

Machine Learning Explains Negative Spatial Marginal Emissions Factors in Transmission-Constrained Decarbonising Power Systems

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Electrification is usually assessed with national average emissions factors, but the true short-run carbon impact of extra load depends on where the load appears and what the system is doing at that moment.

This work asks a simple question: **if demand rises by 1 MWh at a given GB Grid Supply Point, how does total national CO₂ change?**

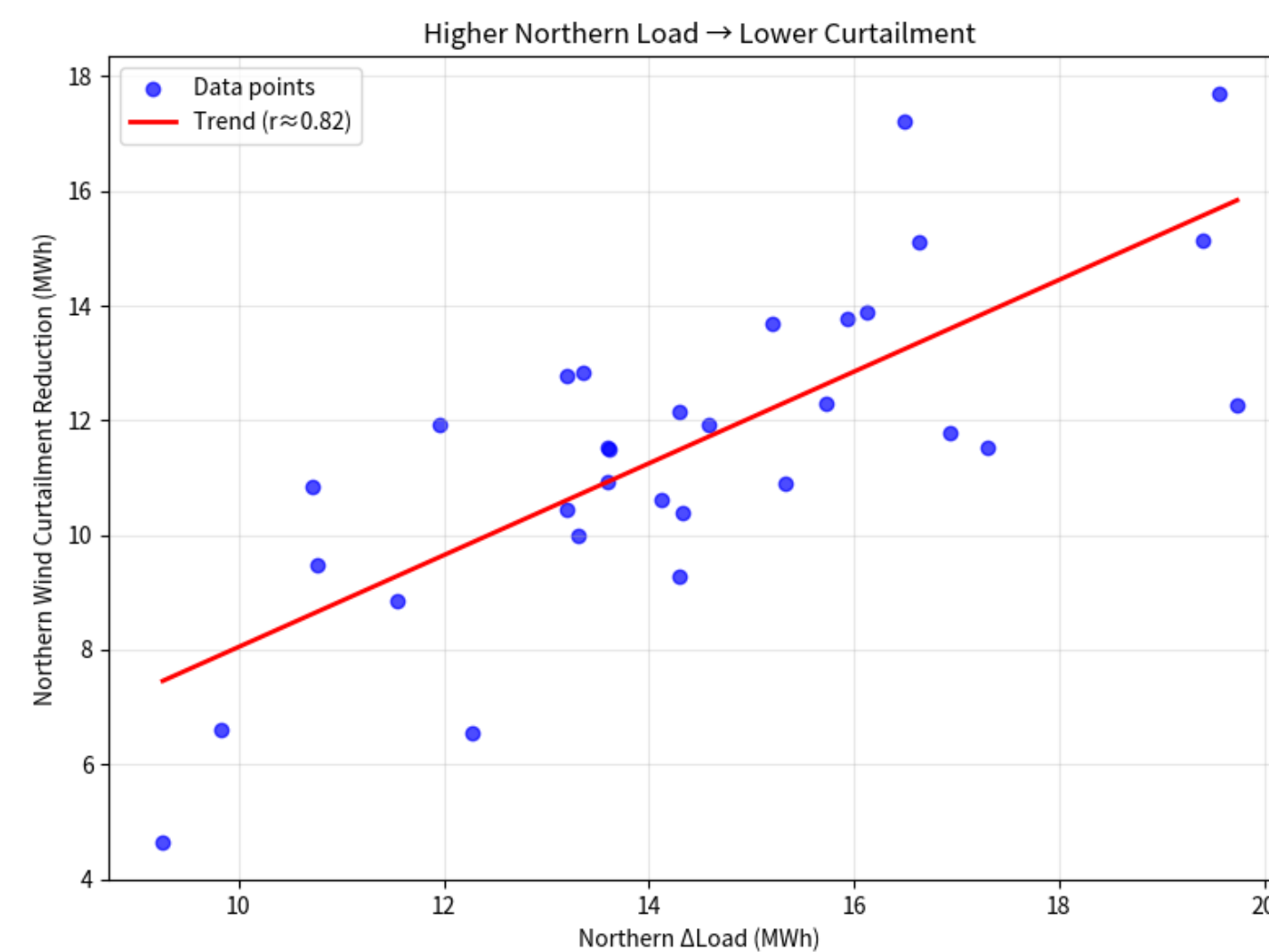
Using July 2025 half-hourly market and network data, we show that the answer is strongly state-dependent. Southern load tends to increase emissions because gas remains marginal. In contrast, some northern load changes can reduce national emissions, but only during a narrow transmission-constrained redispatch regime.

Key research question

- When and why does a negative marginal emissions factor appear in the north of GB?

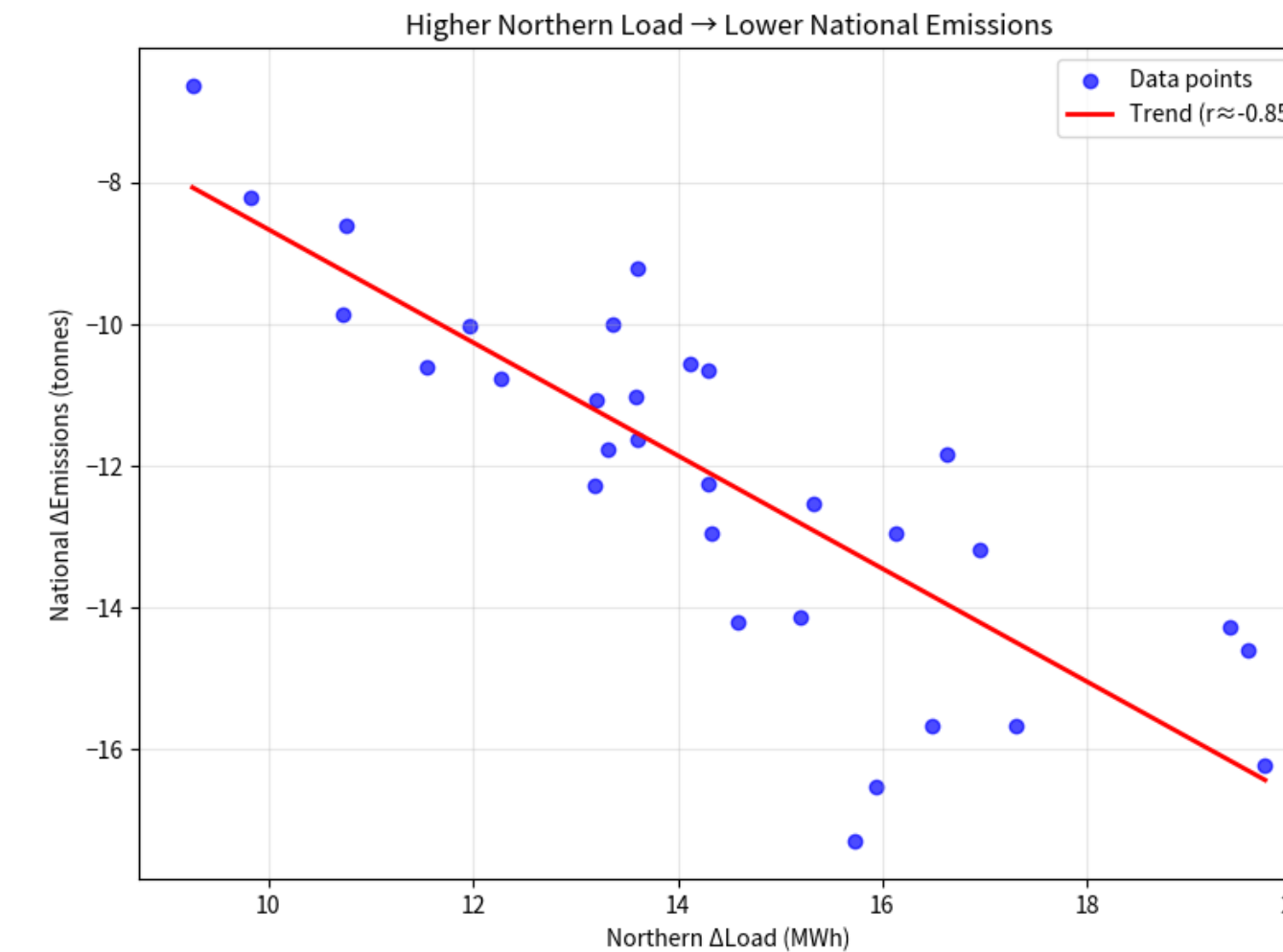
GSP	MEF	Interpretation
London (_K)	+0.41	Gas marginal
South East (_L)	+0.38	Gas marginal
South Wales (_M)	+0.35	Positive
North Scotland (_A)	-0.12	Negative
South Scotland (_B)	-0.09	Negative

- As Northern GSP load increases, wind curtailment volume decreases strongly (positive correlation). This is the key constraint-relaxation step.
- As Northern GSP load increases, national total emissions fall (negative correlation). This helps us prove the displacement of Southern gas by additional Northern wind export.



Data and method

- P315 GSP demand, P114 TRA, BOALF acceptances
- NESO Scottish transfer and B6 boundary tightness
- GB wind outturn plus fuel-price controls
- OLS first, then XGBoost + SHAP as a non-linear check



State Conditioned Approach

State	% hours	MEF	Meaning
S0	66%	+0.34	Positive
S1	12%	+0.02	Near zero
S2	13%	-0.15	Negative
S3	9%	0.00	Zero

Monthly average for North Scotland = -0.12 kgCO₂/kWh, but that average is driven by S2 hours only.

Econometric identification

$$\text{National } \Delta \text{Emissions} = \alpha + \beta \Delta \text{LoadNorth} + \theta (\Delta \text{LoadNorth} \times \text{curtail_active} \times \text{near_B6}) + \text{controls} + \varepsilon$$

$$\theta \approx -0.17 \text{ kgCO}_2/\text{kWh interaction term}$$

Main finding

Negative spatial MEFs arise only when Scottish wind curtailment is active and B6 is near, but not fully at, its southbound limit.

- Unconstrained = positive.
- Fully binding = zero.
- Near-limit curtailment = negative.

XGBoost + SHAP methodology

Rank	Feature	Importance (%)
1	s2_flag (near-B6 × curtail)	34.2
2	delta_load_north	21.8
3	near_b6_flag	12.9
4	curtail_active	9.7
5	wind_outturn_gb	8.1
6	gas_price	5.4
7	delta_total_demand	3.6
8	co2_price / biomass_price	2.3

Implications

Higher load north of B6 can reduce national CO₂ only during a narrow constrained redispatch regime. As north-south transmission is reinforced, these S2 hours should shrink, flattening spatial MEFs while improving wind integration and system efficiency.