Temporal aggregation bias and the flexibility–optimality gap in Direct Air Capture operation under operational variability

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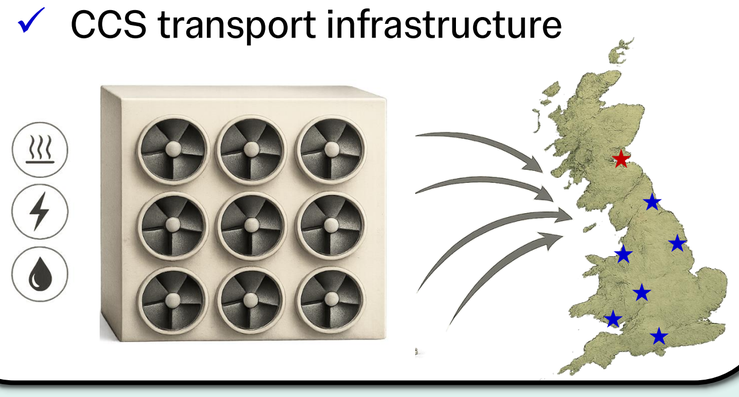
Background

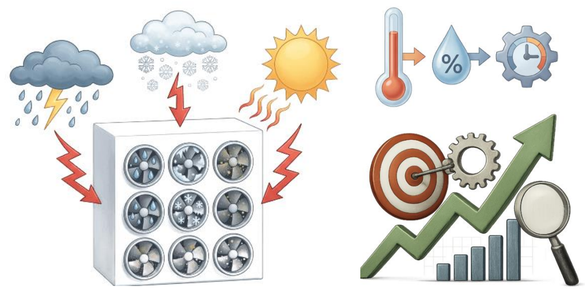
- Direct Air Capture (DAC) is a CO_2 Removal technology that can deliver negative emissions and offset **residual industrial emissions**
- UK industrial clusters have high siting potential [1];
  - ✓ Tap into waste streams
  - ✓ Access to power grid
  - ✓ CCS transport infrastructure



Research Questions

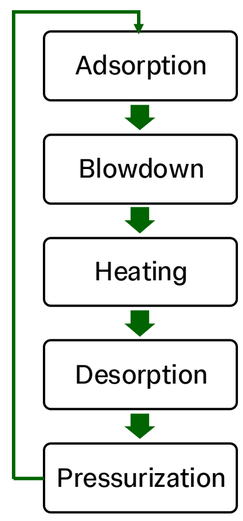
Research Gap: Most modelling studies use fixed weather data hence **they may** misrepresent the system's performance

1. What is the impact of **local weather variability and resolution** on DAC performance?
2. Is continuous **re-optimization** worth the cost, or can stable operation achieve equivalent performance?

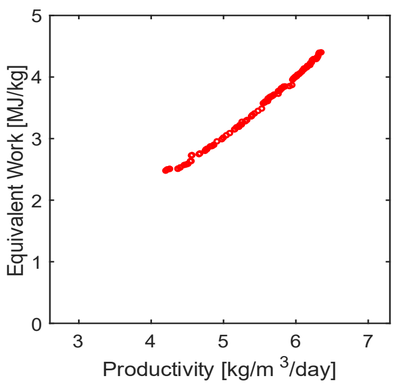


Process Model

- 5-step steam-assisted Temperature-Vacuum Swing Adsorption cycle
- High-fidelity 1D mechanistic model [2]
- Multi-objective optimisation (NSGA-II)

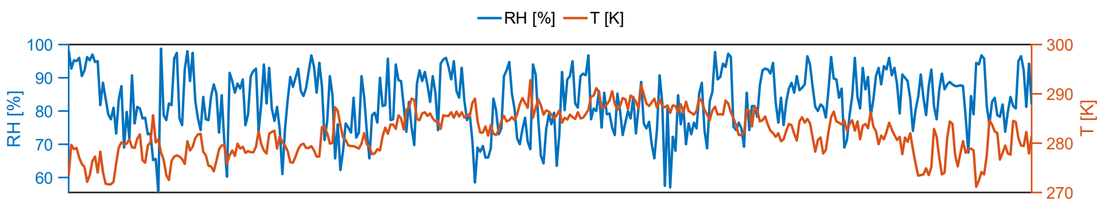


$$\min(-Pr + \varphi, W_{eq} + \varphi)$$
$$s.t\ \theta_L \leq \theta \leq \theta_U$$
$$\varphi = 0.25[\max(0.95 - Pu)]^2$$



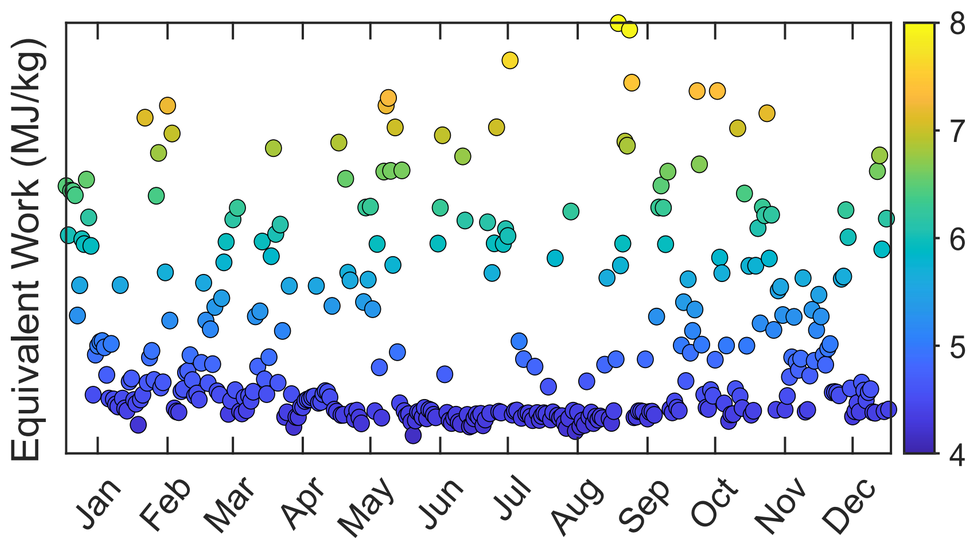
Effect of weather variability

★ Saint Fergus **(Scottish Cluster)** is our case-study location



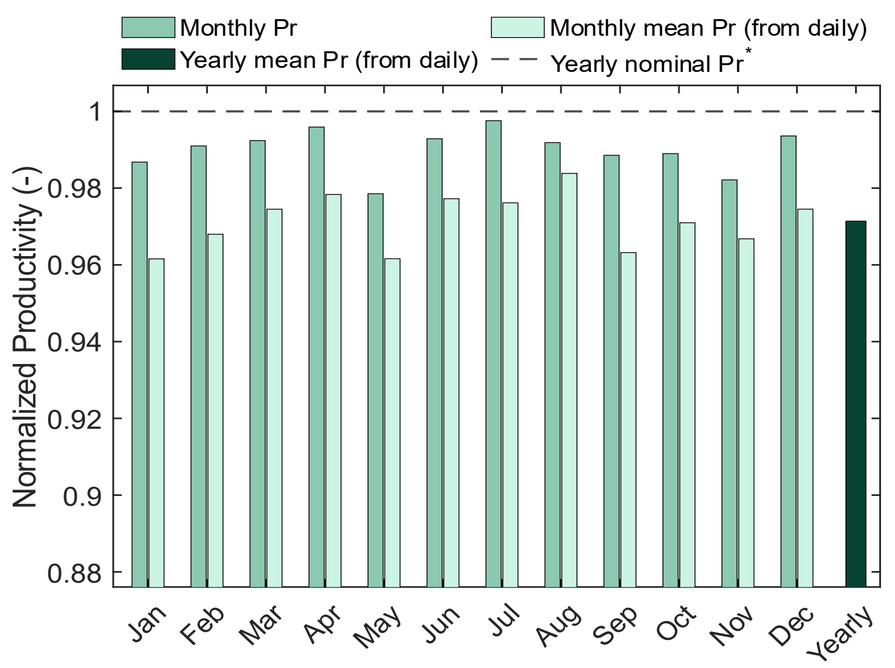
- The DAC system is optimized at the yearly nominal operating weather conditions **(T = 283K, RH = 82.81%)**

Seasonal conditions can drive a +100% increase in energy demand for DAC operation



Effect of weather data resolution

Productivity (Pr) using daily vs monthly-fixed weather data, normalized by the maximum yearly optimized value *



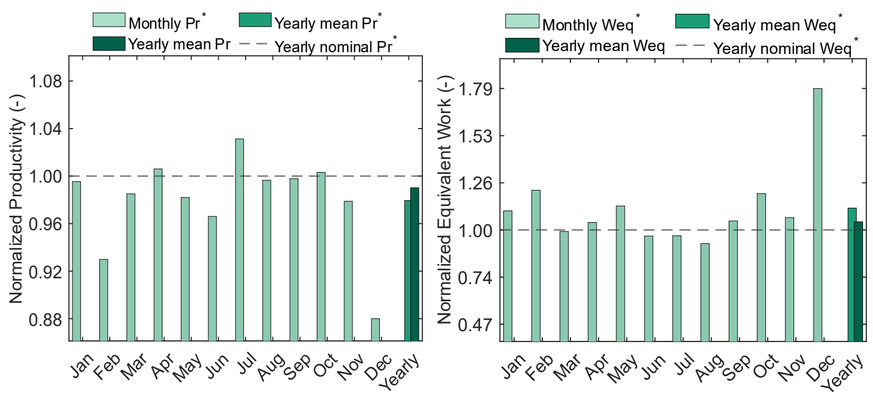
Yearly nominal Pr= 6.3 kg/m³/day

$$Pr(T_{monthly}, RH_{monthly}) \neq \frac{1}{30}\sum_{i=1}^{30} Pr\,(T_{daily,i}, RH_{daily,i})$$

$$Pr(T_{yearly}, RH_{yearly}) \neq \frac{1}{365}\sum_{i=1}^{365} Pr\,(T_{daily,i}, RH_{daily,i})$$

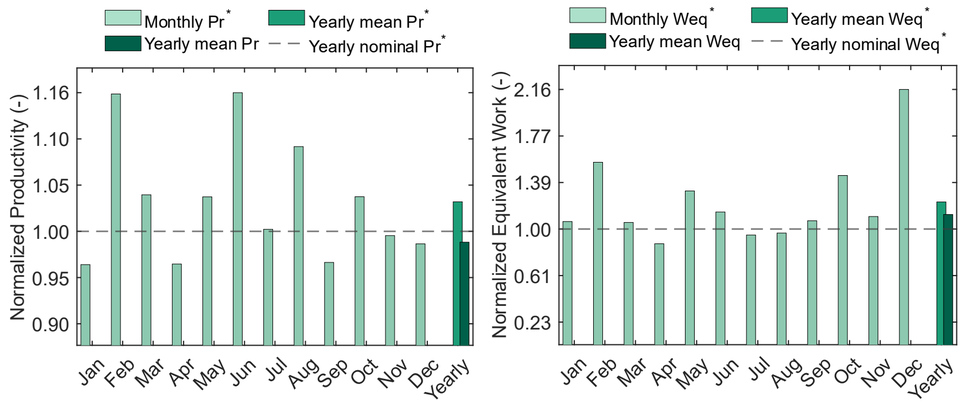
Is (monthly) optimization really needed?

Local peaks/dips of +3% Pr* and -3% Weq* – no yearly performance benefits



Case 1: Pareto point of Pr^*_{max}

Local peaks of +15% Pr* - yearly performance benefits
No annual energy benefits



Case 2* : Pareto point of Weq^*_{min}

Yearly nominal Pr= 4.2 kg/m³/day

Conclusions

1. Seasonal swings can **drive significantly performance**
2. Monthly (optima) KPIs do **not average into the annual** (optima) KPIs
3. Monthly **re-optimization** does not always guarantee better performance

[1] Climate Change Committee, 2025. Assessing the Feasibility for Large-scale DACCS Deployment in the UK. https://www.theccc.org.uk/publication/assessing-the-feasibility-for-large-scale-daccs-deployment-in-the-uk/

[2] Ward, A., Papathanasiou, M. M. and Pini, R. (2024) 'The impact of design and operational parameters on the optimal performance of direct air capture units using solid sorbents', *Adsorption*, pp. 1–20. doi: 10.1007/s10450-024-00526-y.

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