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Estimating the Potential of Residential Load Balancing

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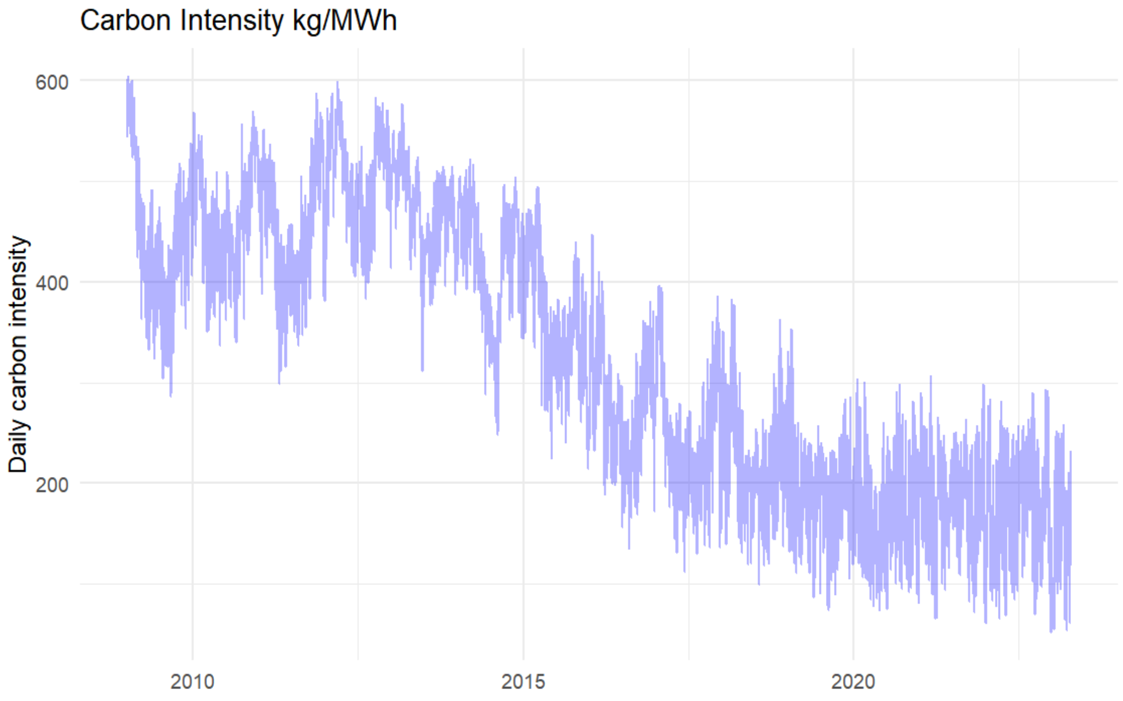
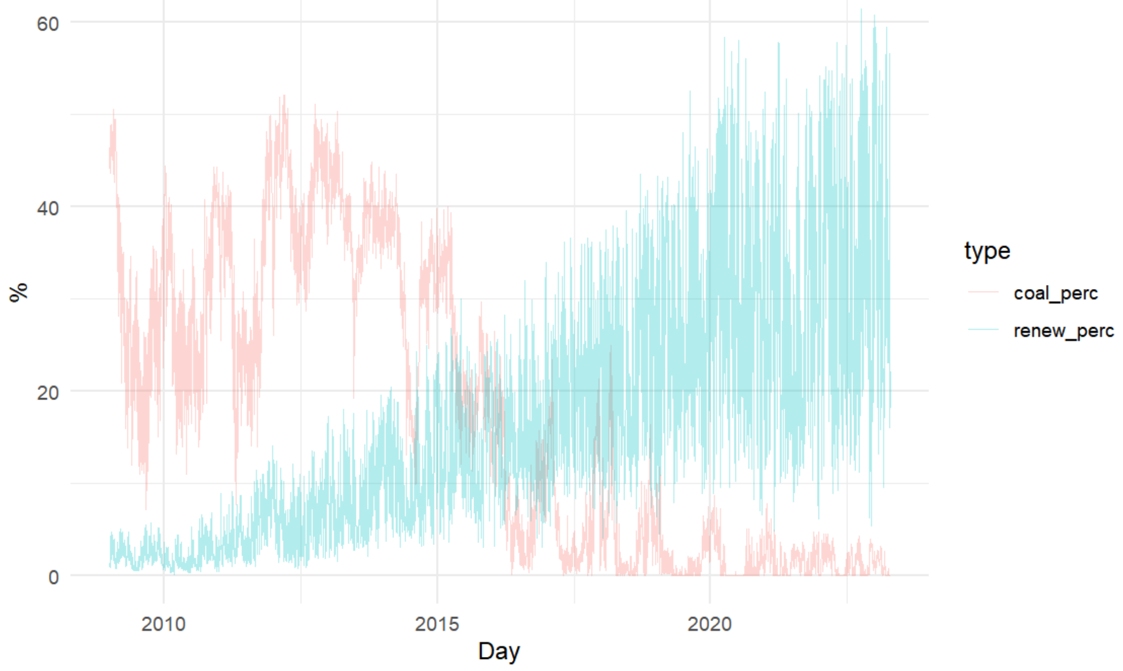
UK energy system has seen a profound transformation in the last 15 years

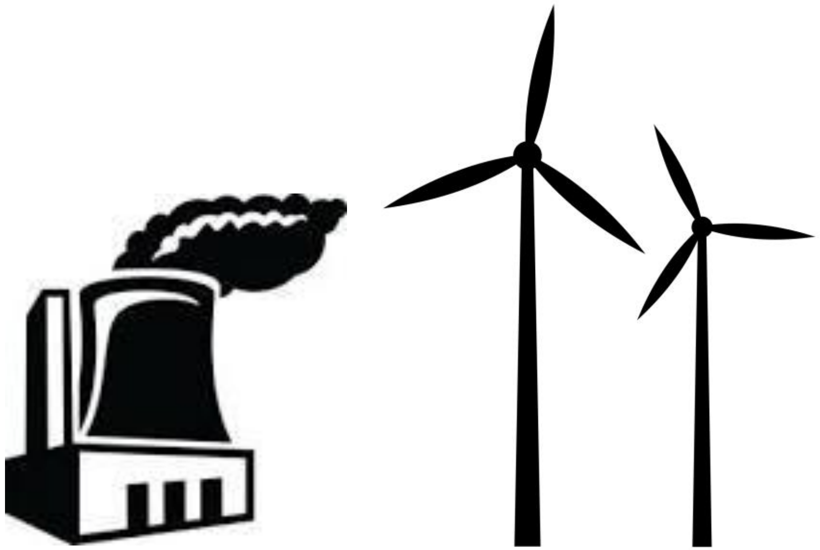




Coal is being phased out and renewables are being phased in

Intermittency of renewables → *when* electricity is used is an increasingly important driver of carbon impact

Carbon impact of demand shifting relies on estimating marginal emissions



Period *t*

Period *t* + 1

- Net effect of shifting 100kW of energy demand from *t* to *t* + 1 depends on energy demand and supply in *t* + 1
- If wind turbines are operating at full capacity in *t* + 1 and system operator needs to ramp up gas turbines, there may not be any net effect on emissions

Encouraging load balancing

Why?

- Shifting consumption to times when grid is less carbon-intensive could deliver **climate and local environmental benefits**
- To the extent load balancing **reduces peak demand**, it could deliver cost reductions

How?

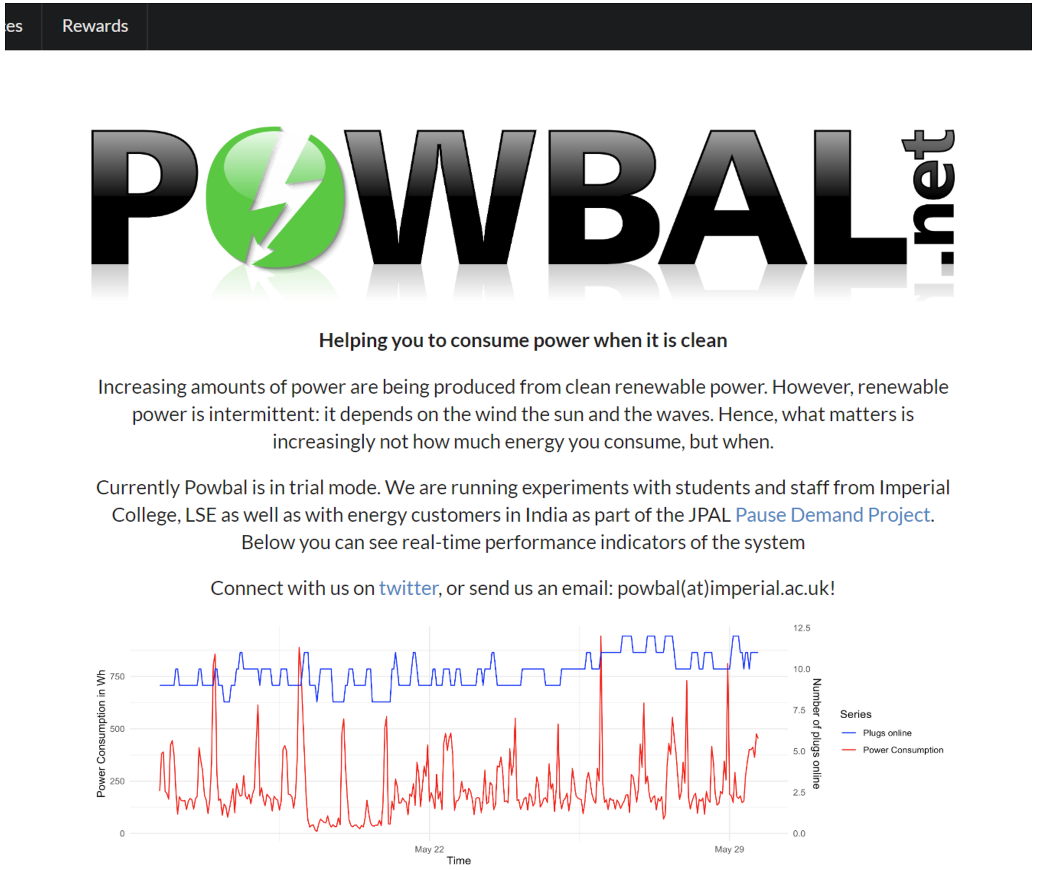
- **Dynamic pricing** provides incentives to shift consumption
- Returns could be larger for consumers that invest in rooftop solar, storage/EVs
- Small changes in energy demand enabled by **automation technologies** could result in sharp supply cost reductions

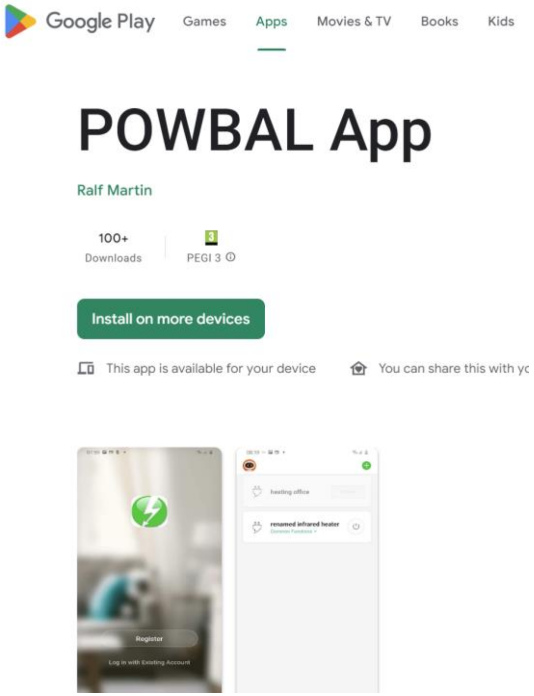
Domestic flexibility could reduce peak electricity demand by up to 23%, new study shows

The UK's largest domestic flexibility study has found that active households could significantly reduce peak electricity demand by using time-of-use tariffs.

Randomised control trials on automated load control underway…

- Offer smart plugs that can monitor and control end users' power consumption
- Reward users per kWh of energy consumption avoided during automated switch-off events
- 600 participants in the UK & India





Decarbonisation potential of load balancing

Conventional approach for estimating the marginal carbon intensity of electricity generation (Graff-Zivin et al, 2014; Holladay and LaRiviere, 2017):

$$\mathrm{CO2_t = \beta_{p(t)} \times \ Q_t + \alpha_p + \epsilon_t}$$

- Higher shares of renewables energy on the grid makes model assumptions less plausible
- Weather is a key determinant of energy demand and supply
  - Sunny weather → more solar → less CO2
  - Sunny weather → more air conditioning → more power required
  - Omitting weather could generate a spurious correlation between $\mathrm{Q_t}$ and $\mathrm{CO2_t}$
- Increasing demand-side response (batteries, EV charging) could further confound the relationship

Our approach

1. Adding weather controls:

$$CO2_t = \beta_{p(t)} \times \ Q_t + \alpha_{p(t)} + \gamma W_t + \epsilon_t$$

2. “Smart” instruments

- Smart meter data from large sample of households $\mathrm{Q_{it}}$
- Not on flexible tariffs
- Use moments of $\mathrm{Q_{it}}$ as instruments for $\mathrm{Q_t}$

$$CO2_t = \beta_{1\,p(t)} \times \ Q_t + \beta_{2\,p(t)} \times \ Q_t^2 + \ \alpha_{p(t)} + \sum_W \bar{W}_t \ \times \ \left[\beta_{W1\,p(t)} \times \ Q_t + \ \pi_{W\,p(t)}\right] + \eta_t$$

- $CO2_t$ and $\mathrm{Q_t}$ specified in log terms
- $\bar{W}_t$: temperature, precipitation, wind speed, humidity and solar radiation averaged over 9x9km grid points
- All parameters are estimates specific to 48 daily 30-minute periods
- Re-estimate parameters for every year using moving 2-year time window

Smart instruments

Household-specific regressions of electricity consumption on binned weather variables:

$$Q_{it} = \sum_j \beta_j T_t^j + \sum_k \beta_k P_t^k + \sum_l \beta_l H_t^l + \sum_m \beta_m W_t^m + \sum_n \beta_n S_t^n + \epsilon_{it}$$

Instruments for each period *t* are constructed by aggregating predicted residuals (i.e., variation in energy demand not explained by weather):

$$IV_t = \frac{1}{U_s} \sum_{i \in U_s} \hat{\epsilon}_{it}$$

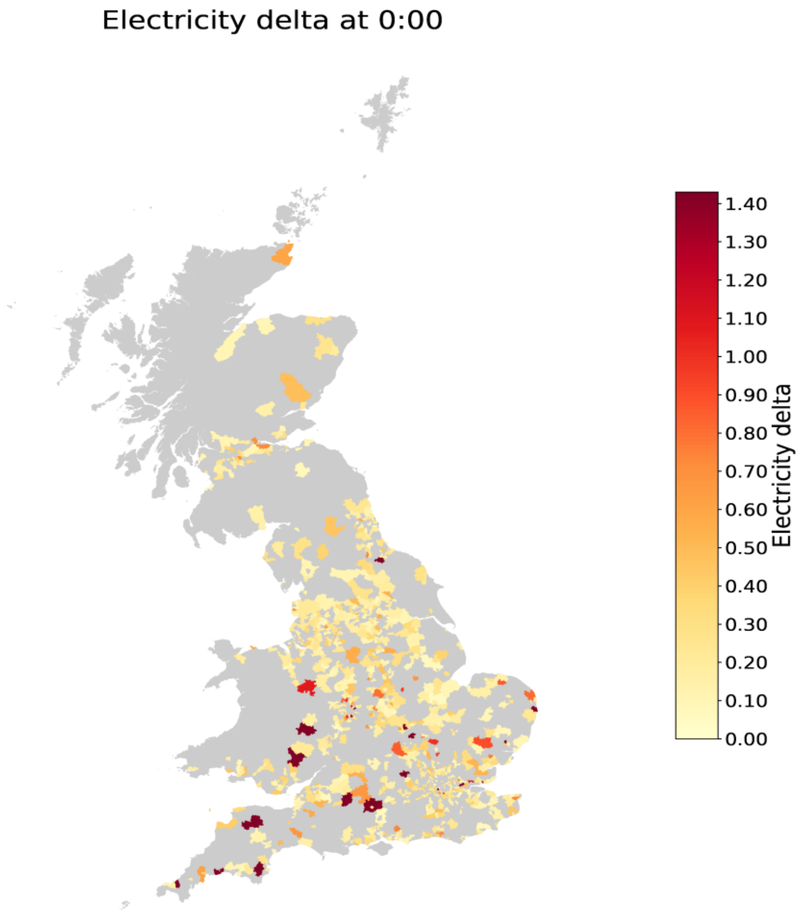
240 first stage regressions: 5 parameters at 48 daily half hourly periods, F-statistics above 10

Data

Half-hourly grid-level emissions and output data from National Grid

Half-hourly weather from ERA5 Land

Smart meter data for 1,100 Octopus Energy residential customers on fixed tariffs from 2019 to 2020

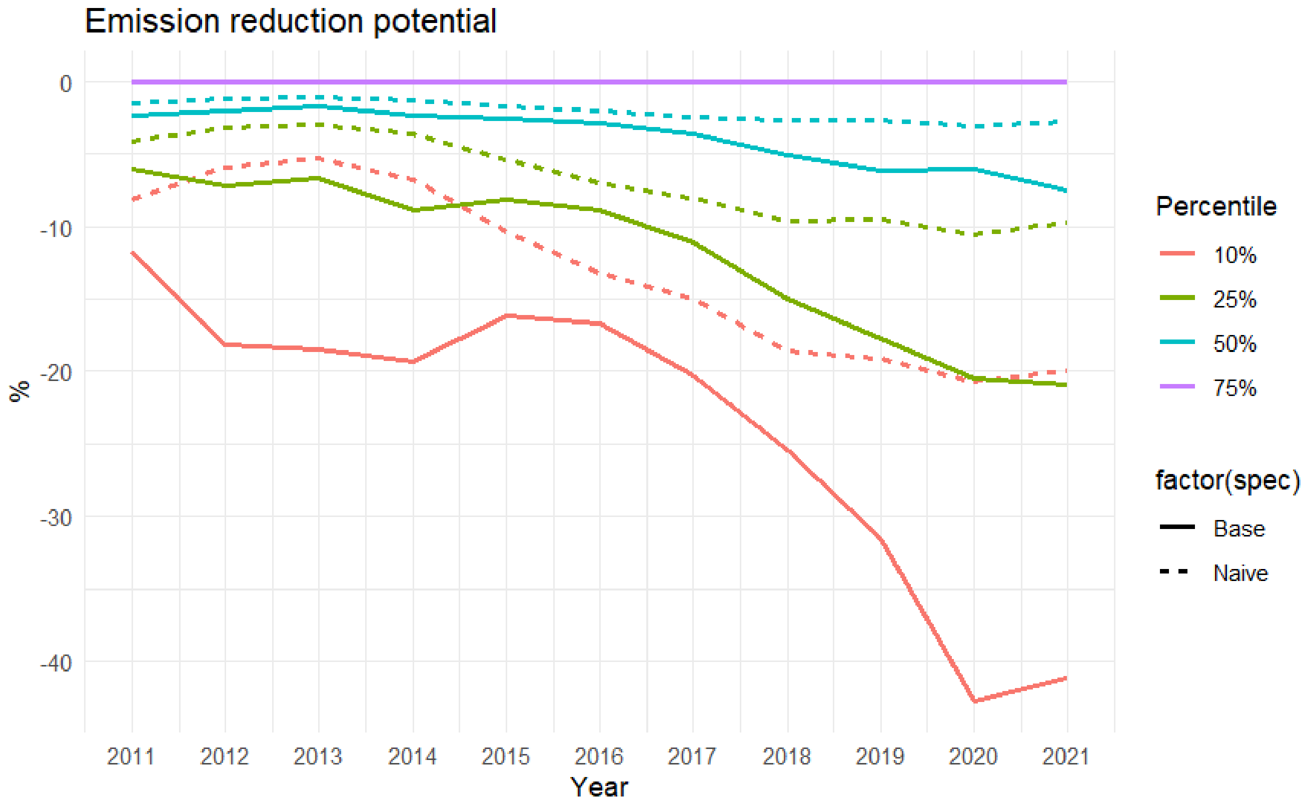


Thought experiment

Suppose we consider delaying consumption in a 30-min interval equivalent to 1MW (i.e., about 140 home electric car chargers) by up to 3 hours

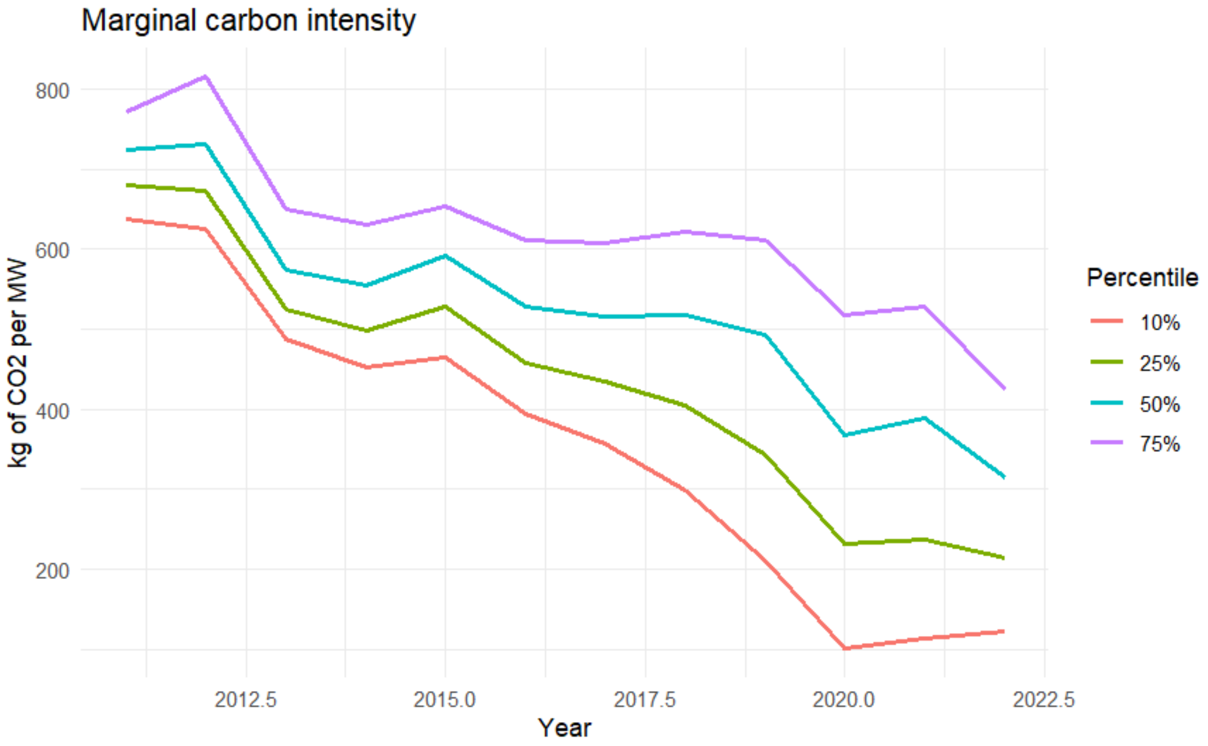
How much would that reduce CO2 emissions in that interval?

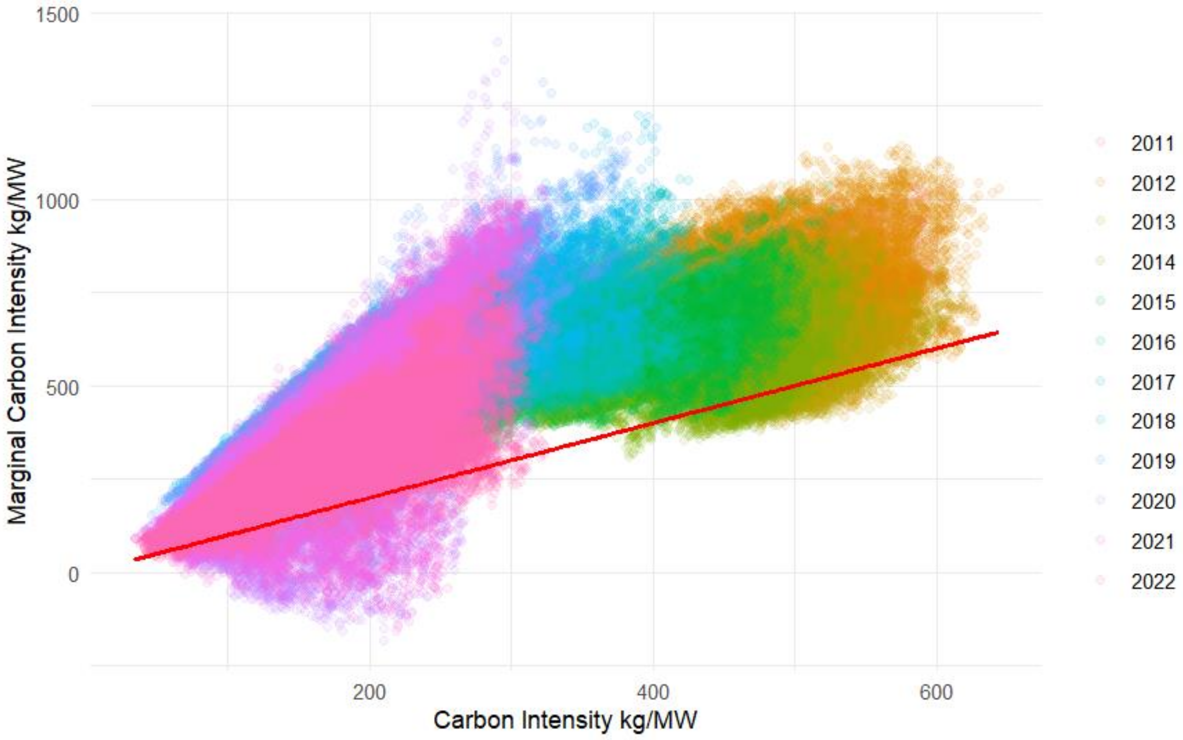
- **Naïve case**: assume marginal emissions are equal to average emissions
- **Baseline case**: no weather controls or interactions
- Potential for reducing emissions by delaying consumption has increased over time



(Baseline) marginal vs average emissions

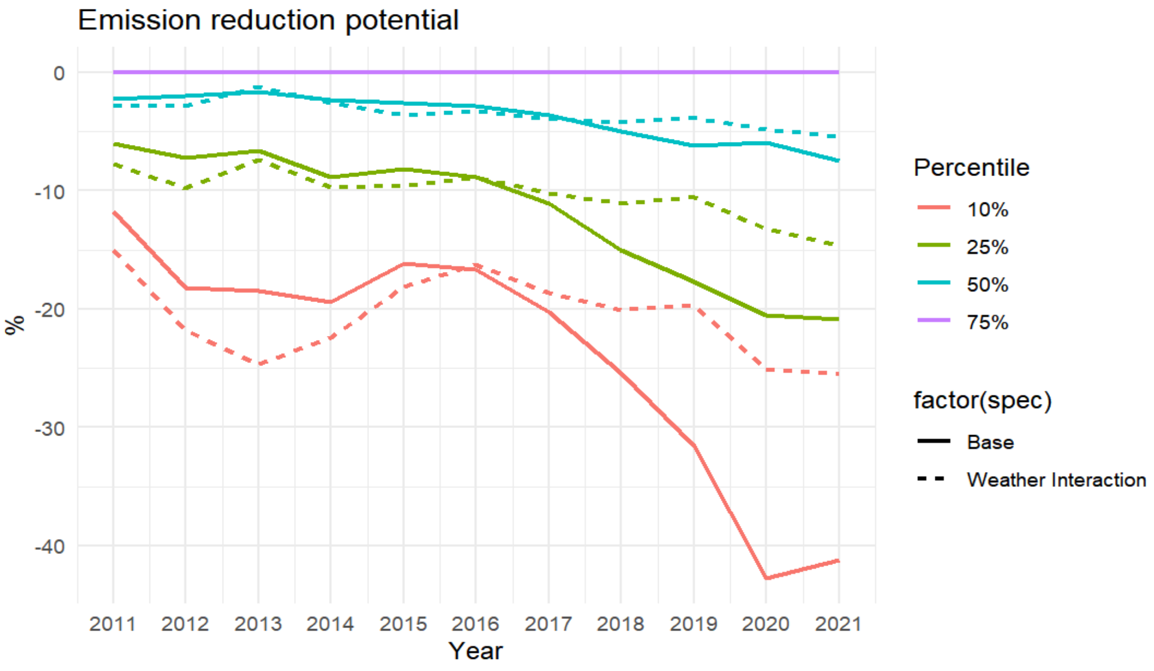
- While marginal emissions have reduced over time, dispersion has increased
- In recent years, marginal emissions have sometimes been lower than average emissions

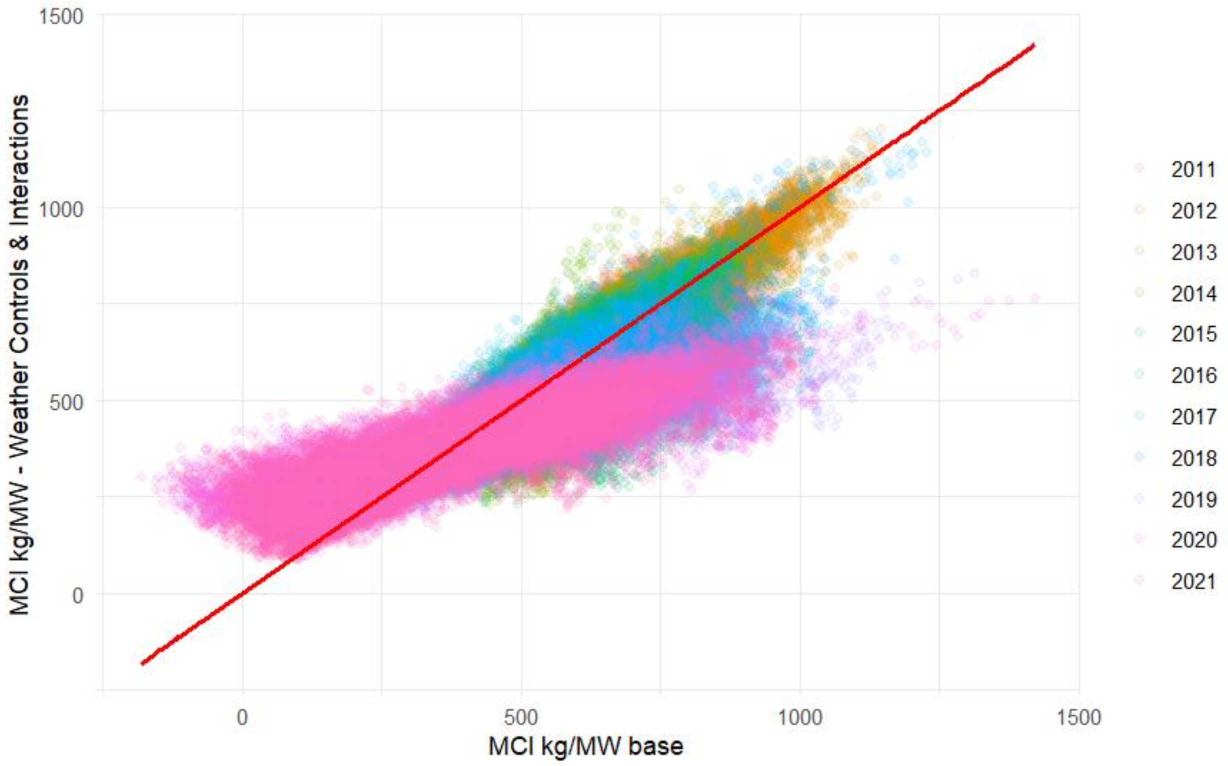




Baseline vs weather controls and interactions

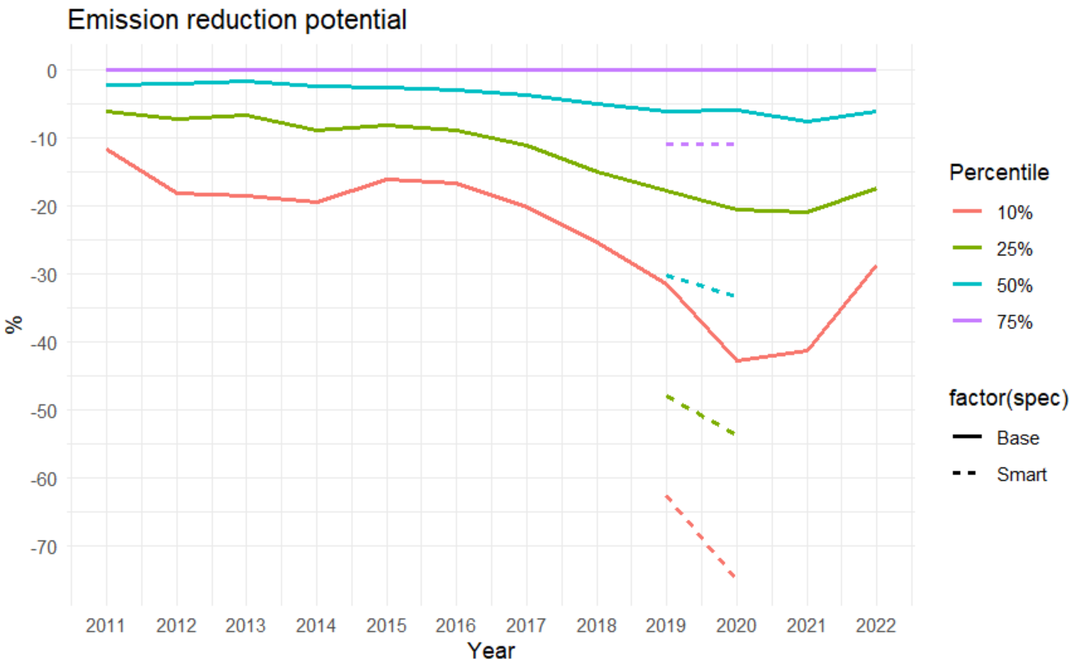
- Smaller estimates of emissions reduction potential with weather controls + interactions (i.e. less benefit from short-term balancing) relative to baseline, but still larger than naïve case

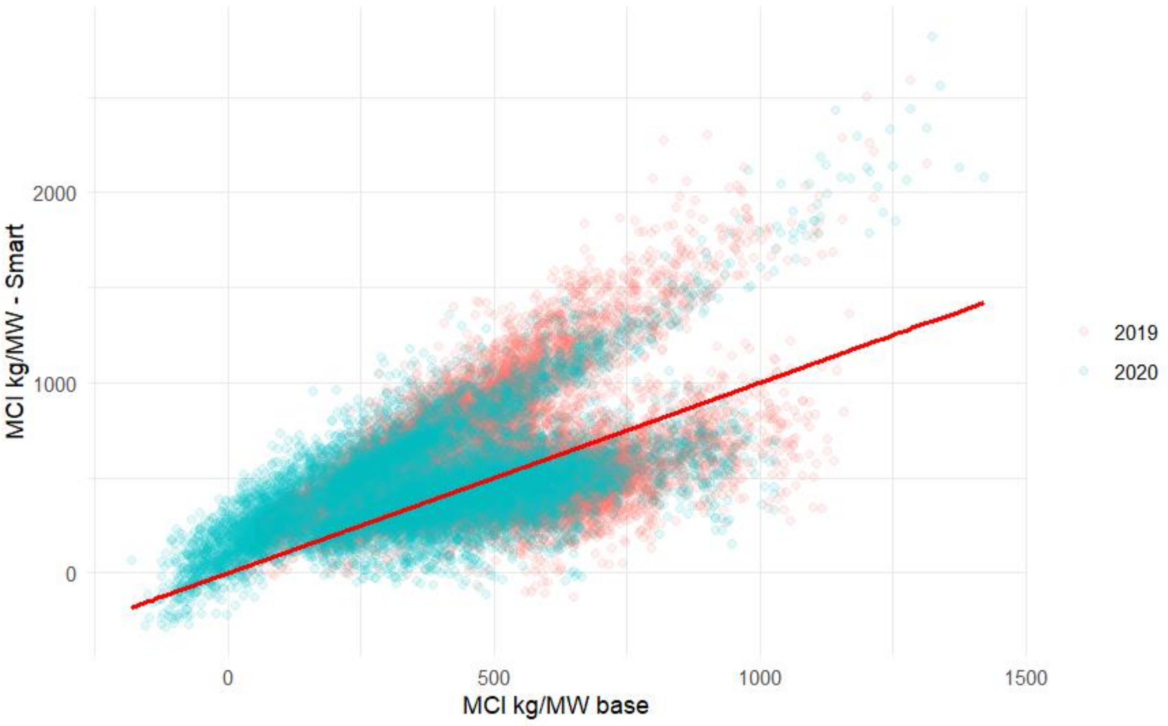




Baseline vs smart instruments

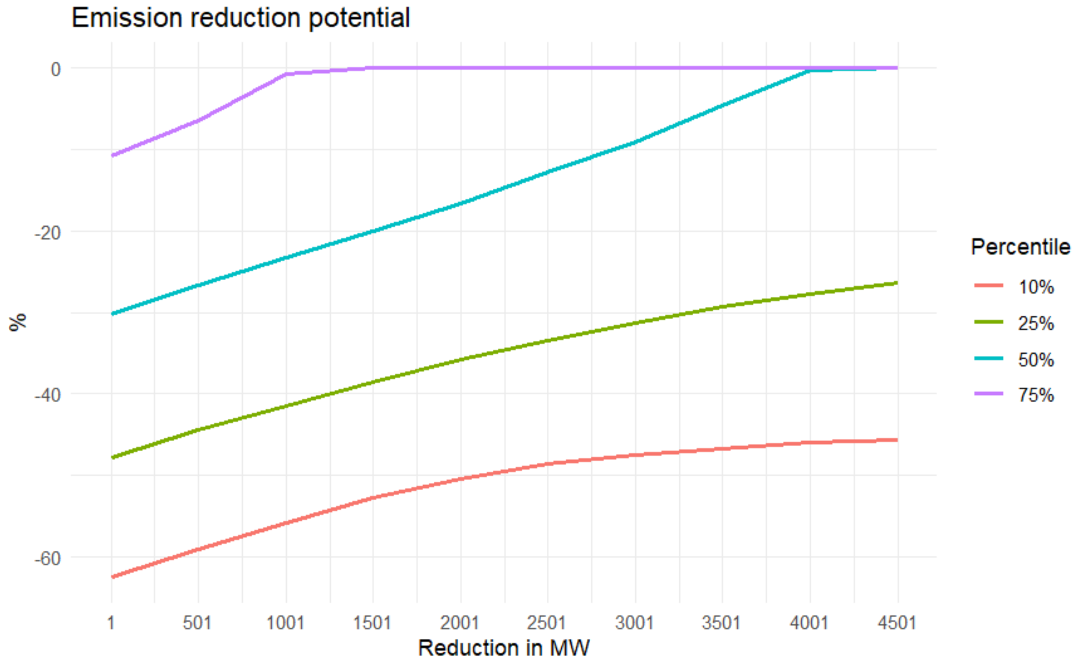
- Substantially larger emissions reduction potential with smart instruments relative to baseline
- For half of the year, there is scope to reduce (marginal) emissions by 30% or more by simply delaying consumption for short periods of time





Non-marginal changes in demand

- Using 2019 smart instruments results, we repeat earlier thought experiment by increasing demand from 1 to 4,500 MW
- Same emissions reductions can be achieved in fewer periods when attempting to shift increasingly larger amounts of power
- Even when trying to reduce 1.5 GW, it is possible to achieve emissions reductions of 20% or more in half of time periods.



Conclusion

- The energy system in the UK has decarbonized substantially and similar transformations are underway in other countries
- This shift towards renewable energy affects not only average, but also marginal emissions, and biases involved in estimating marginal emissions conventionally increase
- Our paper provides two avenues for improvement:
  - Adding weather controls
  - Using increasingly available smart meter data to construct smart instruments
- Accounting for marginal effects and biases on net suggests that scope for short-term load balancing is substantially larger than suggested by “naïve” carbon intensity differences
- Policy implications for how we can target long-run investments in electrification vs short-run incentives for load balancing

Thank you

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