

Virtual Measurement of Emissions from Produced Water Using an Online Process Simulator

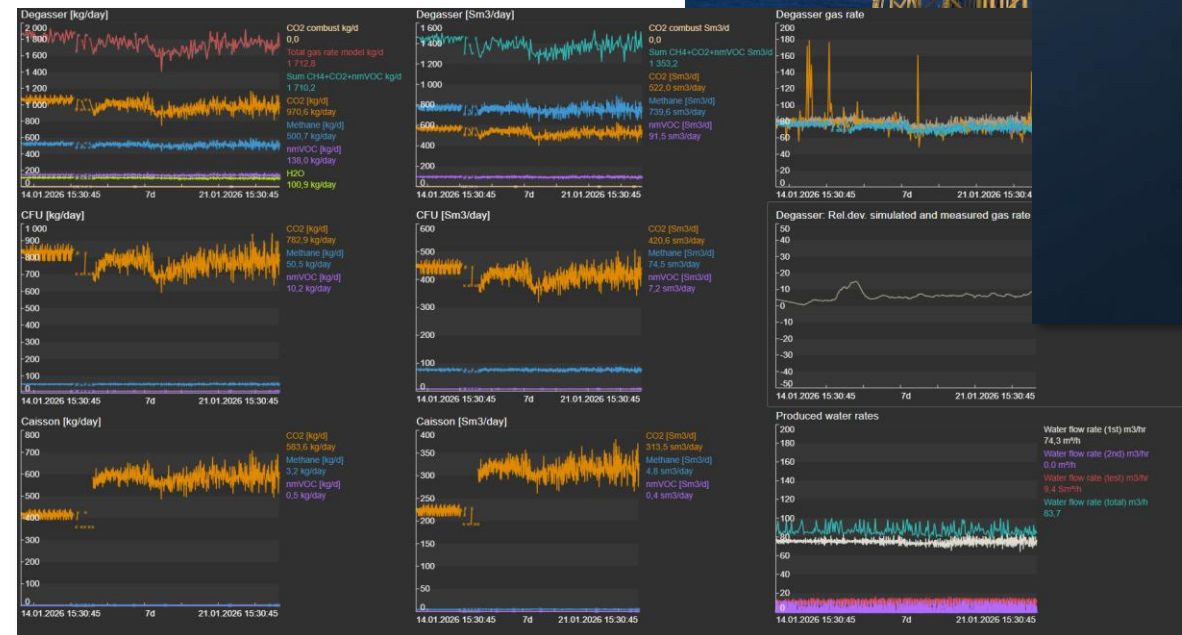
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NFOGM Fagdag
19 March 2026



Contents

- Introduction
- Gudrun produced water process
- NeqSimLive
- Model uncertainty and validation
- Summary and conclusions



Introduction

50% GHG

Equinor's ambition:
50% reduction in Greenhouse-Gas-Emissions by 2030

50% CO₂

- Gudrun vents gas from produced water to air
- These emissions are reported as hydrocarbons, but contain 50% CO₂
- The flare is unlit ~99% of the time (cold flare) due to flare requiring high flow rate**

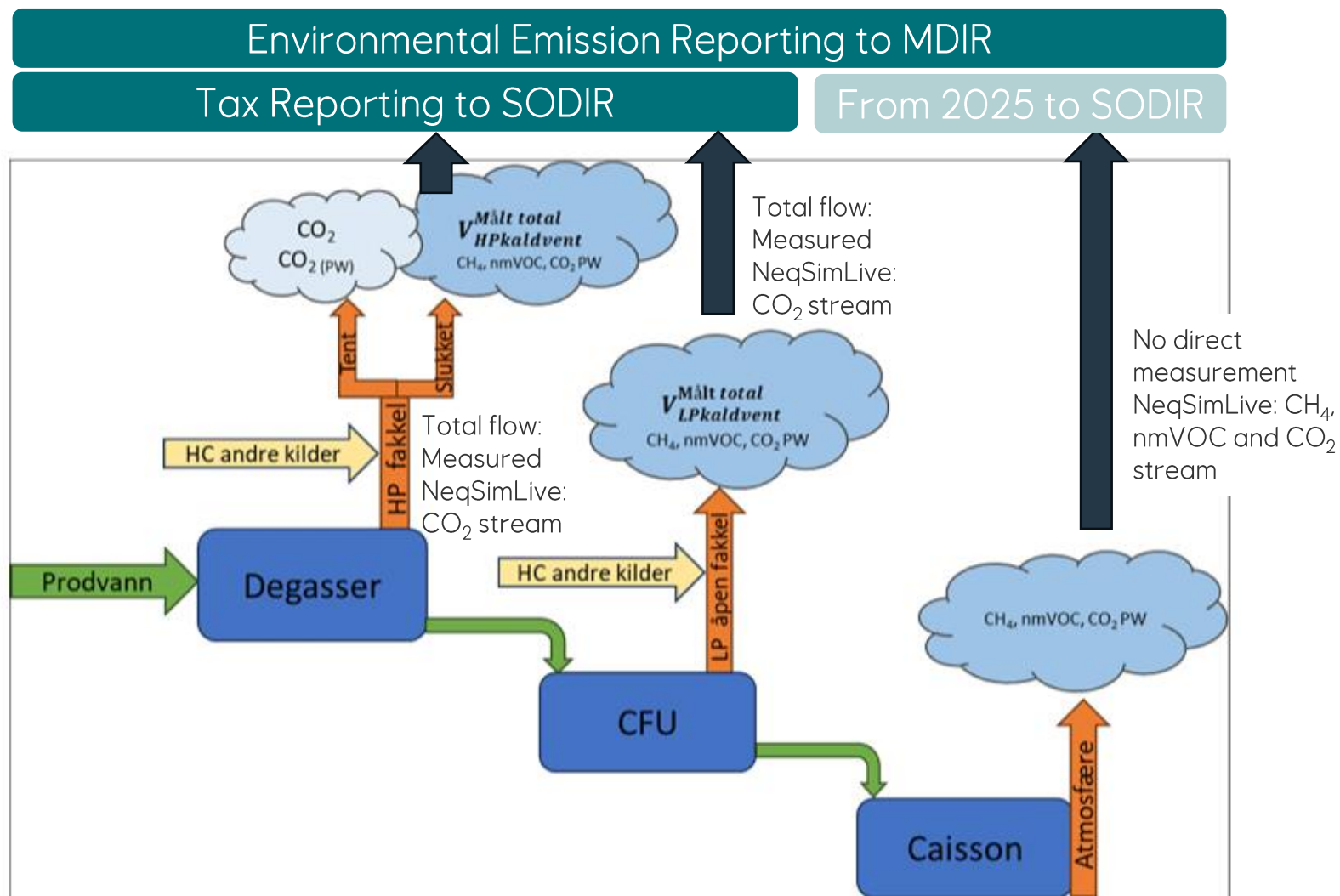
NeqSimLive

- NeqSim process simulator
- NeqSim is open-source
- Fundamental thermodynamic models
- NeqSimLive is Equinor's implementation for live process simulations

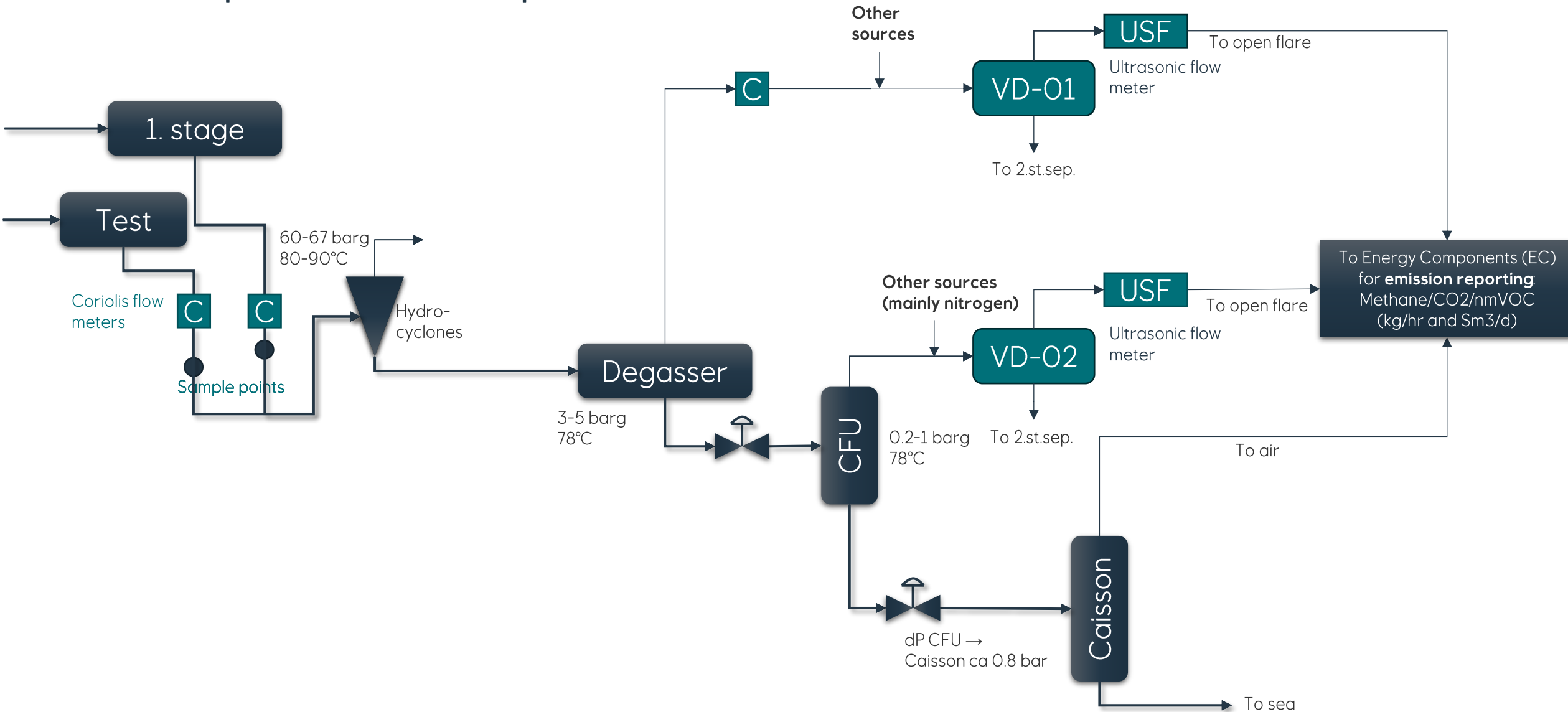
NeqSimAPI

- Cloud computing framework to execute NeqSimLive
- Virtual measurements
- Gudrun digital twin for produced water degassing

Reporting of gas emissions

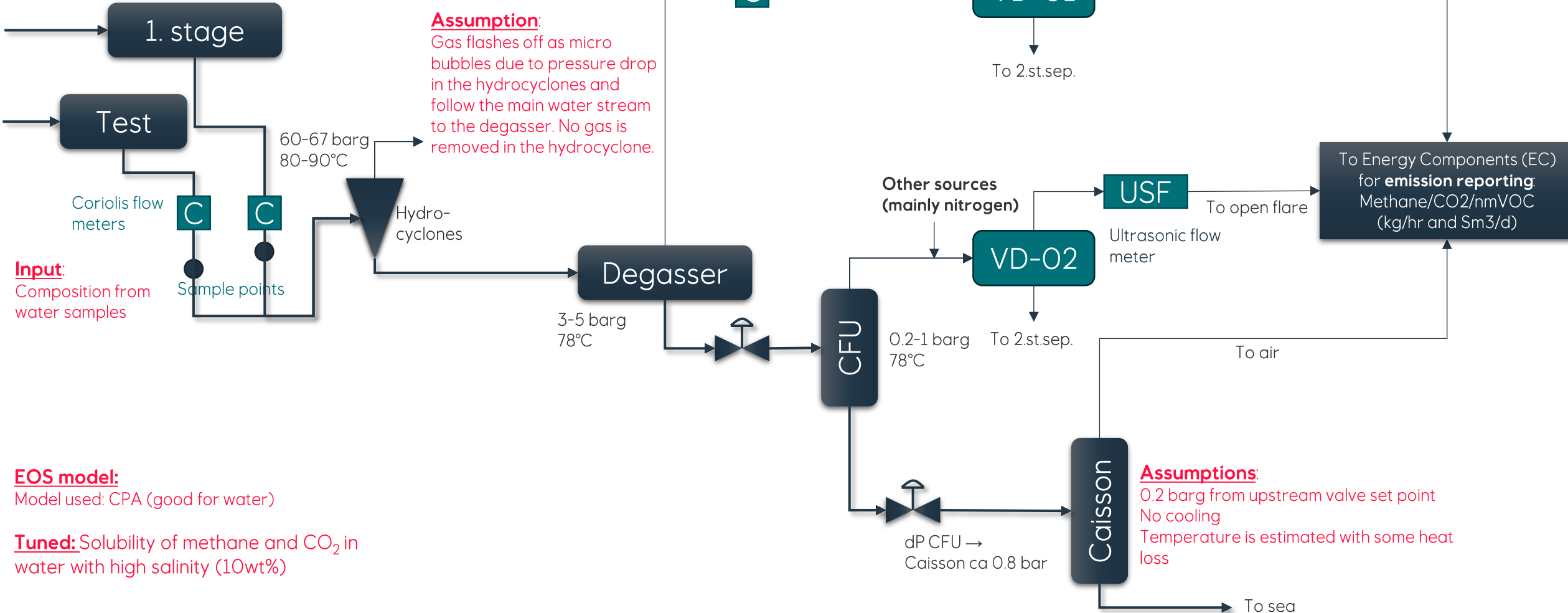


Gudrun produced water process

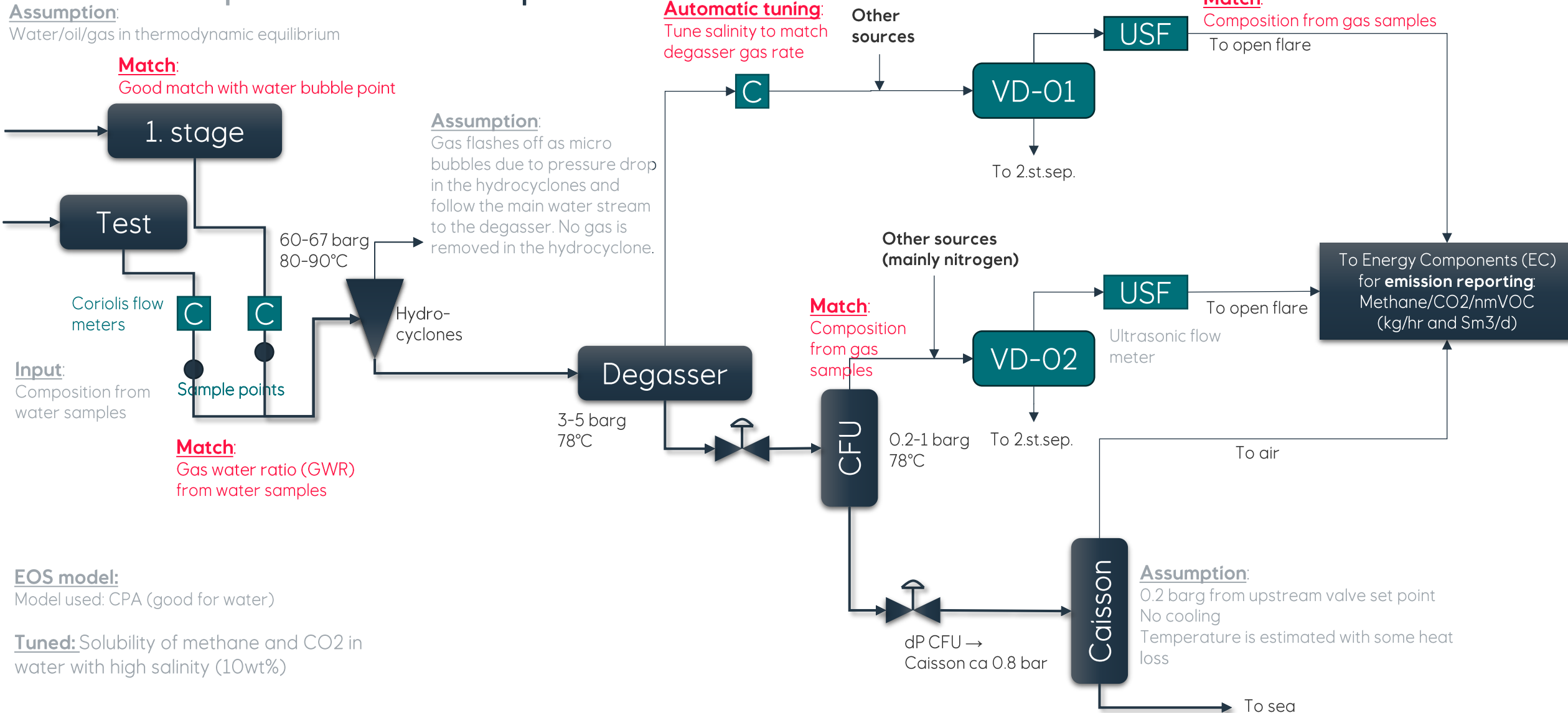


Gudrun produced water process

Assumption:
Water/oil/gas in thermodynamic equilibrium



Gudrun produced water process

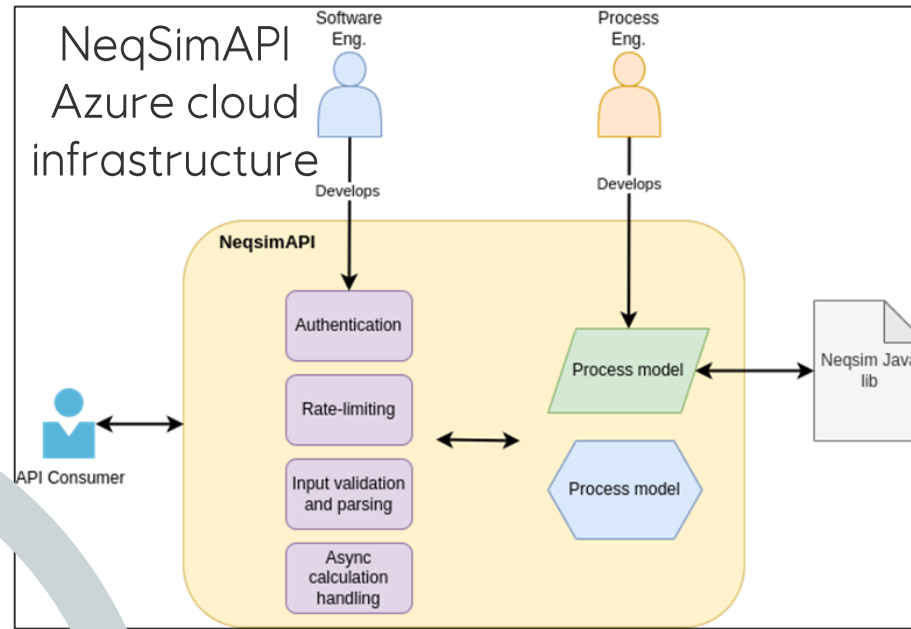


NeqSimLive / NeqSimAPI

Equinor's implementation of online NeqSim simulations



NeqSim is an open-source process simulation software (GitHub)



Call NeqSimAPI to run NeqSimLive process model

SIGMA read process data

Calculation interval 10 minutes

SIGMA read model data output

Energy Components
EC collects daily emission values automatically from PI

Periodic report

Reporting to authorities

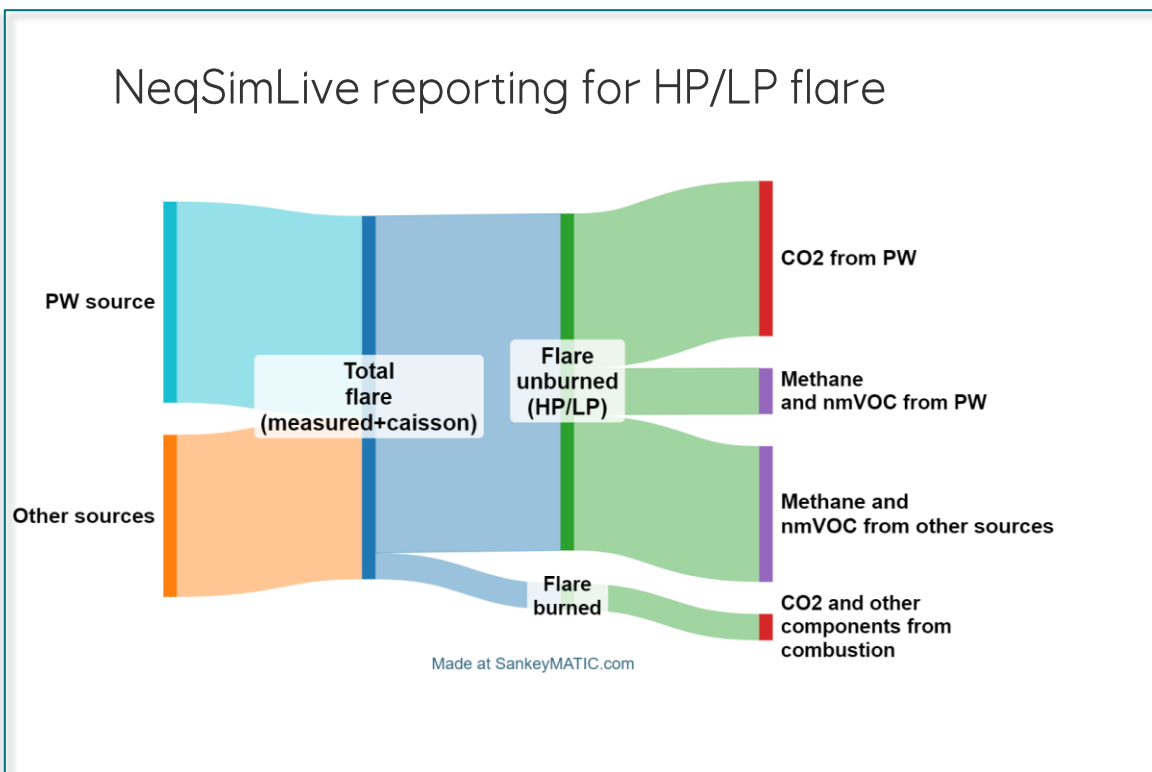
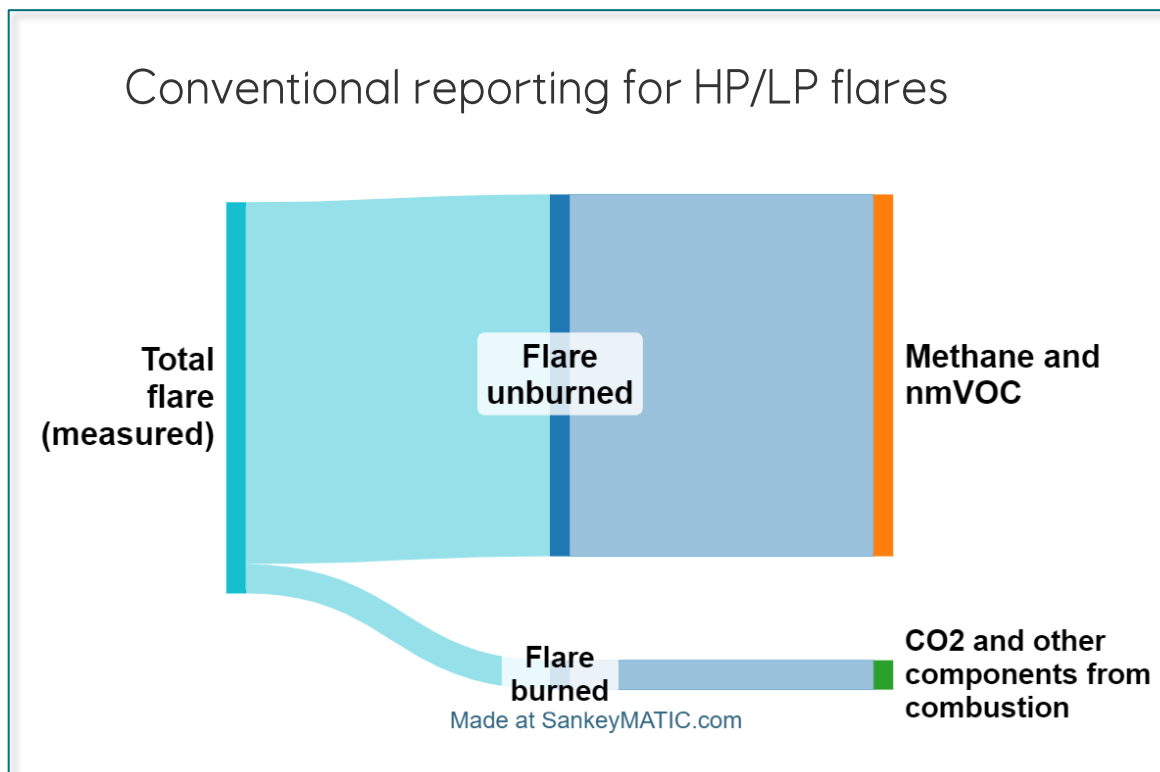
Live Process data Aspen/PI

SIGMA writeback of model process calculations

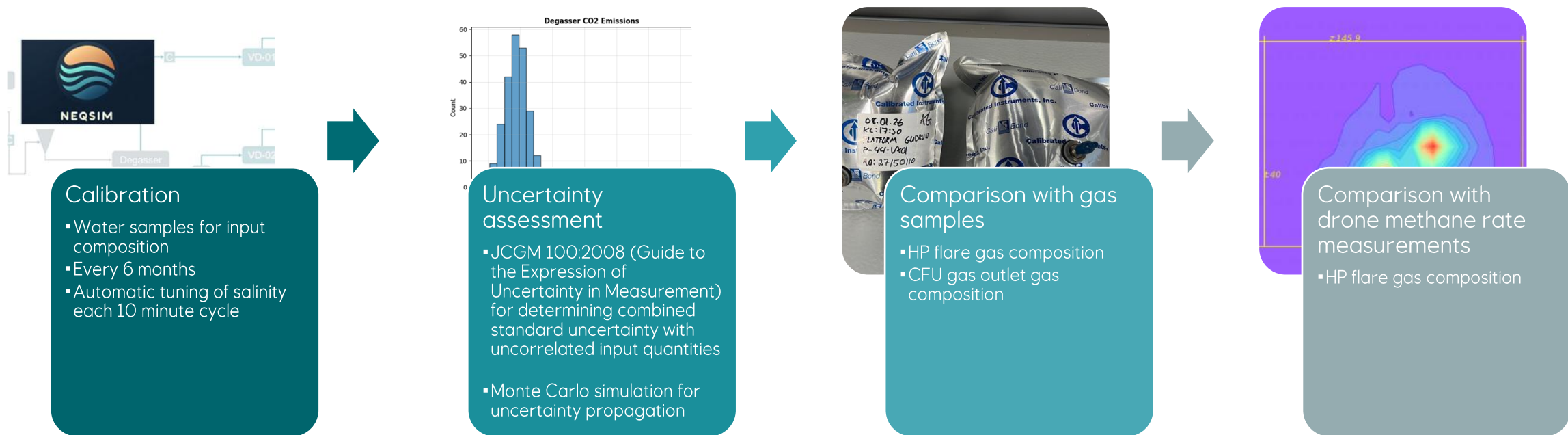
Code change undergoes a predefined results test, and is first run for a period on a test server
IT runs predefined test of NeqSimAPI models every 14 days (covers effects of hardware changes)

Gudrun gas emissions – depending on estimation method

(2022 numbers)



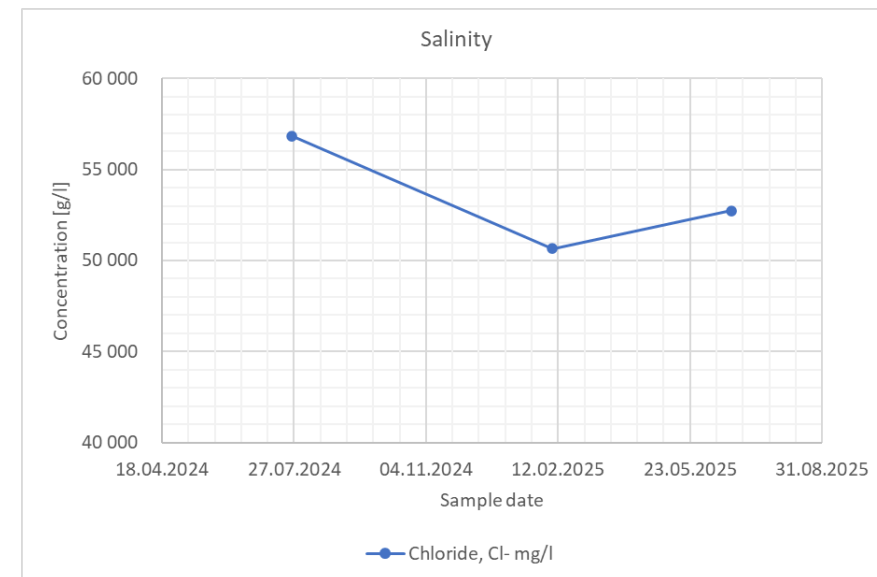
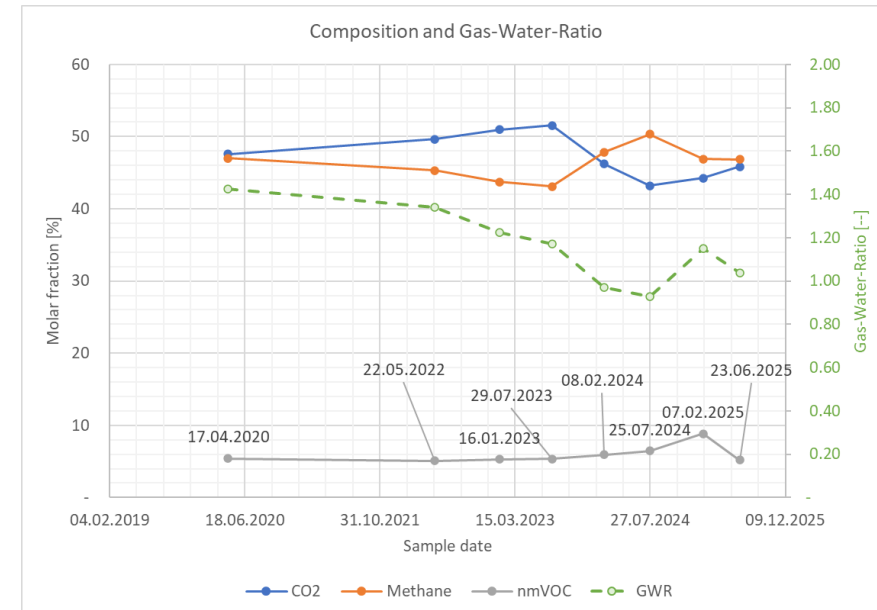
Model validation



Water sample composition

- The model uses fixed composition
- Some variation from sample to sample
- Composition varies between samples due to shifting well configurations
- Pressurized water samples from inlet and test separators are obtained every 6 months (on 6MO maintenance programme)
- Sent to external lab for gas compositional analysis and 9-ion salinity analysis
- Inlet separator has lower standard deviation than the test separator (as expected)

Standard deviation from all samples (1xsigma)			
		Inlet separator	Test separator
GWR	mol%	0.17	0.4
CO2	mol%	3.04	11.0
Methane	mol%	2.36	8.3
Ethane	mol%	0.15	0.8
Propane	mol%	0.30	0.4
i-Butane	mol%	0.26	0.1
n-Butane	mol%	0.62	0.6
nmVOC	mol%	1.00	2.1
Chloride, Cl-	mg/l	2 580	N/A



Model auto-tuning

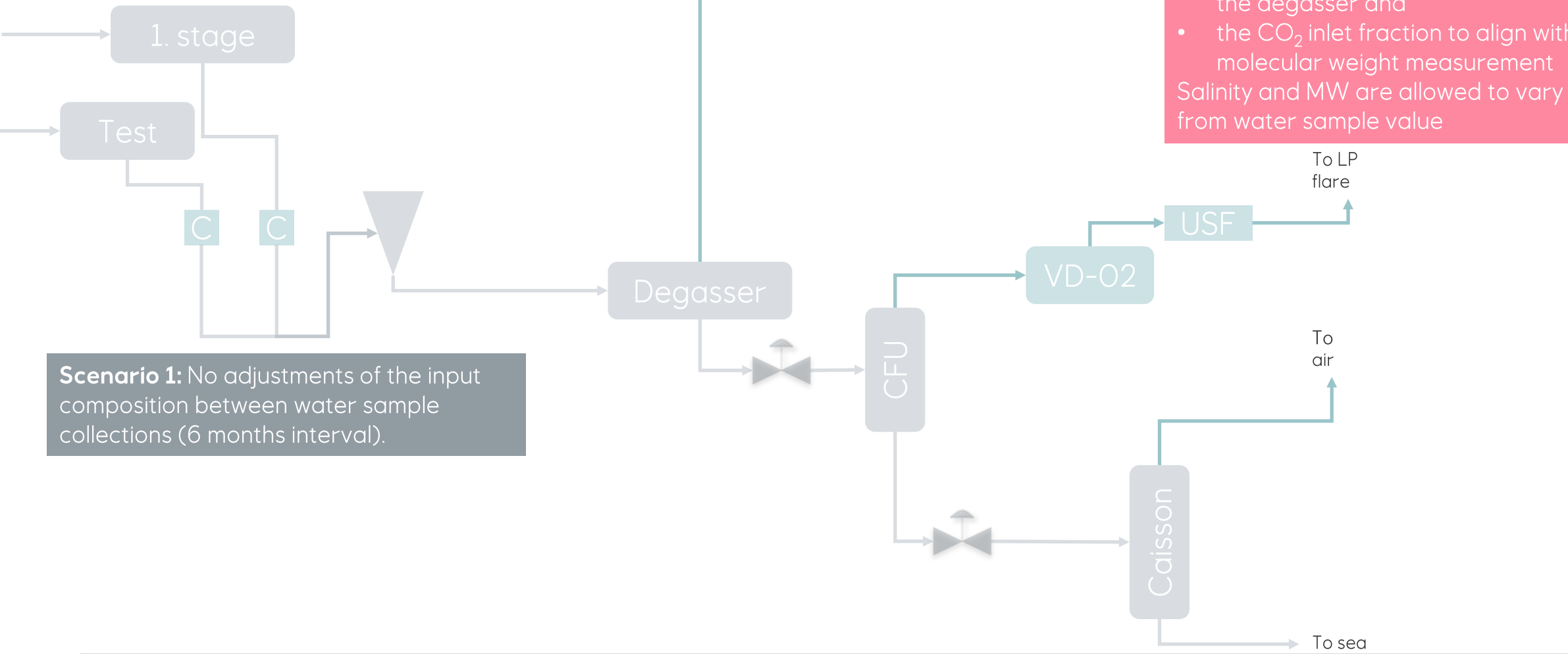
Scenario 2: Automatic tuning of the input composition salinity to align with the degasser gas rate at P-44-FT0512. Salinity is allowed to vary $\pm 10\%$ from water sample value

Scenario 3: Automatic tuning of

- The input composition salinity to match the degasser and
- the CO₂ inlet fraction to align with the molecular weight measurement

Salinity and MW are allowed to vary $\pm 10\%$ from water sample value

Scenario 1: No adjustments of the input composition between water sample collections (6 months interval).



Input variables standard uncertainties

input_name	mean	standard_uncertainty	standard_uncertainty_percent	distribution	min	max	unit	Comment
salinity_prod	1.1	0.6		normal	0	5	mol/l	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
CO2_prod	7.75	0.63		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
methane_prod	77	5.24		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
ethane_prod	8.78	0.71		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
propane_prod	3.66	1		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
i_butane_prod	0.45	1.08		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
n_butane_prod	0.92	2.2		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
i_pentane_prod	0.88	1.4		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
n_pentane_prod	0.62	1.01		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
salinity_test	2.55	1.4		normal	0	5	mol/l	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
CO2_test	12.1	3.3		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
methane_test	67.5	14.8		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
ethane_test	11.36	3.44		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
propane_test	5.68	2.32		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
i_butane_test	0.66	0.9		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
n_butane_test	1.53	4.7		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
i_pentane_test	0.65	4		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
n_pentane_test	0.45	3		normal	0	100	mol%	Engineering judgement, 1*SIGMA of five years of water samples, includes changing well configuration
ProdSep P-20-PT0107	48	0.05		normal	0	198	barg	Based on NFOGM gasmet app
ProdSep P-20-TT0122	85	0.5		normal	0	200	C	Engineering judgement, includes non-optimal placement etc
ProdSep P-44-FT0110	75	0.032	0.05	normal	0	500	m3/hr	Based on Haukalid, Usikkerhetsanalyse P-44-FT-0110, 25.08.2023
TestSep P-20-TT0334	90	0.5		normal	0	200	C	Engineering judgement, includes non-optimal placement etc
TestSep P-44-FT0310	13	0.009	0.05	normal	0	500	m3/hr	Based on Haukalid, Usikkerhetsanalyse P-44-FT-0310, 25.08.2023
TestSep P-20-PT0306	50	0.05		normal	0	198	barg	Based on NFOGM gasmet app
Degasser P-44-PT0503	5	0.05		normal	0	198	barg	Based on NFOGM gasmet app
Degasser P-44-TT0433	88	0.5		normal	0	200	C	Engineering judgement, includes non-optimal placement etc
P-44-FT0512.5mAVG	85	0.1	0.35	normal	0	500	kg/hr	Based on Haukalid, Usikkerhetsanalyse P-44-FT-0512, 07.06.2023
CFU P-44-PT0551	1	0.2		normal	0	198	barg	Engineering judgement, manometer (offline) measurement
CFU P-44-TT0431	80	0.5		normal	0	200	C	Engineering judgement, includes non-optimal placement etc
VD01 P-43-PT0034	1	0.05		normal	0	198	bara	Based on NFOGM gasmet app
VD01 P-43-TT0017	55	0.5		normal	0	200	C	Engineering judgement, includes non-optimal placement etc
VD02 P-43-PT0334	1	0.05		normal	0	198	bara	Based on NFOGM gasmet app
VD02 P-43-TT0319	48	0.5		normal	0	200	C	Engineering judgement, includes non-optimal placement etc
P-43-FT0030.MoleWeight	28.1		5	normal	16	50	mol/g	Engineering judgement, based on MW measurement from P-43-FT0030 fiscal USF
CaissonP	1.01325	0.1		normal	0	198	bara	Engineering judgement, open to atmosphere, no measurement
CaissonT P-44-TT0431	80	5		normal	0	80	C	Engineering judgement, using upstream temperature meas., uncertainty in water heat loss

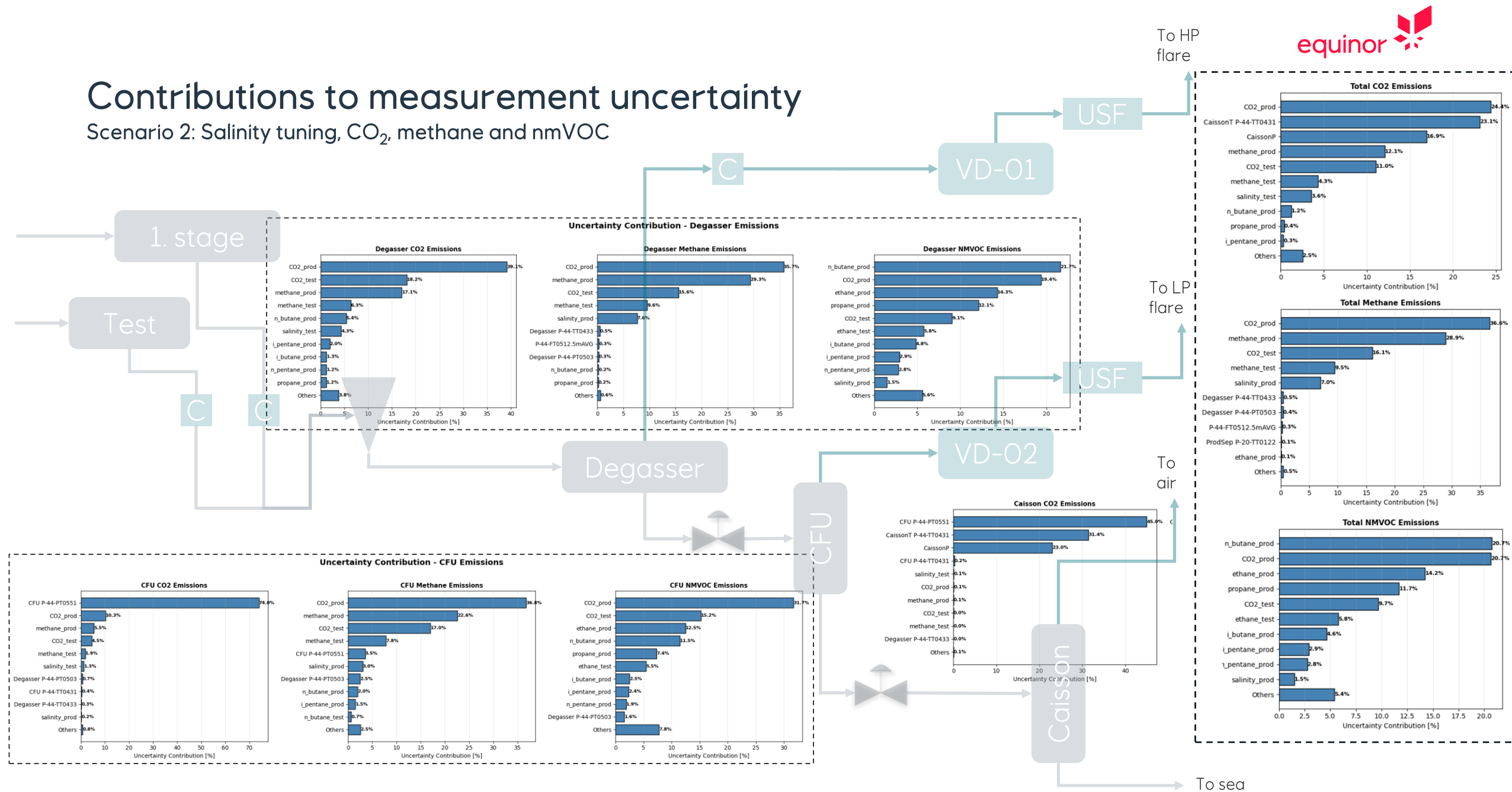
From periodic, pressurized produced water samples

Field instrumentation

Fiskal Estimate
Estimate

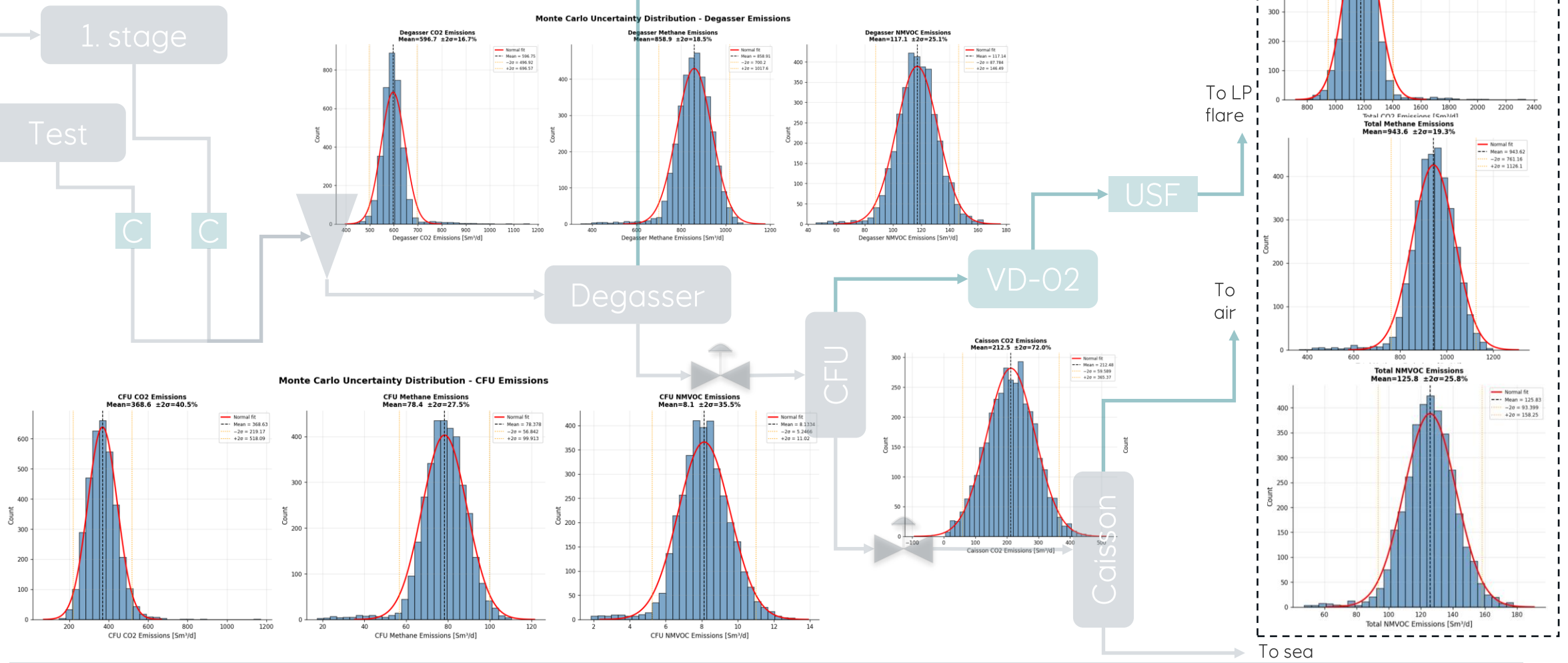
Contributions to measurement uncertainty

Scenario 2: Salinity tuning, CO₂, methane and nmVOC



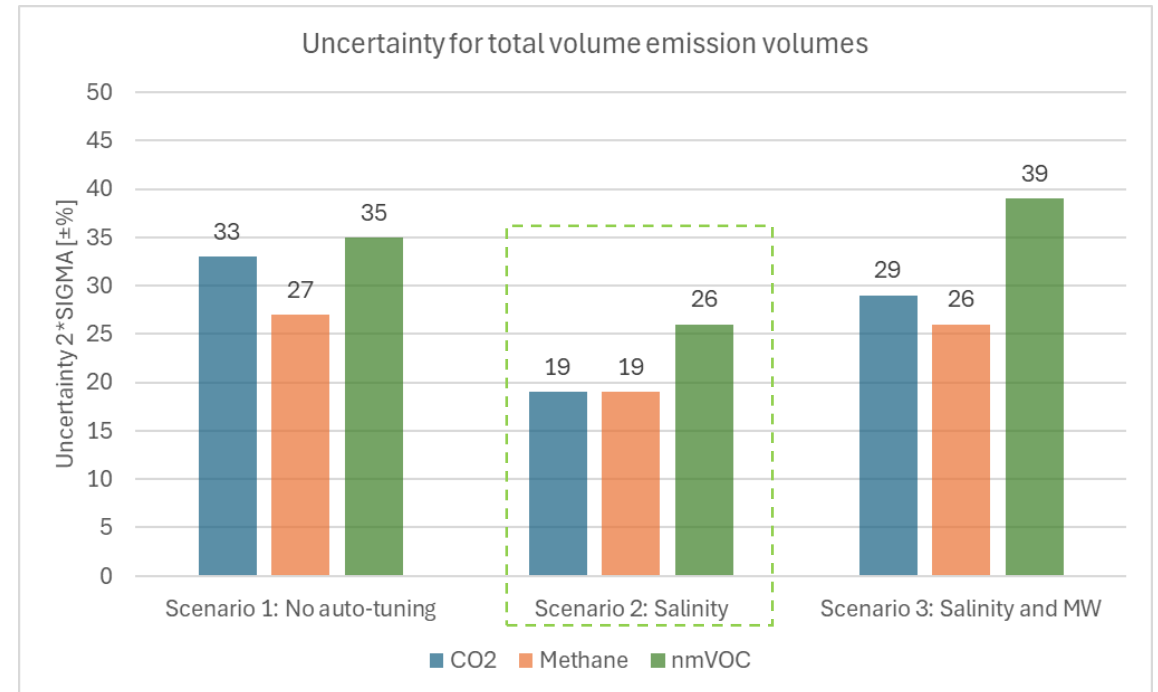
Monte Carlo analysis

Scenario 2: Salinity tuning
3500 simulations



Model uncertainties – comparison of scenarios

- Tuning salinity to degasser gas rate reduces total CO₂ uncertainty.
- CO₂ uncertainty can be further reduced if gas molar mass from the HP flare ultrasonic meter can be verified lower than $\pm 5\%$
- The scenario 2 model was set in operation Q4 2025.
- Prior to this, the same type of adjustment was done manually



Validation of the model

Comparison with process measurements

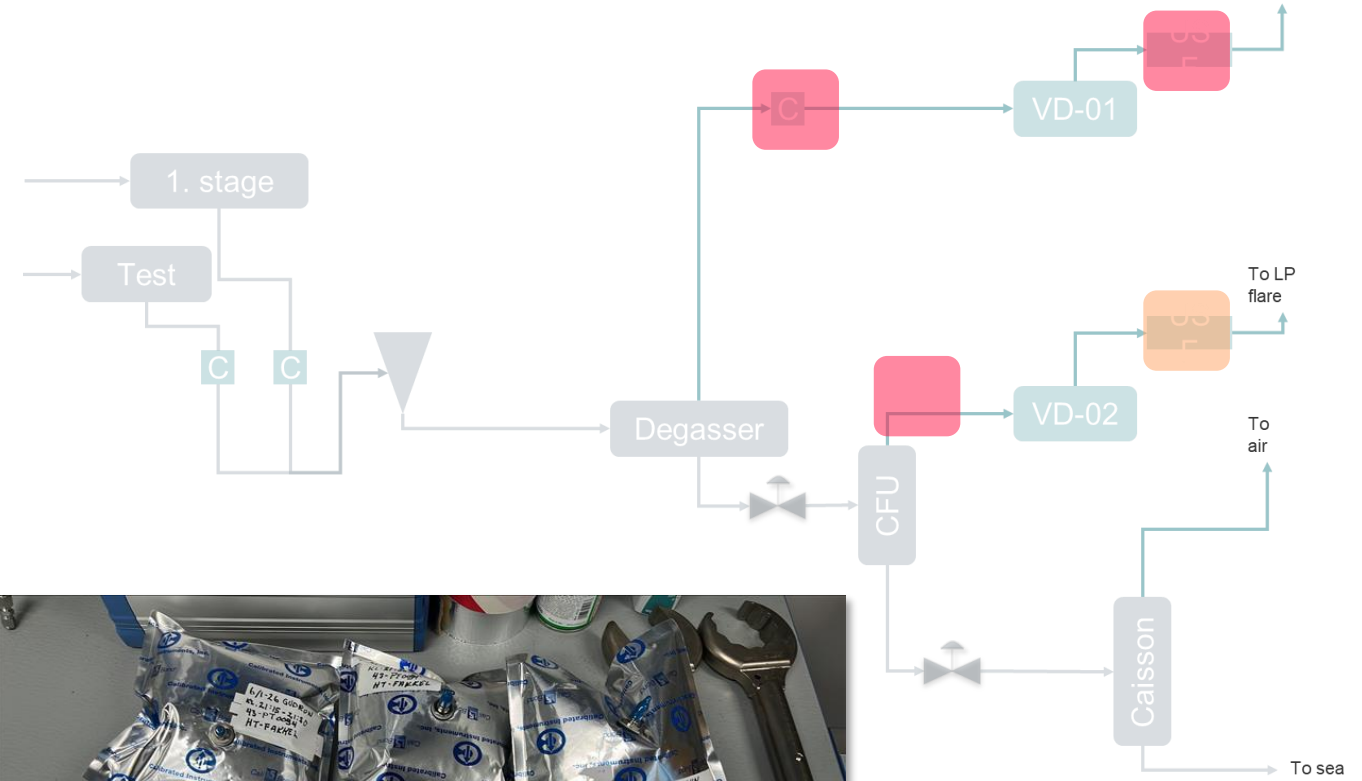
- Comparison with total, measured gas rate from the Degasser
- Back-calculation three years with one water sample as calibration

Gas sampling

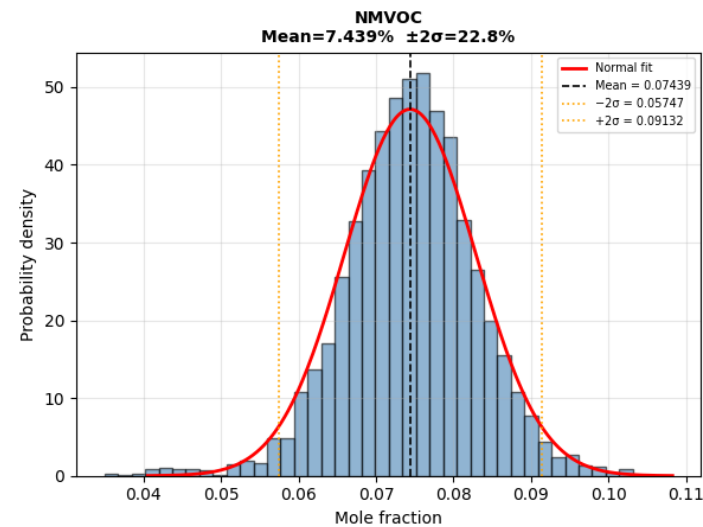
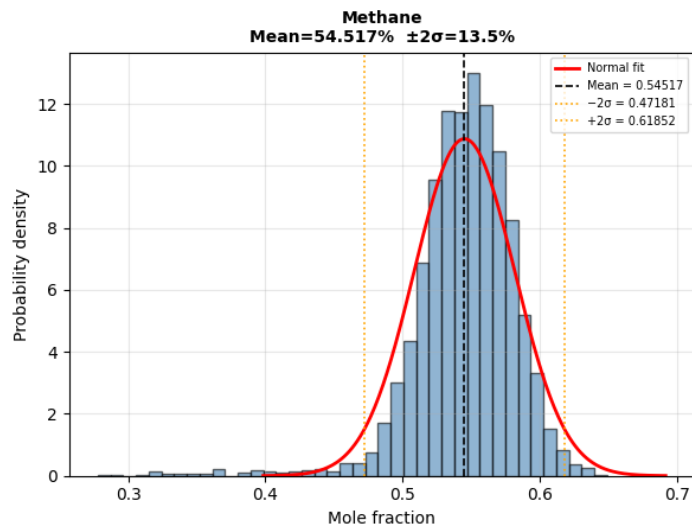
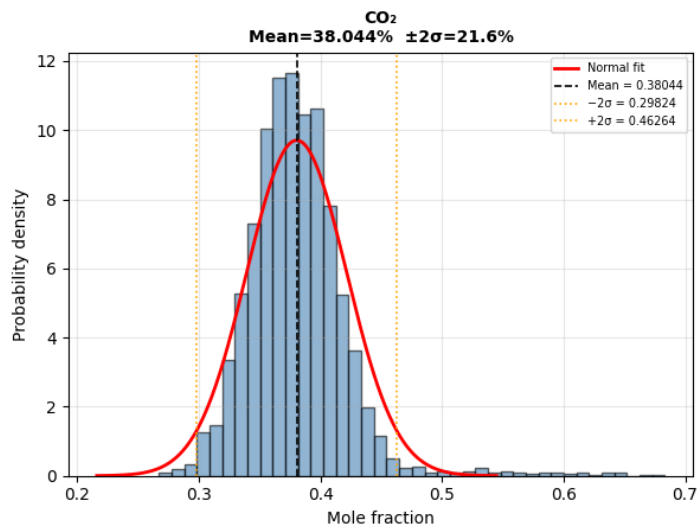
- Gas samples from the emission points to compare with NeqSim output
- Samples were taken during stable production to obtain representative conditions
- Gas samples taken Jan'26 and model was calibrated in June'25

Site measurements

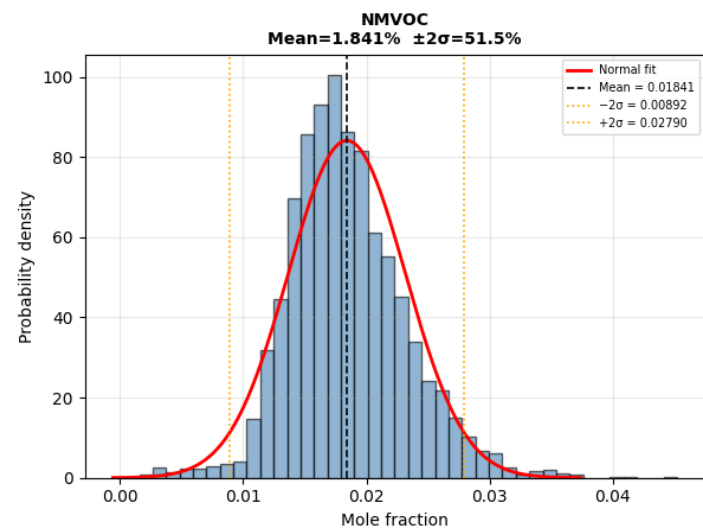
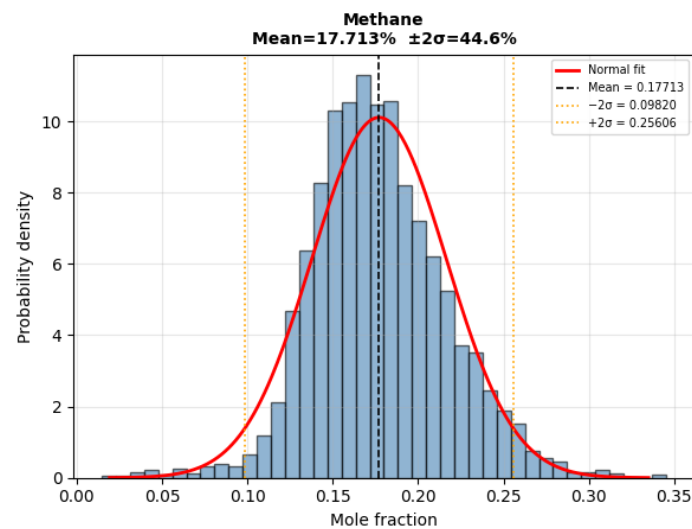
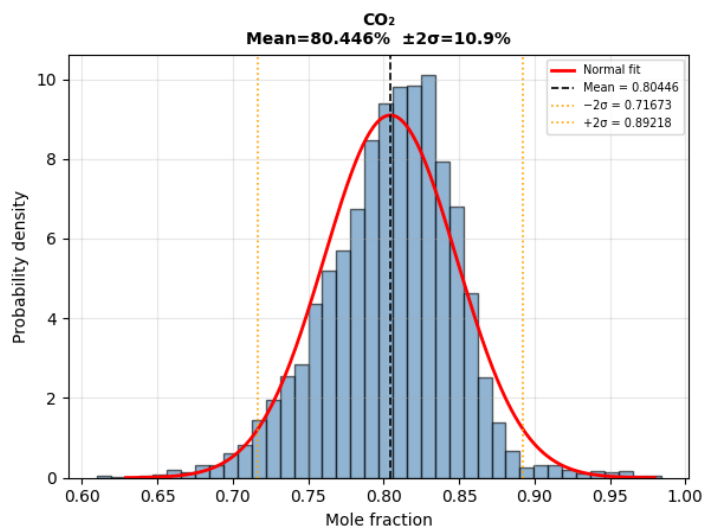
- Comparison with site level methane measurements (drones)

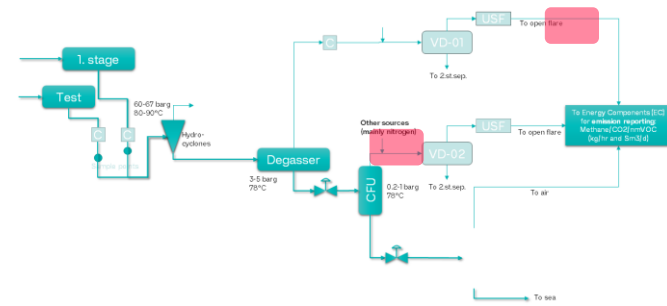


Degasser Gas Molar Composition - Normal Distribution



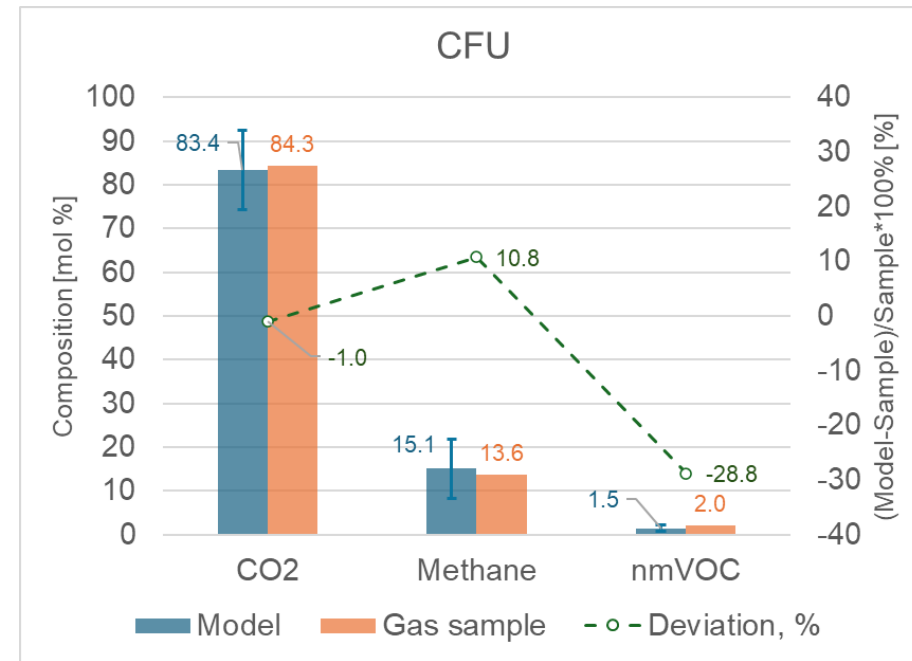
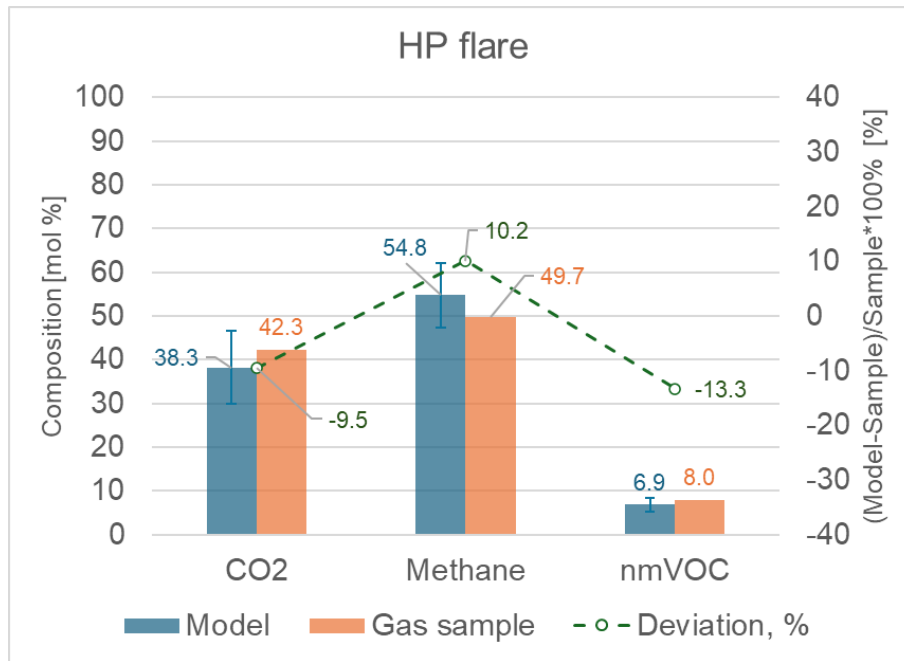
CFU Gas Molar Composition - Normal Distribution





Comparison with gas samples

January 2026



HP flare gas samples are average of three sample parallels. Each parallel was analysed four times.

CFU gas samples are average of two sample parallels. Each parallel was analysed four times.

- The model values are from the same time as the individual samples
- The GC was calibrated with a 93% CO₂ calibration gas.

Comparison with drone measurements

Sammenligning av målinger på site-nivå (drone) og kildemålinger (modell)



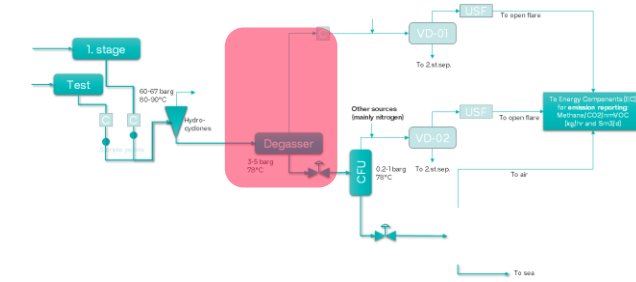
Dato	Rapport	Komponent	Utslippspunkt	Gj.snitt. Dronemåling site-nivå [kg/hr]	Måleusikkerhet drone 95% konf. [%]	Kildemåling NeqSim modell* [kg/hr]
30.06.2024	DFM-GUDRUN-CH4-20240629-685-Flare_tip.pdf	CH4	HP	24,5	+/- 22%	29.0*
25.04.2025	DFM-GUDRUN-CH4-20250425-1081-Flare%20	CH4	HP	24.9	+/- 22%	28.0*
30.06.2024	DFM-GUDRUN-CH4-20240630-684-Platform.pdf	CH4	LP	3.57	+/- 35%	1.75*
25.04.2025	DFM-GUDRUN-CH4-20250425-1083-Platform_and_vent%20	CH4	LP	5.0	+/- 22%	1.7*
30.06.2024	DFM-GUDRUN-CO2-20240629-686-Flare_tip.pdf	CO2	ALL	57	?**	95.0*
25.04.2025	DFM-GUDRUN-CO2-20240629-686-Flare_tip.pdf	CO2	ALL	46	?**	99.0*

*Modell gir kun utslipp fra produsertvann, kan sammenlignes med sitemåling isolert til HP fakkell. I LP fakkell er det andre utslippsskilder i tillegg til produsertvann. I LP fakkell utgjør utslippet fra produsertvann ca 50%.

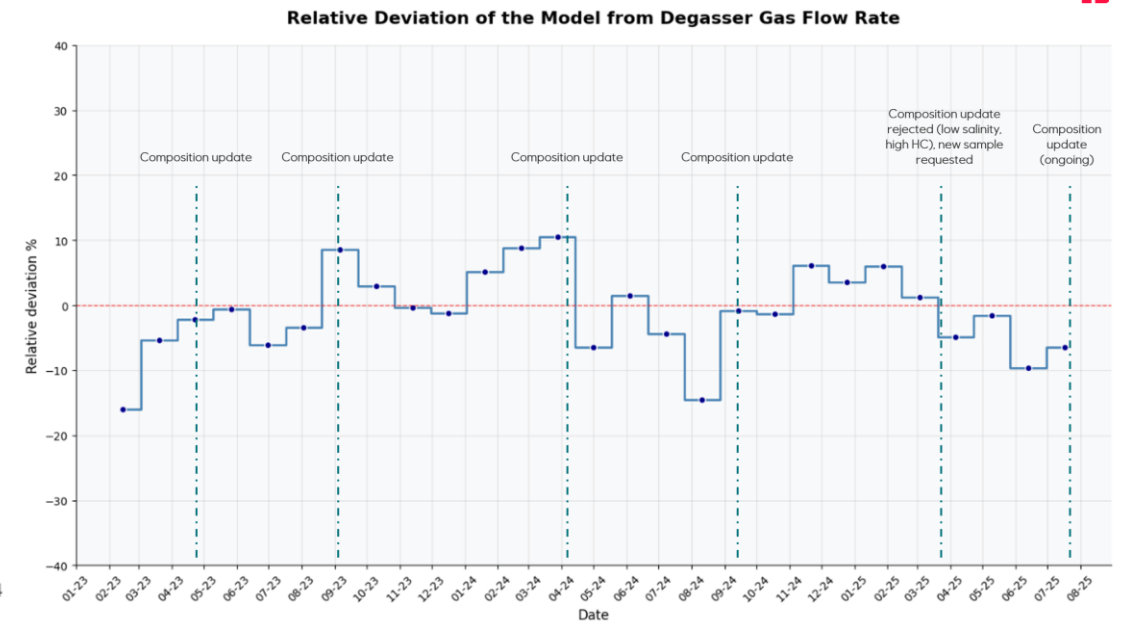
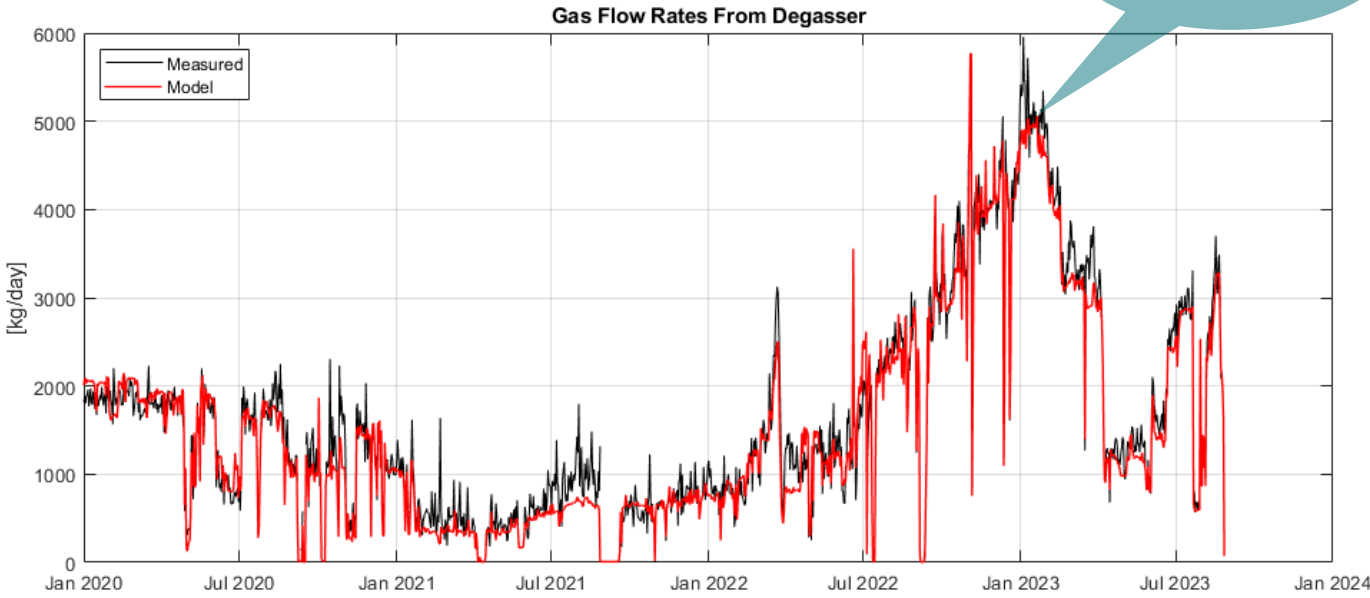
**Måleusikkerheten var ikke estimert. Standardavviket var på ca 55 kg/hr 2024; 31.46 kg/hr 2025

Site-nivå målinger (drone) og kildemålinger (modell) utslippstall i samme størrelsesorden.
Dette øker konfidens i metodene

Comparison with field data

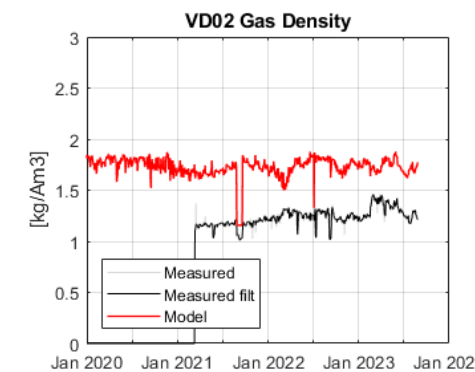
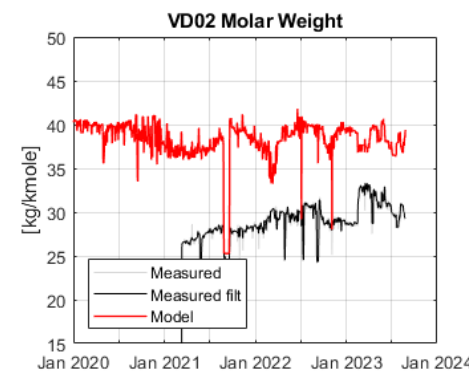
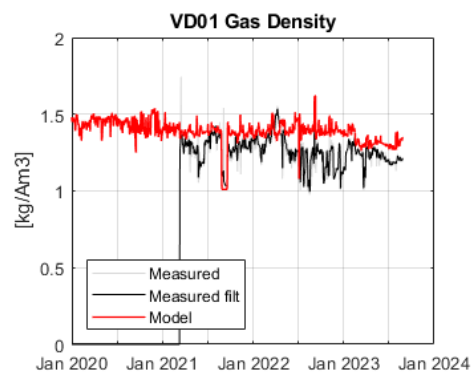
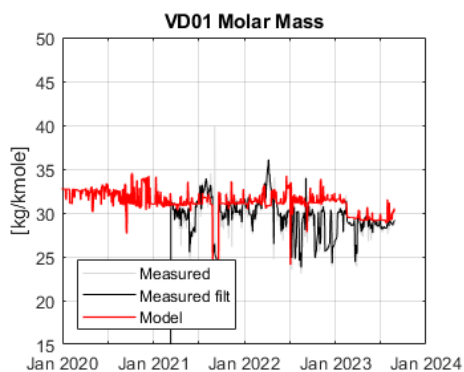
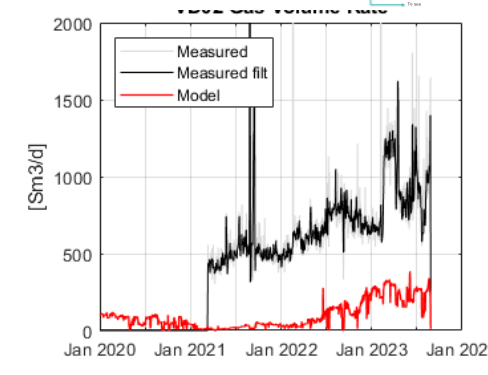
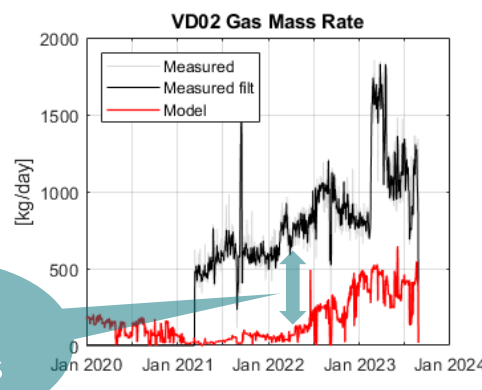
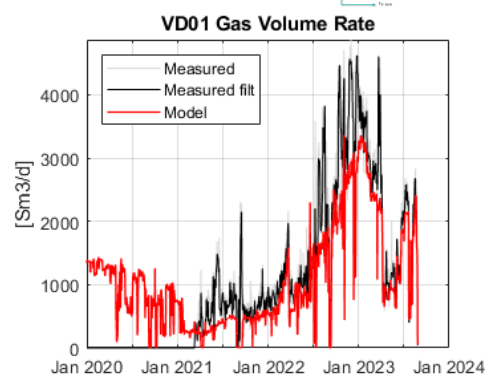
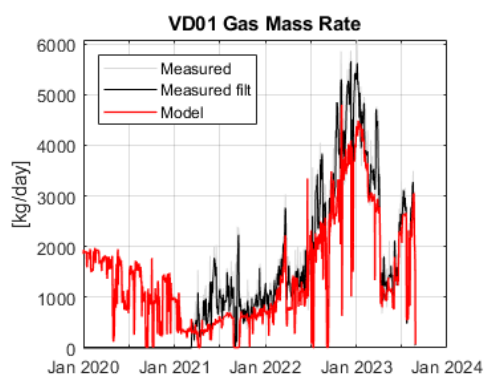
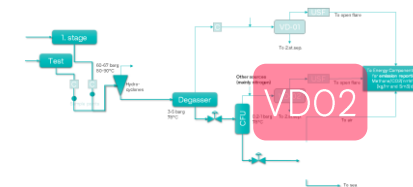
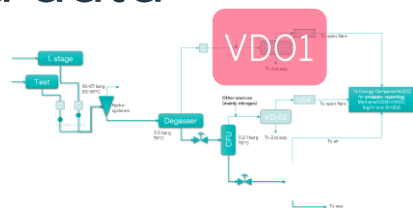


Date of calibration



- Gas mass flow rate from produced water degasser, comparison between measured (Coriolis) and calculated (NeqSimLive)
- Cumulative deviation between model and measured gas mass flow rate:
 - -2 % (2022) and
 - -7.2 % (2023)

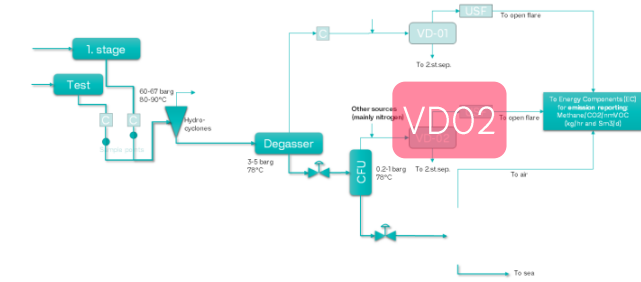
Comparison with field data



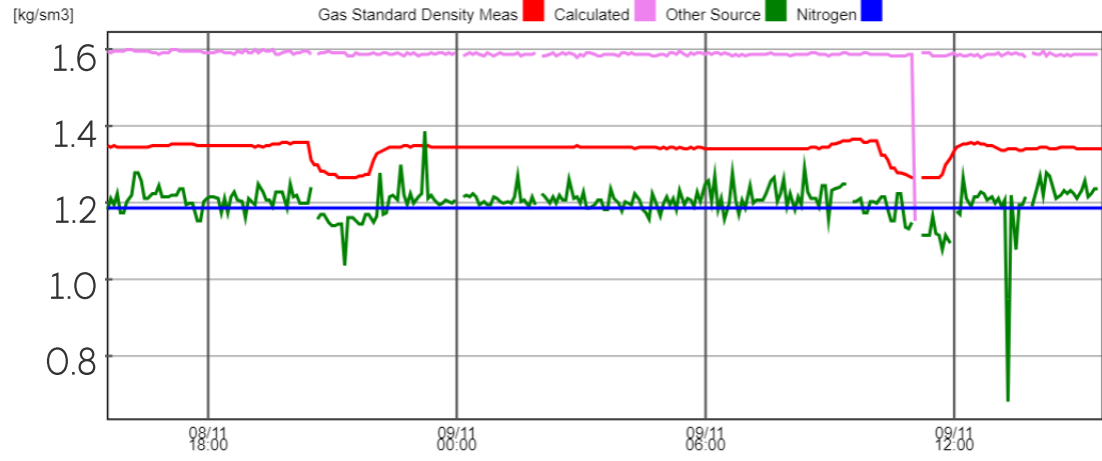
Good fit for flow rate, gas molar mass and density on HP flare

Discrepancies on LP flare due to "other sources"

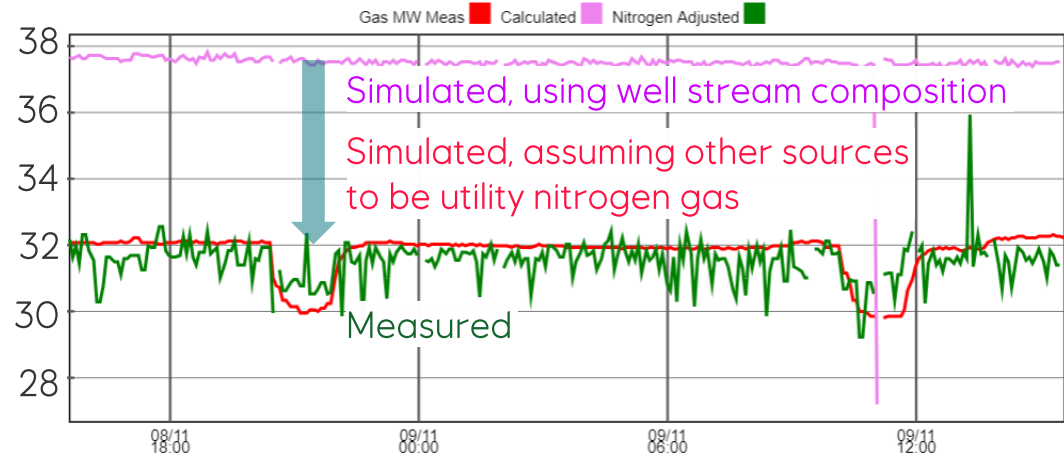
Model prediction of nitrogen in the LP flare



VD02 Gas Density [kg/m³]



VD02 Gas Molar Mass [g/mole]



LP flare		CO2	CH4	NM VOC	N2
		(mol%)	(mol %)	(mol %)	(mol%)
		Gas sample			
Gudrun-060126-2150-2205-PT0334-LPFAKKEKEL	06 January 2026 21:50 - 22:05	47.9	14.9	4.0	33.2

- The model predicted high nitrogen content in LP flare stream
- Gas sample (Jan'26) confirms high amounts of nitrogen from "other sources" in the LP flare
- Gas sample also show some methane from other sources than produced water

Summary

Learnings and key take aways

- CO₂, methane and nmVOC uncertainties are higher than $\pm 7.5\%$ (95% conf.int.), but **the precision is good** when comparing to gas samples and drone measurements.
 - CO₂ $\pm 19\%$, methane $\pm 19\%$ and nmVOC $\pm 26\%$
- Uncertainty calculations need to consider compositional variations caused by well configuration changes between water samples. **This gives high uncertainty impact from inlet composition.**
- Automatic tuning reduces uncertainty: Tuning salinity to degasser gas rate reduces total uncertainty and is currently in operation
- The inlet composition gives the – by far – most significant uncertainty contribution
- Field instruments can be used, but we need to ensure that there are no systematic biases

Mitigating actions to reduce uncertainty

- Periodic water sampling with composition and salinity analysis to be continued, 6 months intervals
- Periodic collection and analysis of gas samples from degasser and CFU for comparison with model predictions would further increase confidence in the model results.
- Including the integration of auto-tuning using the molecular weight measurements from the HP flare flow meter would further enhance the model's accuracy. This will require lowering the uncertainty in the molecular weight measurement to well below $\pm 5\%$.
- Adding temperature and pressure sensors on the Caisson could reduce uncertainty for Caisson CO₂ emission estimates
- Technology for live composition per well is being investigated in Equinor.

Acknowledgements

- Thanks to Gudrun license partners for the opportunity to publish this work:
 - Vår Energi
 - OMV (Norge)
 - Repsol Norge
- Thanks to Gudrun organization for supporting this work and doing the gas sampling
- Uncertaintylib was developed/implemented by Dagfinn Mæland and Christian Hågenvik at Equinor K-lab
- Kjetil Haukalid (Equinor) has been giving valuable contributions and understanding in developing uncertainty budgets
- Gudrun Operations and Nils Aubroeck at Equinor T-lab and have performed field gas sampling and compositional analysis



Virtual Measurement of Emissions from Produced Water Using an Online Process Simulator

Olav Kristiansen, Principal Researcher Process Technology

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