Deep Removal of CO_2 &
InnoVative Electrification concepts

Effect of Solvent Aging on the Performance of CESAR1 at Highest Capture Rates of 98.0-99.9%

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Objectives of the 14 months testing of highest CO_2 capture efficiencies at the capture pilot plant at Niederaussem

- **Confirm technical feasibility** of achieving deep removal using amine-based solvents with thermal regeneration, real flue gas, 24/7 operation:
  ▸ **long-term tests**
- Assess the **impact** of deep removal in **energy demand, emissions, solvent degradation, and operability** for the CESAR1 solvent:
  ▸ **holistic performance analysis**
- **Update models** for the Technical Economic Analysis (TEA) and Life Cycle Analysis (LCA):
  ▸ **highest capture efficiency is not for free, analysis of the trade-off**

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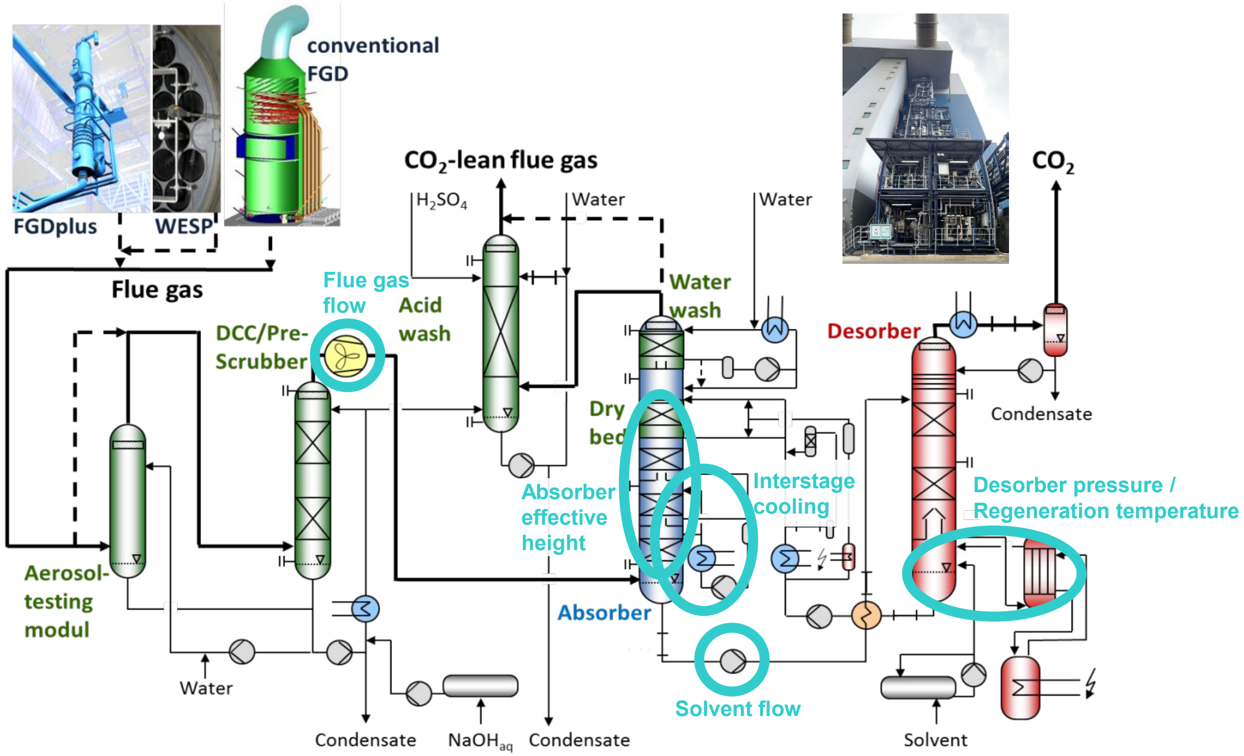
Deep removal with thermal regeneration at the capture pilot plant at Niederaussem – 24/7 operation without extra components or reclaiming

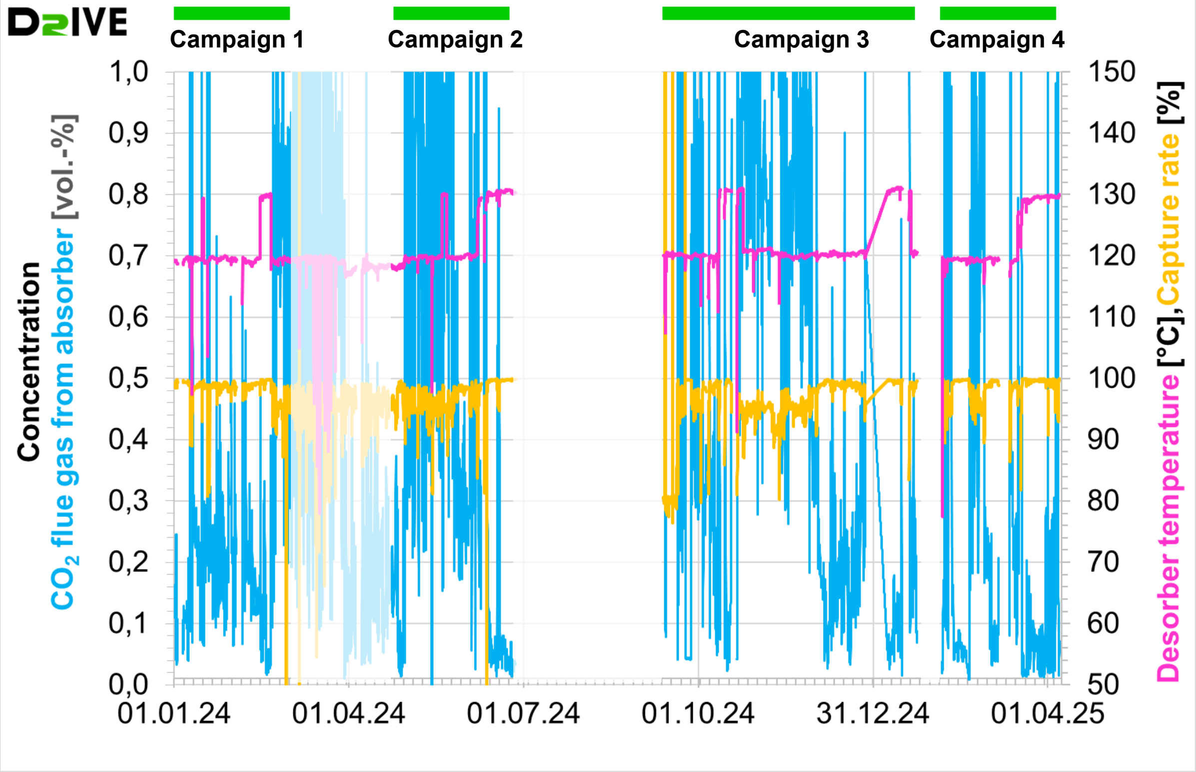


- **Flue gas source**: 1,000 MW lignite-fired power plant
- **Solvent**: CESAR1 (blend 3.0 M AMP/1.5 M PZ)
- **Flue gas composition**: 14.5 vol.-% CO_2, 5 vol.% O_2
- **Calculation capture rate**: Absorber balance - calibration gas for IR analyser is a mixture of 99.98 vol.-% N_2 and 200 ppmv CO_2
- Campaign 1: testing 3 and 4 active packing sections
  Campaign 2: testing 3 active packing sections
  Campaign 3: testing 4 active packing sections

  Exchange of the solvent inventory before start of Campaign 4, after 15,700 testing hours

  Campaign 4: testing emission control configurations

Overview testing campaigns with highest capture efficiencies >98%



Operating hours	Campaign 1	Campaign 2	Campaign 3	Campaign 4
Capture rate >98.0% [h]	1,011	588	1,234	1,006
Desorber temperature >128.0°C [h]	154	454	450	469
Total testing time [h]	1,214	975	2,044	1,196
Average CO_2 capture efficiency entire campaign [%]	**98.30**	**96.68**	**96.88**	**98.52**

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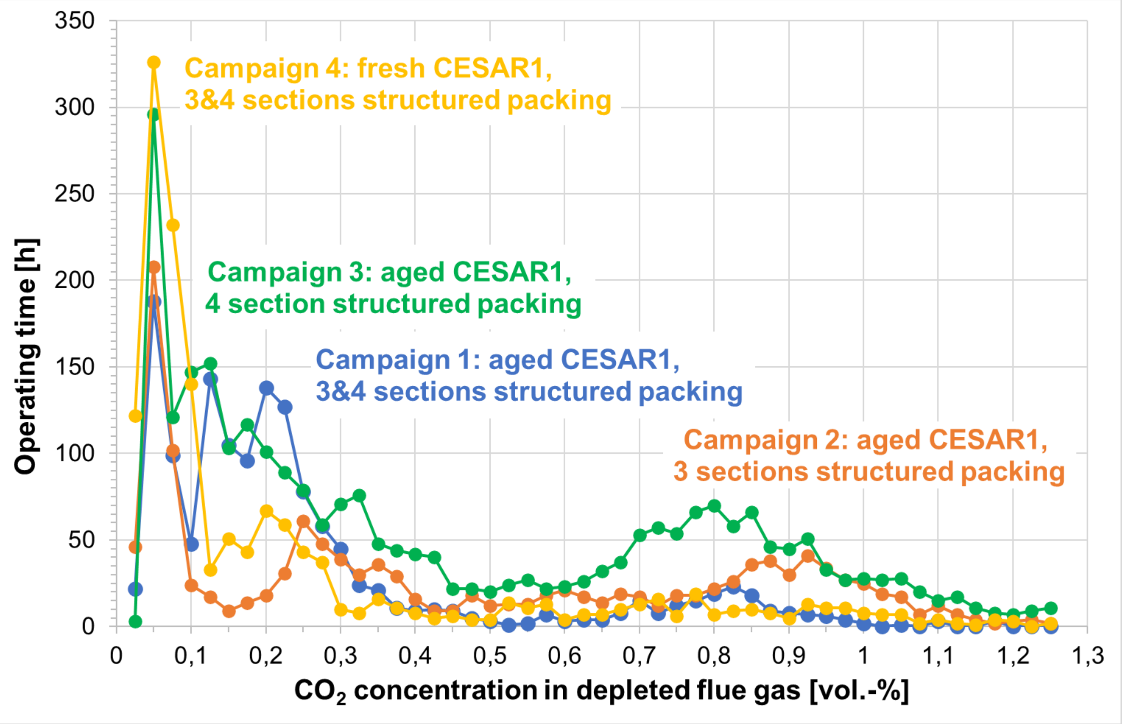
Longer, non-interrupted testing periods with capture efficiencies >99%



- More than 2,100 operating hours during the four campaigns with residual CO_2 concentration in the depleted flue gas <1,000 ppm
- Highest capture efficiencies have been achieved in non-interrupted longer test periods:
  - **Campaign 2**: at 130.5°C regeneration temperature **193 hours: 99.69%, 436 ppm**
  - **Campaign 4**: at 129.1°C regeneration temperature **292 hours: 99.70%, 539 ppm**
  - **Campaign 4**: at 119.5°C regeneration temperature **100 hours: 99.75%, 514 ppm**

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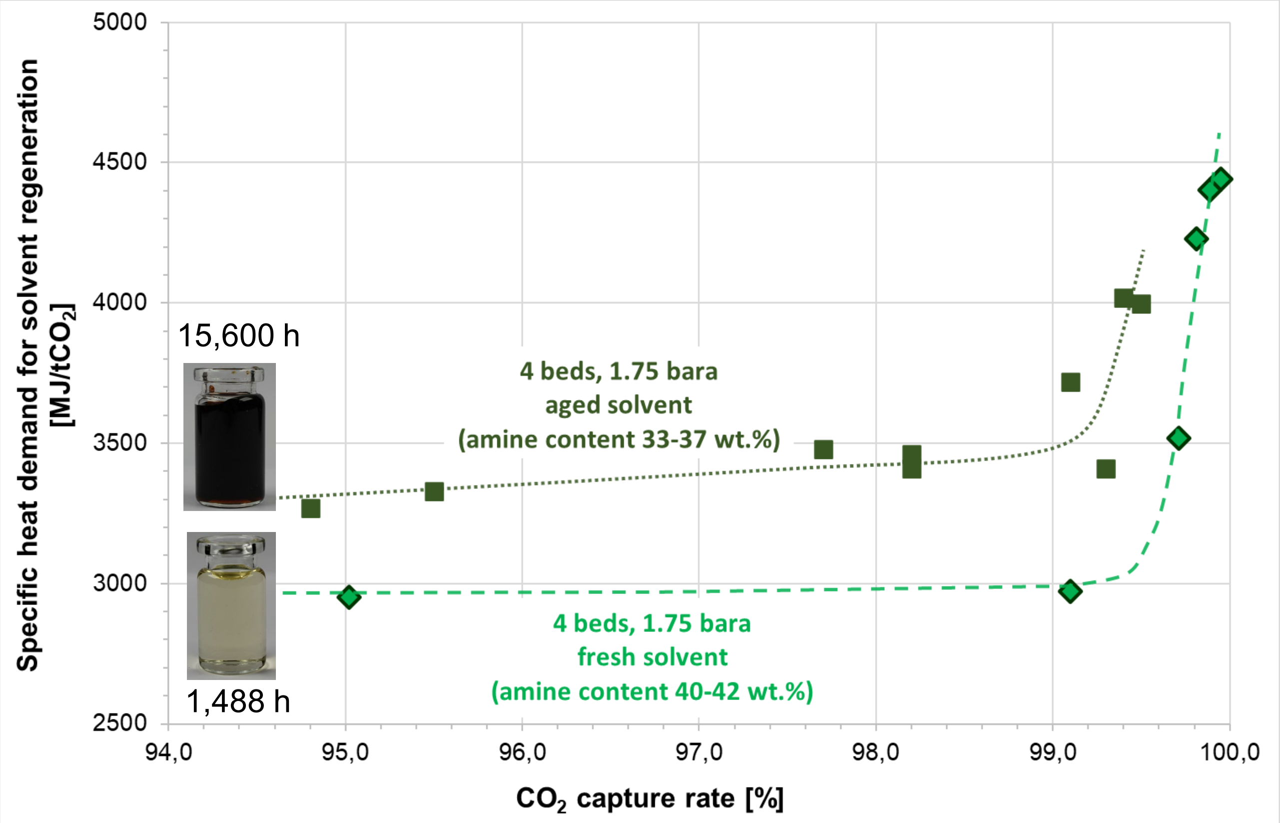
Capture rate & Specific Reboiler Duty for fresh and aged CESAR1



- Lower amine content of aged CESAR1 increased the specific reboiler duty up to a capture rate of 99.0% by 30% compared with 90% capture rate
- For fresh CESAR1 the specific reboiler duty is almost constant up to 99.0% capture efficiency
- For capture efficiencies >99.0% we see a strong increase of the reboiler duty

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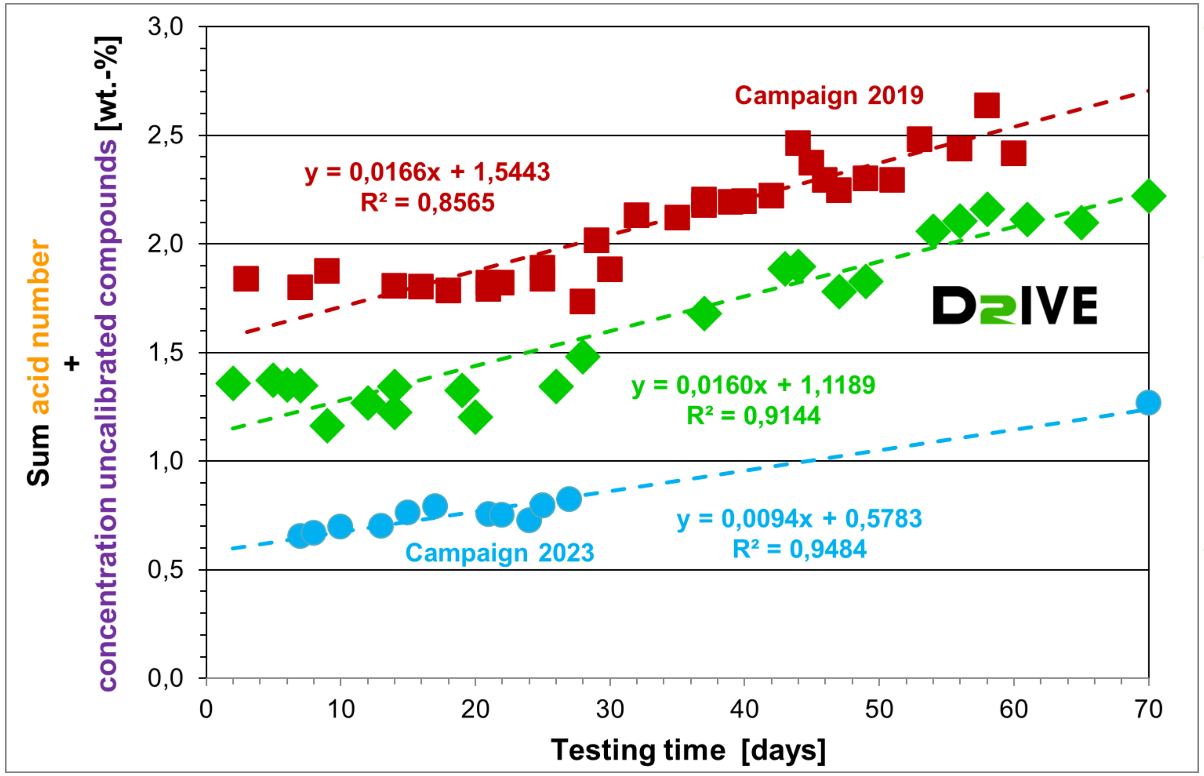
Comparing degradation of fresh CESAR1 depending on capture efficiency



- Slope of the sum of the acid number and the concentration of uncalibrated compounds as a measure of solvent degradation
- No significant change of the accumulation of degradation products in the fresh solvent caused by the capture efficiency >98% compared with 90-95%
- Despite four testing campaigns with more than 5400 operating hours, continuous operation over 6 months at high capture efficiency is needed to evaluate degradation behaviour

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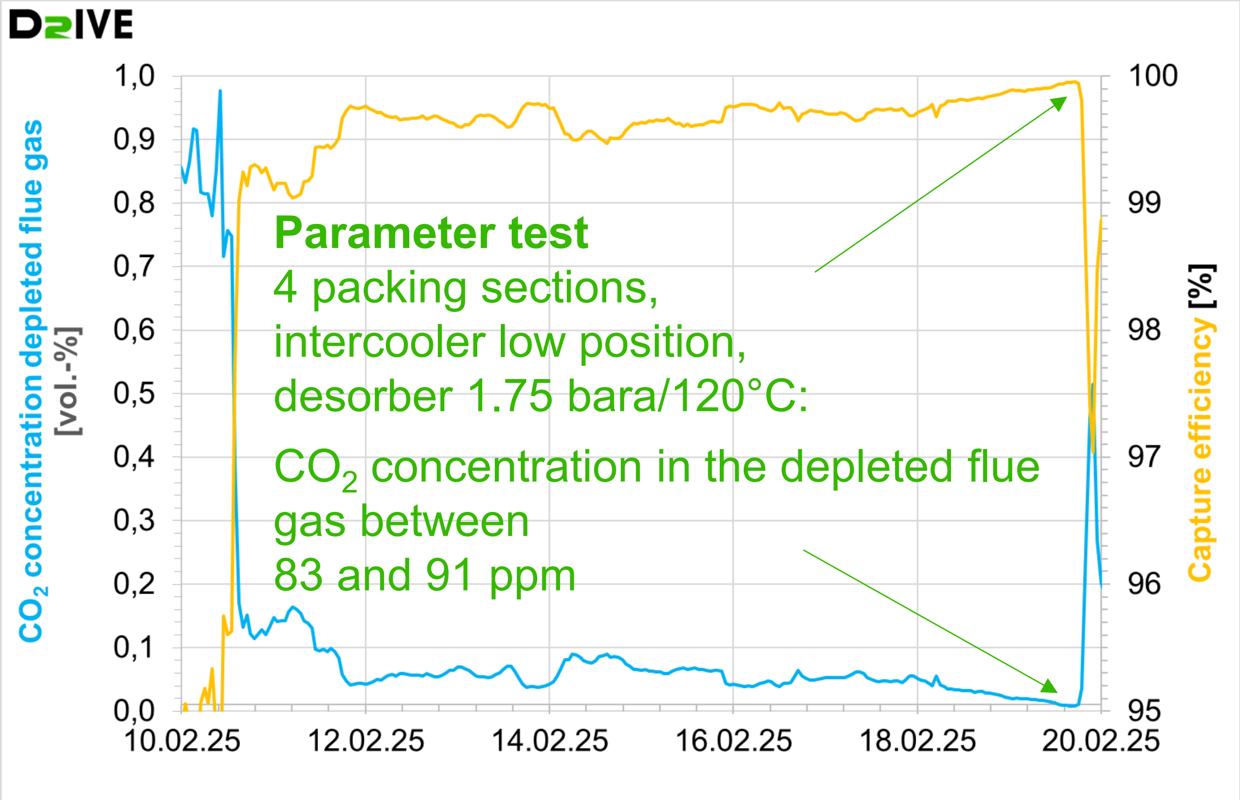
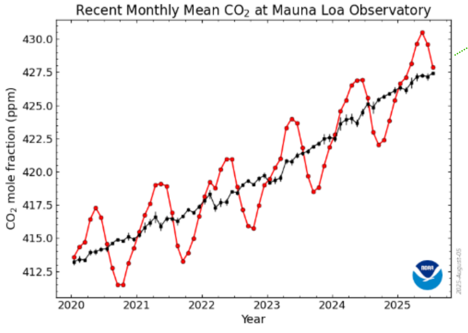
Highest capture efficiency achieved: 99.95% - CO_2 content in depleted flue gas 91 ppm - 50% higher Specific Reboiler Duty than at 90% capture efficiency



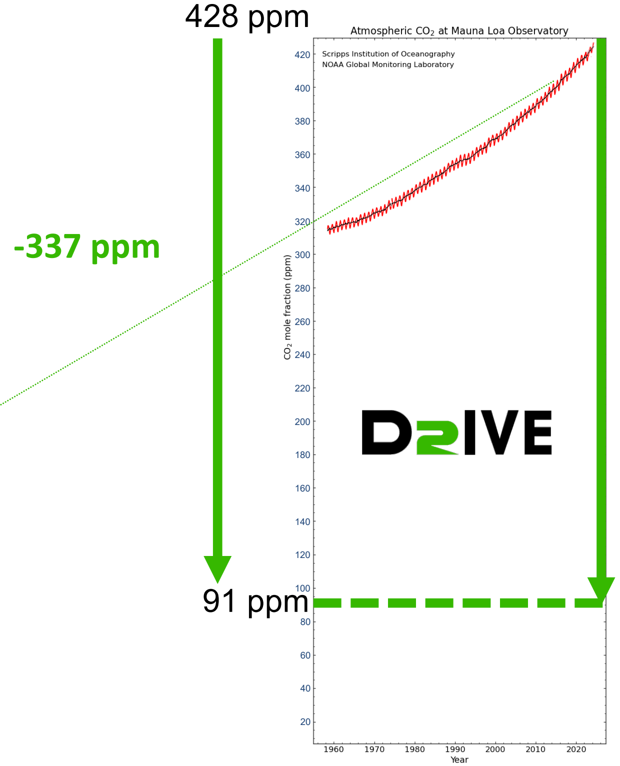
CO_2 concentration
in ambient air:

July 2025: 427.87 ppm

July 2024: 425.55 ppm



https://gml.noaa.gov/ccgg/trends/mlo.html



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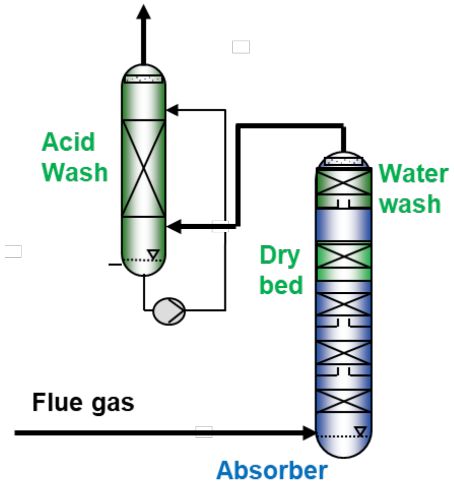
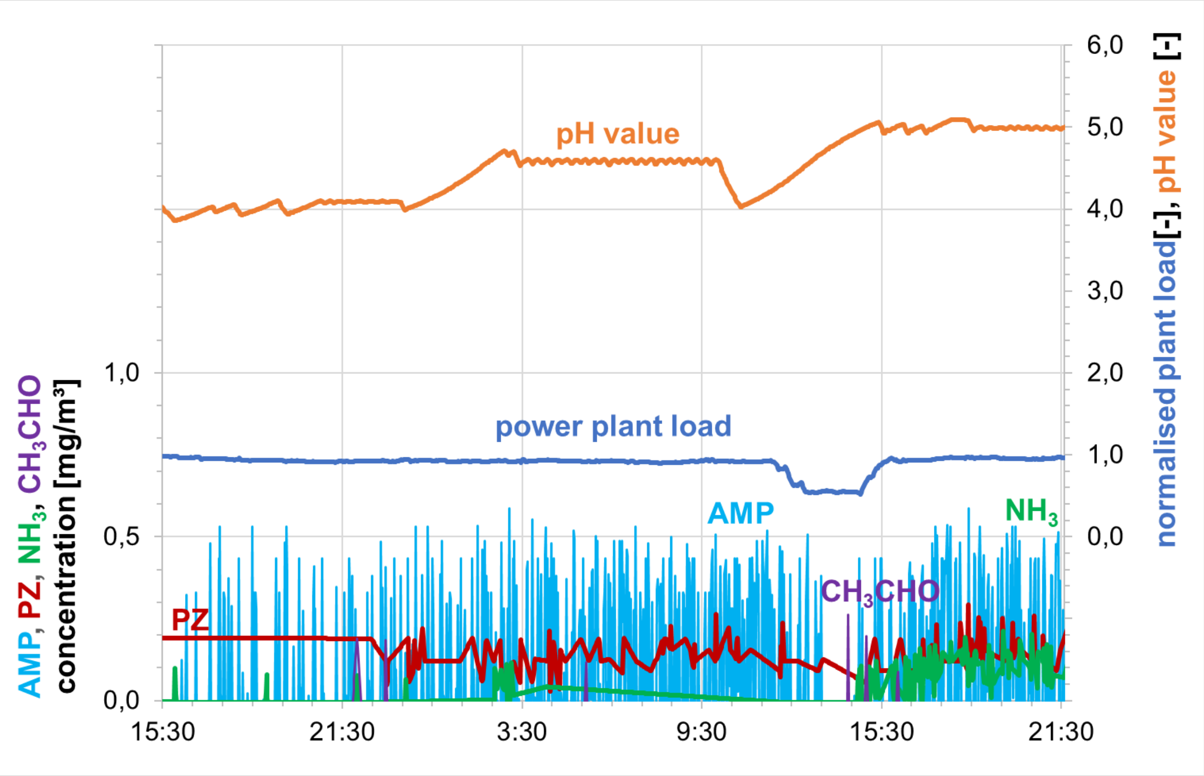
Emission control – Dry bed and acid wash with pH value 4 to 5, 98.82% capture efficiency





- Combination of Dry bed (OASE aerosone™) and acid wash effectively reduced the emissions well below 1 mg/m³
- NH_3 emissions show highest dependence on pH value
- Power plant load affects emissions due to temperature effects in the absorber

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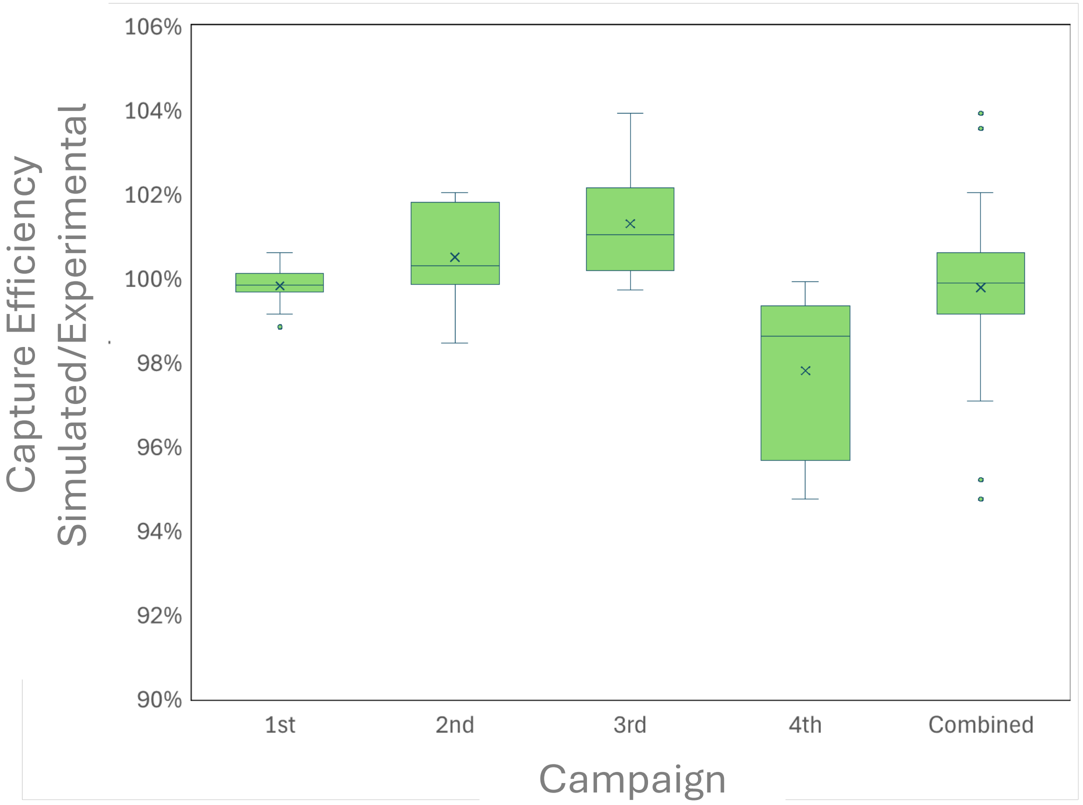
Process simulation with ProTreat® - CO_2 capture efficiency



- CO_2 capture efficiency calculated based on measured inlet liquid and gas specifications, and reboiler duty
- Majority of the data is calculated within 2% deviation
  - few runs reaching up to 5% deviation
- 4th campaign seems to produce larger deviations compared to the previous campaigns
  - median is kept within the 2% deviation
  - Deviations 4th campaign under investigation

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Conclusions and Outlook

- The feasibility of deep CO_2 removal has been demonstrated in four campaigns at the capture pilot plant at Niederaussem.
- More than 3,800 operating hours with capture rates >98% and CO_2 concentrations in the depleted flue gas <100 ppm have been achieved.
- Emission mitigation technologies are available to control the emissions.
- Simulations with ProTreat® are able to represent the experimental data regarding capture rates and volatile emissions well for aged CESAR1.
- Deep removal means an environmental and economic trade off regarding high CO_2 capture efficiency, energy demand and cross-media effects.
- A comprehensive TEA and LCA will provide a holistic assessment for different use cases, based on the results of the six-months testing campaign on solvent degradation at deep removal conditions.

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