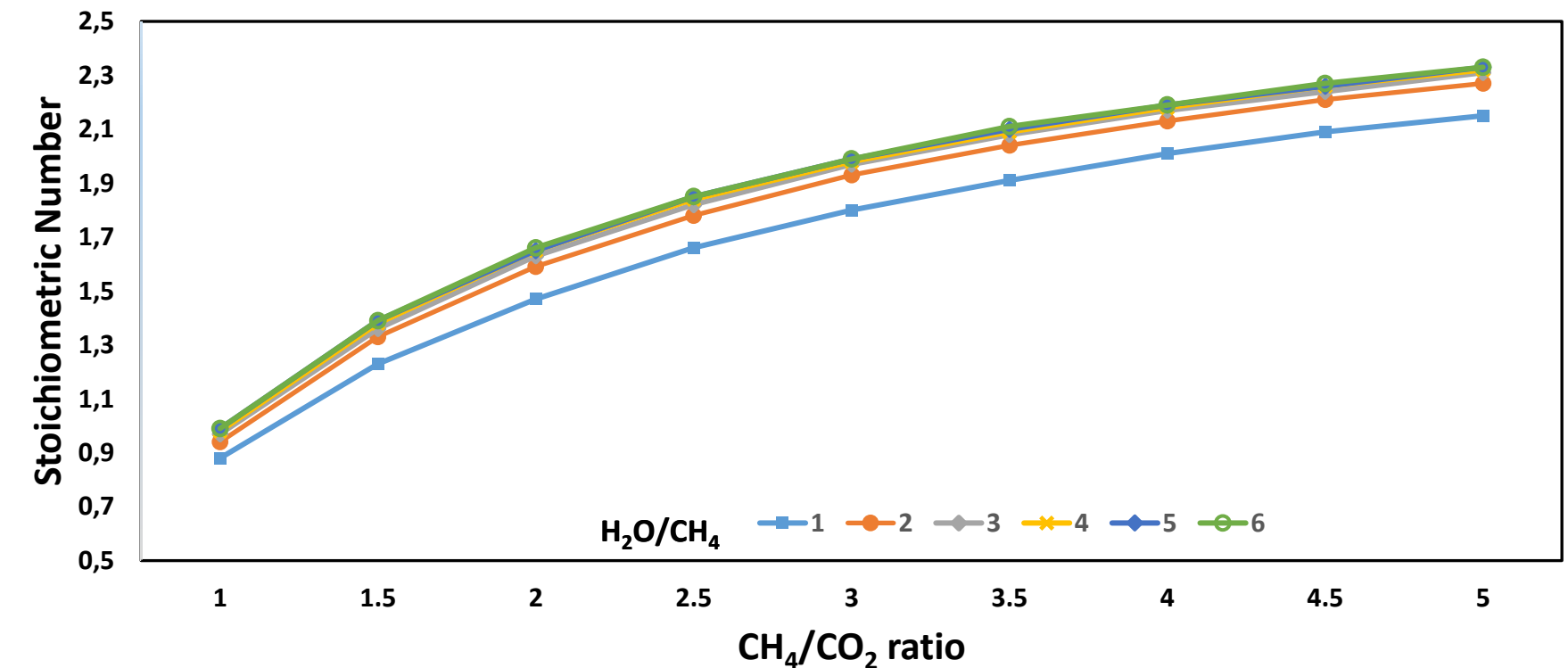
Question: how much do reformer conditions and biogas composition change SN? (Target SN = 2.01)

SN vs. reformer temperature (lines = pressure, 10–35 bar)



At high temperature SN levels off at ≈ 1.4 for every pressure: reformer conditions alone cannot reach 2.01.

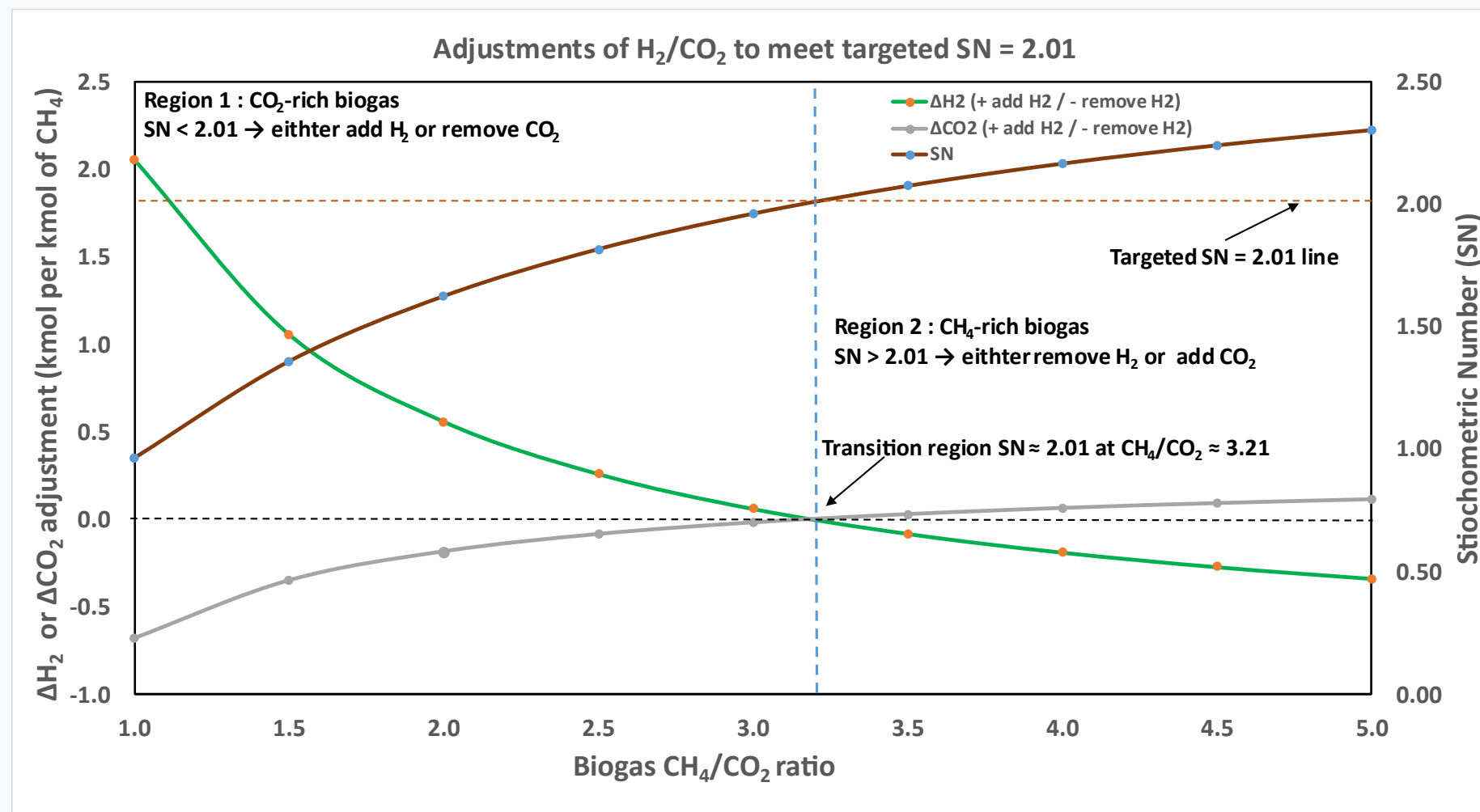
SN vs. biogas CH_4/CO_2 ratio (lines = S/C)



CH_4/CO_2 from 1 to 5 moves SN from ≈ 0.9 to ≈ 2.3 : feed composition is the dominant factor; S/C adds little above 3.

Reference: 60/40 biogas, S/C = 3, 950 °C, 25 bar.

H₂ & CO₂ Adjustment Required

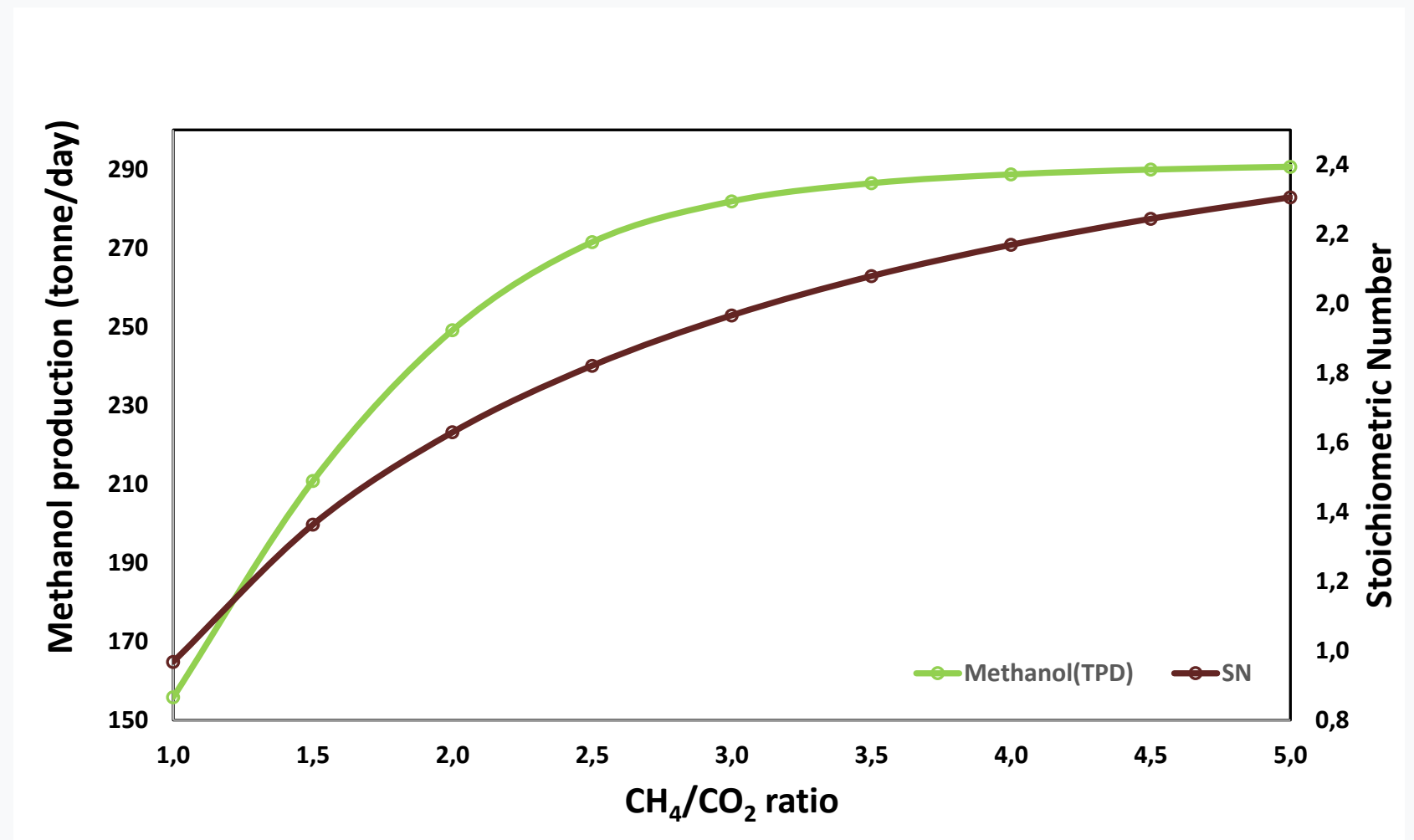


CH₄/CO₂ < 3.21: H₂-deficient synthesis gas → add H₂ to reach SN = 2.01

CH₄/CO₂ > 3.21: H₂-excess synthesis gas → add CO₂

At ≈ 3.21: no correction needed

Methanol Production vs. CH₄/CO₂



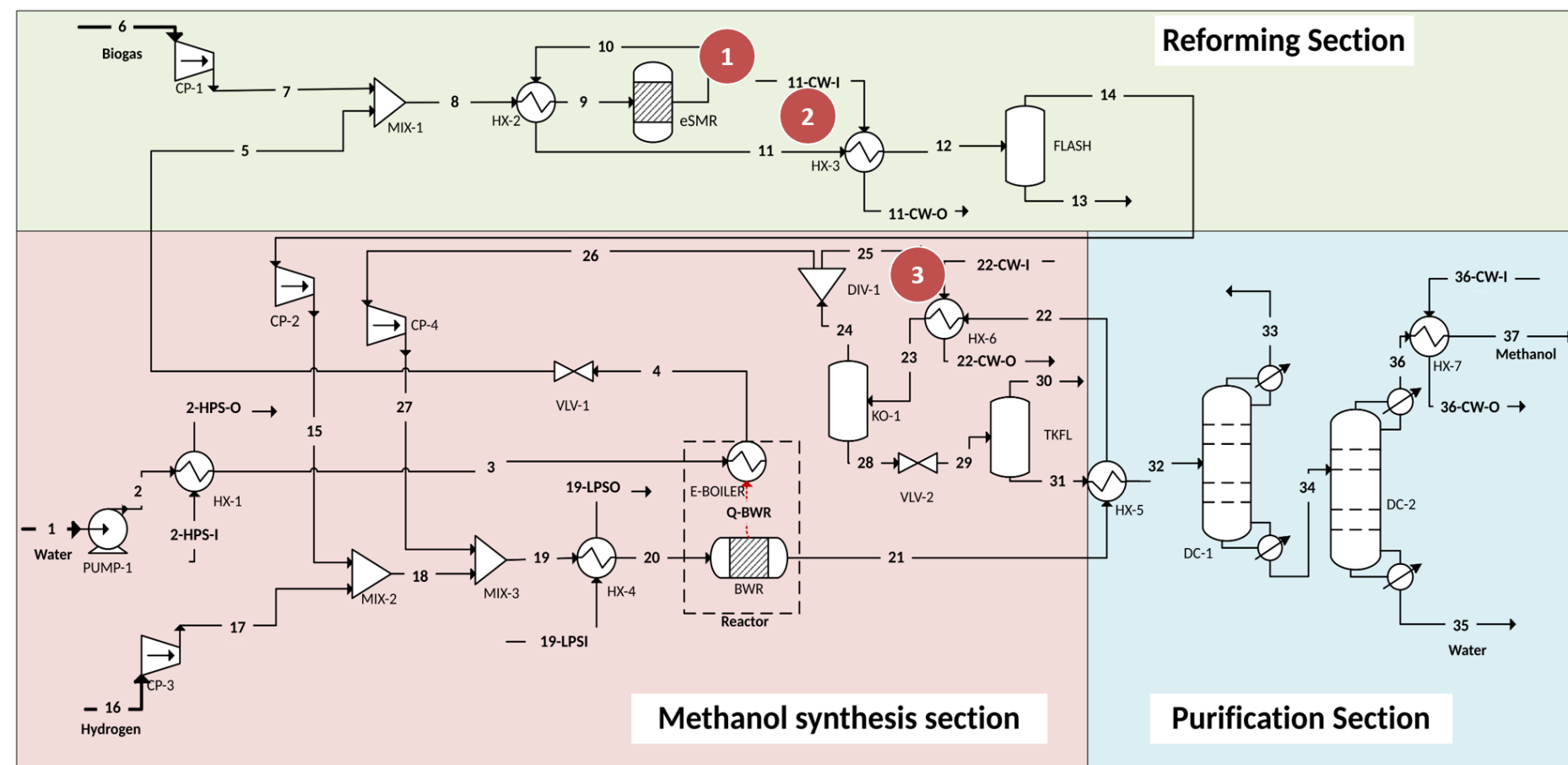
Methanol output rises as SN approaches 2.01, with little gain above it.

Surplus H₂ is not converted, so SN should be kept near the target.



Two-thirds of the exergy loss happens in three units

Accepted · PRES'26



12.5 MW

of exergy destroyed in the base case,
67 % of it in the three marked units

Lower loss is not always better

At 850 °C and 35 bar, the reformer loses 22 % less exergy, but converts 76 % of the methane instead of 96 %.

1 27.5 %

Electric reformer

Uses 92.6 % of its exergy usefully, but the largest exergy flow passes through it.

2 22.9 %

Hot-gas heat goes to cooling water, at 6.5 % task efficiency.

3 16.8 %

Cooler after the methanol reactor

Same pattern, at 15.1 % task efficiency. Recovering this heat comes first.

Shares of the plant's total exergy destruction in the base case. Source: M. Zulkefal et al., Exergy-Based Assessment of an Electrified Biogas-to-Methanol Process, Chemical Engineering Transactions (PRES'26), accepted.

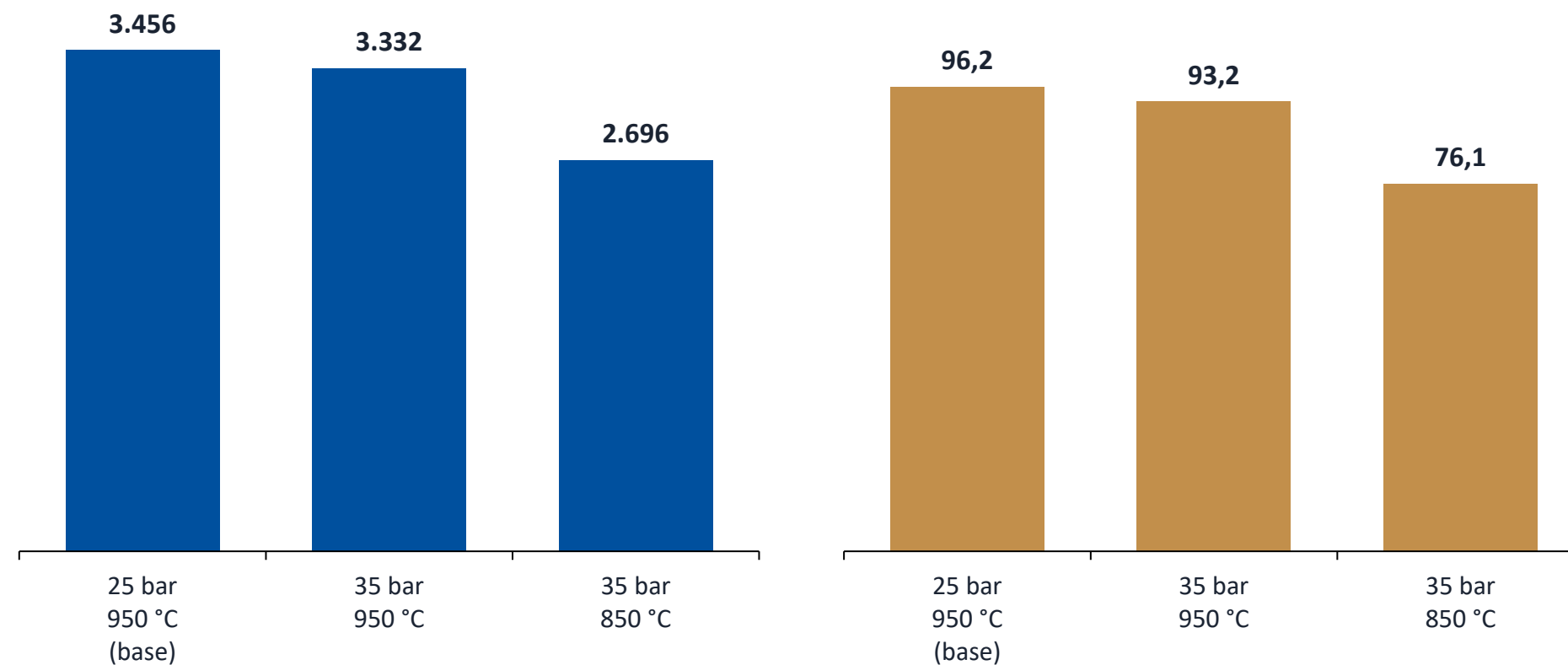


Reactor Conditions: Less Exergy Loss, but Less Conversion

Electrified steam methane reformer (eSMR)

Exergy destruction (kW)

CH₄ conversion (%)

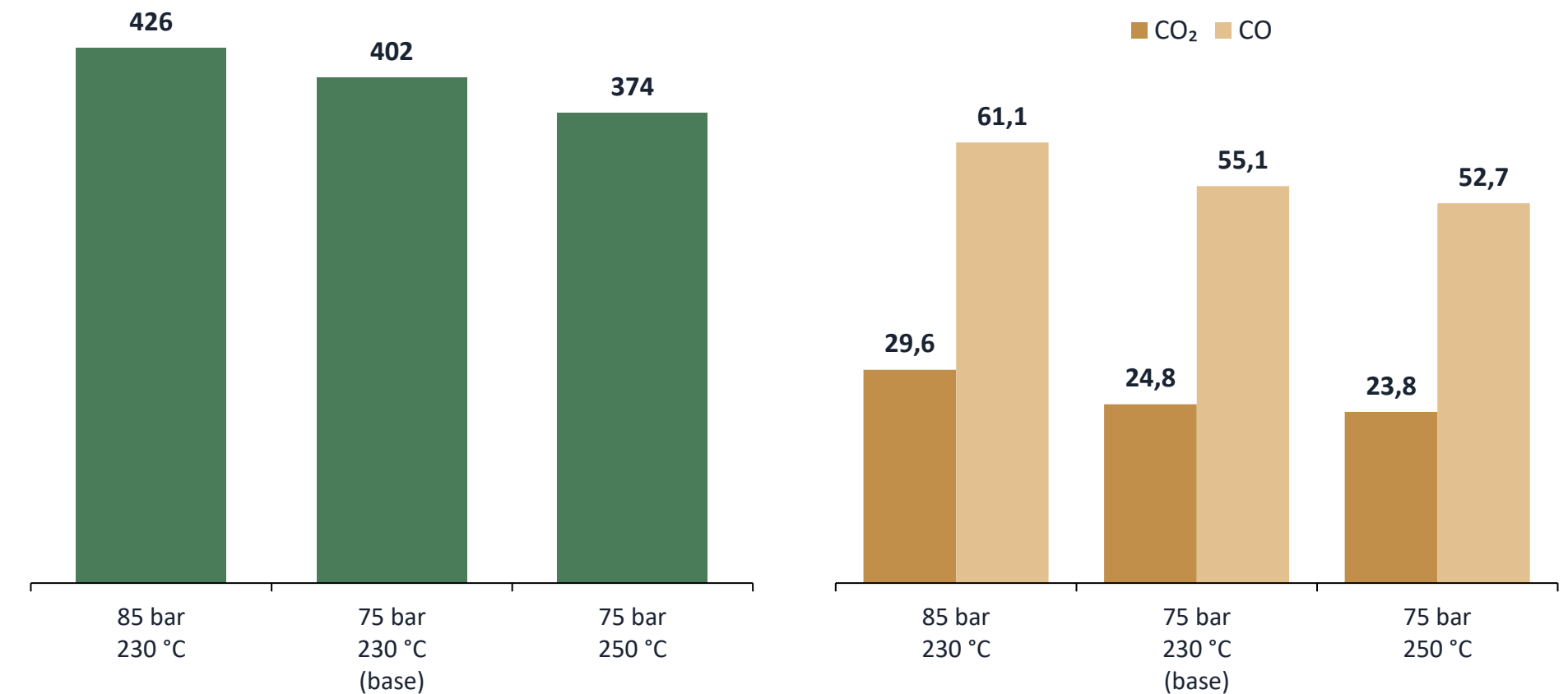


Lower T and/or higher P: –22 % exergy destruction (3,456 → 2,696 kW), but CH₄ conversion falls from 96.2 to 76.1 %.

Boiling-water methanol reactor (BWR)

Exergy destruction (kW)

Conversion per pass (%)

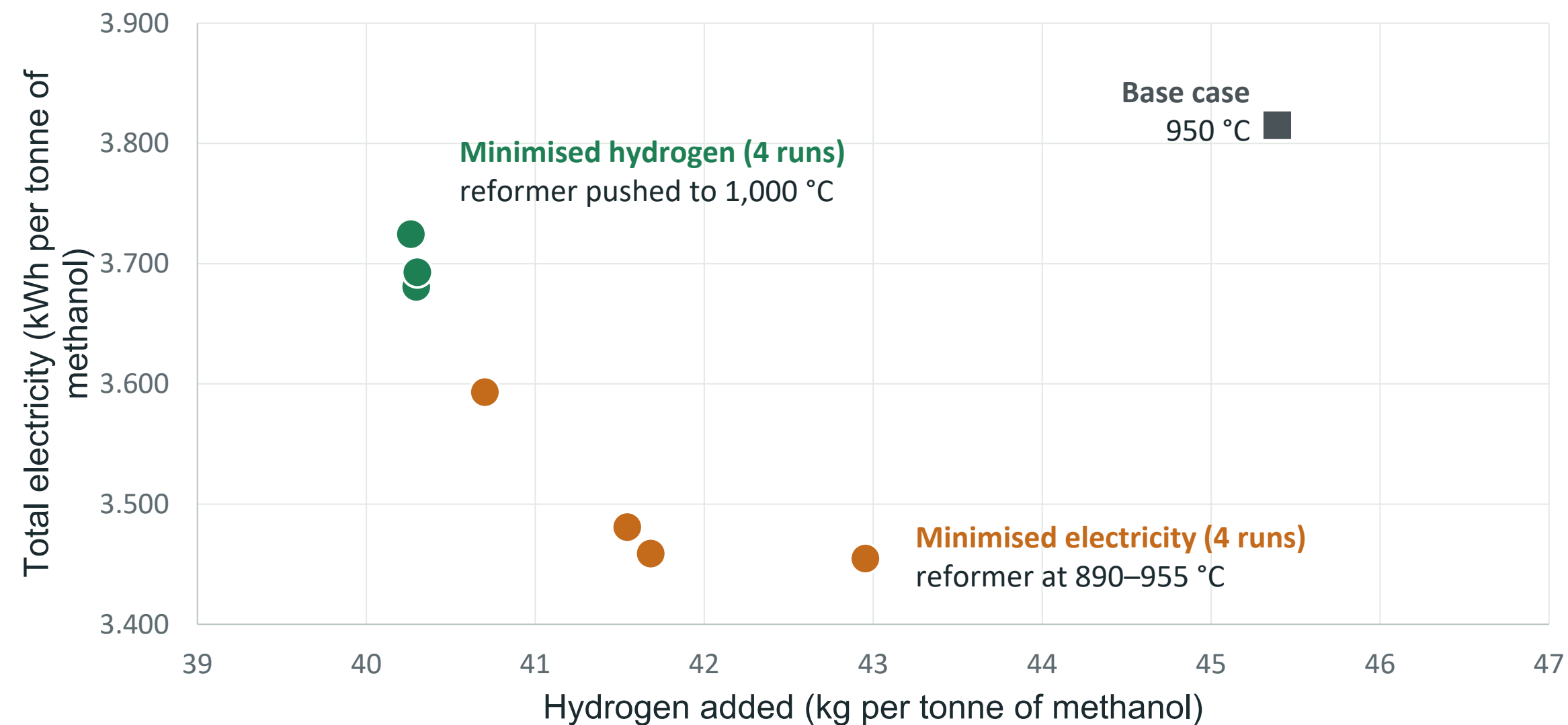


Higher T and/or lower P: less exergy destruction, but lower CO₂ and CO conversion. Changes are much smaller than in the eSMR.

Lower exergy destruction is not automatically a better design: loss and conversion must be judged together.



Saving hydrogen is not the same as saving electricity



Hydrogen-minimising runs

~11 % less hydrogen, but only ~2-3 % less electricity. The reformer makes more hydrogen, but it is electric too.

Electricity-minimising runs

~6-10 % less electricity and still ~5-10 % less hydrogen.

Carbon efficiency

Every run reached ~93-96 %, so the 80-95 % targets never limited the result.

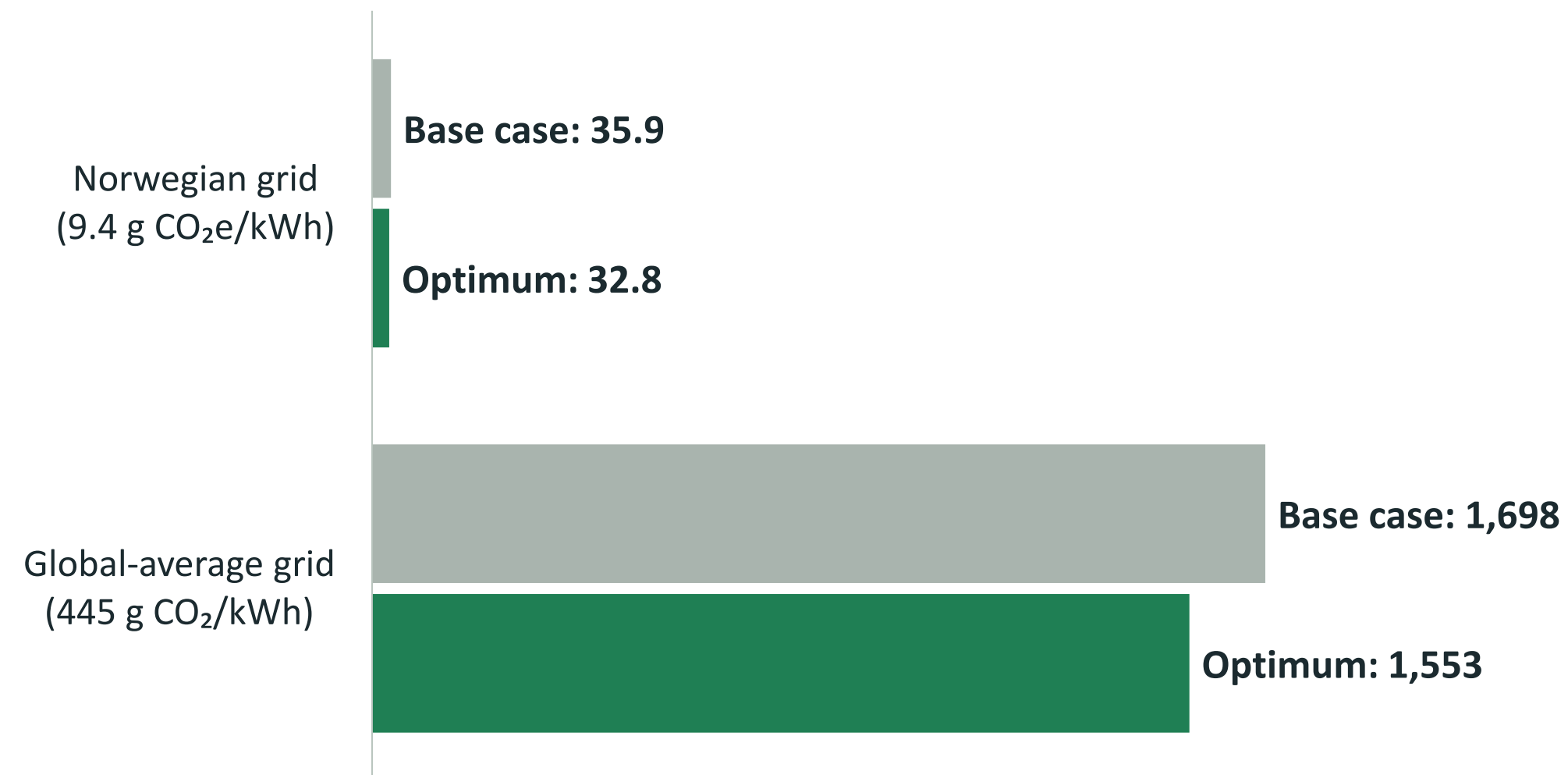
So we are now optimising total electricity per tonne, with the added hydrogen counted at 38 kWh/kg (SOEC).

Stage 1 screening: particle swarm optimisation coupled to Aspen Plus, 2 objectives $\times$ 4 carbon-efficiency targets, 32 particles $\times$ 30 iterations; purity $\geq$ 99.85 wt %, production $\geq$ 150 t/day.

Same methanol, very different GHG: the electricity decides

Manuscript in preparation

CO₂ from the plant's electricity (kg per tonne of methanol)



~47 ×

more CO₂ per tonne on a global-average grid than on the Norwegian grid

-8.5 %

CO₂ per tonne from the optimisation, on either grid

Life-cycle methods such as the IMO LCA Guidelines and FuelEU Maritime include emissions from fuel production.

At the optimum: ≈ 33 kg CO₂ per tonne on the Norwegian grid, ≈ 1.6 t on a global-average grid.

Operational electricity only, not a full life-cycle assessment. Grid intensities: NVE climate declaration for Norway (2025) and IEA global average (2024). Source: M. Zulkefal et al., optimisation study, manuscript in preparation (preliminary results).



What my work shows

1

The biogas decides the hydrogen need.

Reformer conditions cannot lift SN above ≈ 1.4 for typical biogas. Below 76 % methane, add H_2 ; above it, add CO_2 .

2

Most exergy is lost in the reformer and two coolers.

Recovering the coolers' heat comes first. Lower loss is not automatically a better design.

3

Saving hydrogen is not saving electricity.

Minimising total electricity cuts it by $\sim 9\%$ and gives $\sim 6\%$ more methanol at $\sim 93\%$ carbon efficiency.

4

Clean electricity makes the route low-carbon.

About 33 kg CO_2 per tonne on the Norwegian grid, 1.6 t on a global-average grid.



Thank you

Questions are welcome in the Q&A

Muhammad Zulkefal

muhammad.zulkefal@ntnu.no

Norwegian University of Science and Technology (NTNU), Trondheim

Based on

M. Zulkefal et al., Systems & Control Transactions (ESCAPE 36), 2026

M. Zulkefal et al., Chemical Engineering Transactions (PRES'26), accepted

M. Zulkefal et al., optimisation study, manuscript in preparation

Organised by NextFuel, FUEL-UP and REFOLUTION