Covid-19 lockdown: impacts on GB electricity demand and CO_2 emissions

RESEARCH

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ABSTRACT

In early 2020 a wide range of social and economic restrictions were implemented in most countries in response to the global coronavirus pandemic (Covid-19). This paper uses national electricity generation data to examine the extent to which overall British electricity consumption deviated from 'normal' consumption patterns during the UK's spring lockdown period, and how the combination of consumption reduction and variation in carbon intensity affected greenhouse gas emissions (GHG) associated with electricity consumption. The paper shows that ongoing trends in the reduction of electricity demand and generation carbon intensity mean that lower year-on-year demand and lower emissions would have been expected even in the absence of Covid-19. Controlling for this, the paper estimates lockdown-driven below-trend electricity reductions of up to 20% in the morning peak period, 11% in the daytime and 9% in the evening peak period in April, declining to 6%, 4% and 4%, respectively, by June. These correspond to marked reductions in morning (06:00–08:00 hours) and daytime demand during all restriction periods studied, but relatively smaller reductions in evening demand, and some evidence of a relative increase on Friday and Saturday evenings.

PRACTICE RELEVANCE

The observed changes in demand are likely to be repeated in future national or local restriction periods and provide insights of value for grid and local distribution network management. This is especially true if such restrictions are required in spring 2021, as looks increasingly likely, but are also relevant to the winter 2020–21 heating season, which is likely to exacerbate the demand for electric heating, although gas remains the dominant heating fuel source in homes. However, unlike fossil fuel-based transport, the changes observed do not translate to direct emissions reductions due to the mixture of fuels used to generate electricity in Britain. Electricity generation emissions were either close to or above the trend during this period, and the effect is especially noticeable for the traditionally carbon-intensive evening peak period.

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1. INTRODUCTION

In early 2020, a wide range of social and economic restrictions were implemented in most countries in response to the global coronavirus pandemic (Covid-19). In general these resulted in complete 'non-essential travel' bans and enforced closure of most workplaces, public spaces and schools (Hale *et al.* 2020). By late March 2020, it was reported that over 20% of the world's population was living under 'lockdown' measures (Davidson 2020), with all activity outside certain essential sectors, such as agriculture, essential manufacturing and health services, conducted either from home or not at all.

In the case of the UK, on 16 March 2020 the government invited people to voluntarily use social distancing measures to reduce the spread of Covid-19 (Prime Minister's Statement on Coronavirus 2020a), before imposing a full lockdown from 00:00 hours on Tuesday, 23 March 2020 (Prime Minister's Statement on Coronavirus 2020b). This resulted in restrictions on human activities and movement, which, at that time, were applied consistently across the constituent countries of England, Scotland, Wales and Northern Ireland.

Analysts in the media, industrial, non-governmental organizations (NGO) and academic sectors quickly reported apparent subsequent reductions in a range of indictors, such as air pollution levels, both in the UK (Duncan 2020) and abroad (BBC News 2020), and in demand for electricity (Jones 2020). The latter suggested that electricity demand fell by up 15% in the UK and by 13% in the EU-27 over the 30 days to 29 April 2020 compared with the same period in 2019.

It is not surprising, therefore, that recent peer-reviewed analysis of the impact of Covid-19 on European Union (EU) (Bahmanyar *et al.* 2020), Brazilian (Carvalho *et al.* 2020) and Australian (Snow *et al.* 2020) electricity consumption patterns all report changes in daily and half-hourly demand, which vary according to climatic, cultural and seasonal contexts. However, this work fails to account for underlying trends in demand that may have already led to reductions in demand in 2020 compared with previous years. As a result, the estimates of demand reduction and any consequent reduction in generation emissions may be overstated.

2. ELECTRICITY DEMAND UNDER COVID-19 RESTRICTIONS: WHAT WOULD BE EXPECTED?

Overall, reductions in both demand and emissions compared with previous years would be expected due to underlying reductions in electricity demand and the carbon intensity of generated electricity (Staffell 2017). Downward trends through spring 2020 would also be expected simply due to seasonal effects such as temperature and lighting (BRE 2013a, 2013b). The latter in particular would have reduced evening electricity demand during the course of the initial UK 2020 lockdown periods with a distinct reduction in the evenings likely to be visible at the daylight savings break (29 March 2020).

Clearly, the extent to which restrictions on movement impact electricity demand depends on the uses to which electricity is put in a national context. In the UK, domestic demand constituted 30% of total electricity demand in 2019 (a 10% reduction from 2010), with industry (27%) and commercial (21%) the next largest use sectors (BEIS 2020a). Industrial use comprised 'other' (39%), engineering (19%), chemicals (16%), food (13%) and paper (11%). Transport comprised just 2% of the overall total, of which rail comprises 93%.

Whilst lockdown restrictions would reduce demand from some industrial and most non-essential commercial processes, in nations where electricity provides substantial heating or cooling services the finding that residential demand increased during national lockdowns is not unexpected (Bahmanyar *et al.* 2020; Snow *et al.* 2020). However, natural gas remains the main heating fuel for 85% of English households, with 5% using electric storage heaters and less than 1% electric heat pumps in 2019 (MHCLG 2020). Further, detailed studies of UK domestic electricity use in 2011 suggested that, at the time, heating contributed 3% to evening peak residential electricity demand, whereas audiovisual appliances and lighting contributed 14% each and cooking 20% (Palmer *et al.* 2013b). Since storage heaters tend to draw power in overnight off-peak periods, it is unlikely that the 5% of households using them would have altered operation, although it is feasible that additional midday boost heating would be required in the winter. It seems unlikely, therefore, that additional electric heating demand in homes would be visible in aggregated national-demand data. However, use of plug-in heating and cooling appliances or other home-based activities may contribute to increased residential demand, as the Australian work showed (Snow *et al.* 2020).

While there are little public data available on the relative contribution of different sectors to overall demand profiles in the UK, the shape of sectoral mean-demand profiles suggests that such suppression would accentuate evening peak-demand periods when non-domestic demand is already tending to reduce (see the supplemental data online: electricity load profiles by class). Further, one would expect the evening peak period to see much less suppression since it is known to be strongly driven by temporally fixed household energy-using practices (Darby & McKenna 2012; Palmer *et al.* 2013a; Torriti 2015; Nicholls & Strengers 2015). Many household activities, such as food preparation, media use as well as those that require lighting, are still likely to take place at this time, as would increased in-home leisure while hospitality venues remained closed. It is possible that some activities such as showering, household chores (Anderson 2016) and food preparation may have shifted from their 'normal' temporal location due to disruption to work and school routines, and also increased in frequency and extent.

On the other hand, the significant disruption to work patterns for much of the population, together with the lack of space-conditioning requirements for many workplaces, reductions in peak-time electrified transport and the closure of schools, may all have led to lower morning peak consumption. This is especially true where household practices are no longer temporally constrained by school or work schedules or drop-off/commute times (Anderson & Torriti 2018).

The analysis of the significance of Covid-19 restrictions for both electricity demand and associated emissions therefore needs to take account of underlying trends in both demand and carbon intensity to assess the true impact of the Covid-19 lockdown period. This will enable an estimation of how far below trend any observed but temporary reductions might have been. Further, to provide insights for electricity system operation in future lockdown periods, it is important to understand when these reductions have taken place, which energy usages may have changed, even if temporarily, and what this implies for future energy-use scenarios.

This paper responds to these knowledge gaps by addressing the following research questions:

- To what extent has Great Britain's (GB)[1] electricity consumption shown deviation from 'normal' consumption patterns during the spring 2020 lockdown periods?
- To what extent has the combination of consumption deviation and variation in carbon intensity reduced greenhouse gas emissions (GHG) associated with electricity generation?

The remainder of the paper is structured as follows. The next section introduces the data and analytical methods used. It then presents the results of the analysis structured according to the above questions. It concludes with a summary of the implications of the results and an outline of further research required.

3. DATA AND ANALYTIC METHODS

3.1 DATA

This research uses half-hourly electricity supply and carbon-intensity data for GB (*i.e.* England, Wales and Scotland, but not Northern Ireland) for 1 January 2017–30 June 2020 published by the UK's electricity system operator (National Grid ESO 2020a) and time-series data on the level of Covid-19 restrictions in the UK published by the Oxford Covid-19 Government Response Tracker (Hale *et al.* 2020) to define the lockdown periods of interest. The electricity generation data were processed from their original MW per fuel per half-hour form to give total GWh and associated tCO_2e emissions per half-hour (see the supplemental data online).

In order to clarify trends within critical electricity system 'peak demand' periods, half-hourly values were coded into the early morning (00:00–06:59 hours); morning peak (07:00–08:59 hours); daytime (09:00–15:59 hours); evening peak (16:00–19:59 hours) and late evening (20:00–23:59 hours).

Table 1 shows mean half-hourly electricity use in GWh for these periods by year since 2017, and it confirms the continued steady decline in overall consumption in all periods (Staffell 2017). It also illustrates that from an overall system perspective, morning 'peaks' do not necessarily represent higher mean consumption compared with the daytime period due to the school/workplace, industrial and commercial daytime use of electricity (see the supplemental data online: electricity load profiles by class).

YEAR	EARLY MORNING	MORNING PEAK	DAYTIME	EVENING PEAK	LATE EVENING
2017	12.49	16.19	17.63	18.14	14.56
2018	12.50	16.21	17.65	18.02	14.45
2019	12.29	15.92	17.32	17.62	14.27
1 January–30 June 2020	*11.67*	*14.77*	*16.31*	*16.73*	*13.63*

Table 1: Mean half-hourly GWh electricity consumption by year, 2017–19.

Table 2 reports mean $MtCO_2e$ per half-hour for the same time periods. It shows both the relatively high carbon intensity of the evening peak period and the general decline in mean half-hourly emissions deriving from an overall 59% reduction in carbon intensity from about 299 gCO_2e/kWh in 2017 to about 214 gCO_2e/kWh in 2019 (see Table S1 in the supplemental data online), confirming and extending the previous analysis (Staffell 2017).

YEAR	EARLY MORNING	MORNING PEAK	DAYTIME	EVENING PEAK	LATE EVENING
2017	3.13	4.62	4.77	5.43	4.02
2018	2.68	4.16	4.29	4.96	3.49
2019	2.37	3.74	3.85	4.33	3.14
1 January–30 June 2020	*1.97*	*2.92*	*3.00*	*3.60*	*2.65*

Table 2: Mean half-hourly $MtCO_2e$ by year, 2017–19.

Figure 1 shows mean monthly electricity consumption in GWh against mean monthly heating degree-days for the entire period. It provides initial evidence of the scale of 'below normal' electricity demand in April–June. As would be expected, there is a correlation between the two in every year except 2020 (points labelled), with March somewhat below the expected curve and April–June substantially below. Winter 2019–20 was unusually mild with fewer frosts than average, and February was unusually wet and stormy. April and May were both warmer (1.0–1.7°C) and sunnier (143–151% of the average) than usual, although there was a cold spell between 11 and 15 May (MetOffice 2020). June, on the other hand, was closer to trend (1°C warmer than average), with a mixture of hot, sunny weather, showers and longer spells of rain. In combination with the low level of domestic electric heating in GB (see above), this is interpreted this as evidence that if the Covid-19 lockdown did increase demand for residential electric heating or cooling, this effect was swamped by the suppression of other demand.

Finally, the stringency index from the Oxford Covid-19 Government Response Tracker was used to define the UK's Covid-19 lockdown periods used in this analysis. This index focuses on restrictions that reduce social interaction and travel (see the supplemental data online: Oxford Covid-19 Government Response Tracker) and the paper used the period definitions described in ***Table 3*** to estimate levels of reduction compared with the same periods in previous years.

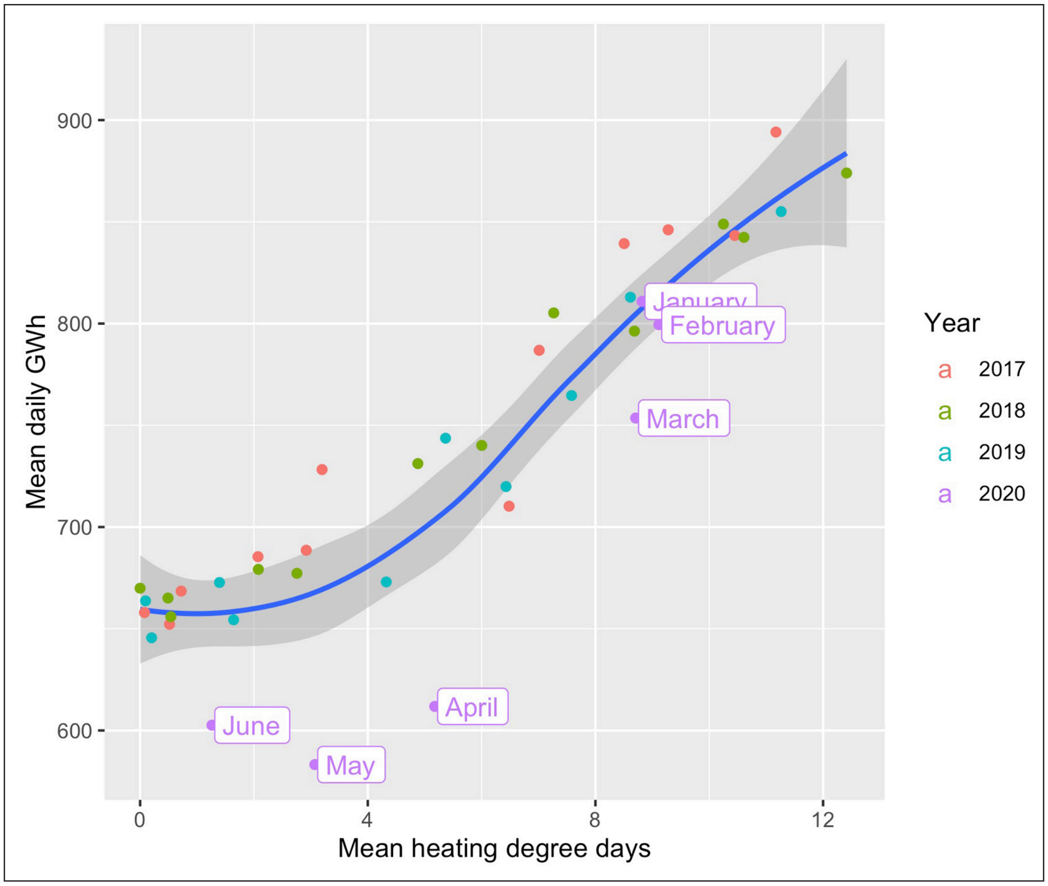

Figure 1: Plot of mean daily GB electricity consumption (GWh) against average monthly heating degree-days, 1 January 2017–30 June 2020.[a]

Note: [a] Smoothed fit line for all years except 2020 via locally estimated scatterplot smoothing (LOESS). Implemented via geom_smooth() from the R ggplot2 package (Wickham 2009).

Sources: Authors' calculations using National Grid Electricity System Operator (ESO) data and average temperatures and heating degree-days and deviations from the long-term mean (ET 7.1) (BEIS 2020b).

3.2 ANALYTICAL METHODS

In order to take account of longer term multi-year trends, the paper uses Theil–Sen trend plots from the openair R package (Carslaw & Ropkins 2012) to visualise change over time. It then uses the derived median slope model to estimate the expected monthly values for 2020 given historical trends and to calculate the percentage difference between these expected values and the actual observations. This allows the analysis to take account of underlying decreasing trends in both demand and carbon intensity, which would otherwise lead to potential overestimates of lockdown effects. This method does not support sub-monthly analysis and so it was not possible to use the strict Oxford Covid-19 Government Response Tracker derived period definitions for this analysis, although as ***Table 3*** shows, Period 1 corresponds to all April, Period 2 corresponds to the latter half of May and Period 3 corresponds to all June.

DATE	PERIOD	RATIONALE
Up to 22 March 2020	Pre-lockdown	No or minor restrictions (not enforced)
23 March–12 May 2020	Period 1	Major restrictions on travel, closure of non-essential workplaces and schools
13–27 May 2020	Period 2	Some relaxation of 'stay at home' on 13 May, but schools and non-essential workplaces remain closed
28 May–30 June 2020	Period 3	All Period 2 restrictions remain; workplaces start to reopen

Table 3: Lockdown periods derived from the Oxford Covid-19 Government Response Tracker stringency index.

In order to visualise shorter term changes in the level and timing of consumption, the paper then compares electricity consumption patterns for 1 January–30 June 2020, with mean consumption in the same period in the reference years of 2017–19 coded by the Covid-19 lockdown period (***Table 3***). Since dates in consecutive years generally do not fall on the same day of the week, the 2017–19 dates were adjusted so that the days of the week align with those observed in 2020. It should be noted that Covid-19 lockdown Period 1 included both Easter (10–13 April), a moveable

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feast which occurred on different dates in previous years, and Victory in Europe (VE) Day (with an additional public holiday on Friday, 8 May). For clarity, both these weekends are labelled on the daily plots presented below. Due to the inherent day-to-day variation in electricity consumption, moveable bank holidays and weather effects, the calculation of the percentage above/below trend for specific days in 2020 compared with the same days in 2018–19 is likely to be unreliable and has not been attempted. As a result, the interpretation of the daily data plots must take account of the year-on-year trends shown in the Theil–Sen plots.

Finally, in order to examine demand reduction at specific times of day, Section 4 uses simple percentage change plots to compare half-hourly demand and emissions (mean 2017–19 *versus* 2020) by day of the week for each lockdown period, as defined in ***Table 3***.

4. RESULTS

4.1 VARIATION FROM EXPECTATION: MONTHLY ANALYSIS

Figure 2 presents a Theil–Sen plot of the overall de-seasoned trend in mean half-hourly electricity generation (GWh)/month split by peak period. The plots show that there was a steady decline in mean half-hourly generation of about 0.2 GWh/year since 2017 in each period. However, the effects of the unusually cold January 2017 and February 2018 are visible, as are the substantial below-trend falls in generation during early spring 2020 with all periods affected, especially the morning peak and daytime.

This is confirmed by the estimated percentage above/below-trend results reported by month in ***Table 4***. The results show that January was slightly below trend, February and March were on trend, but April and May were substantially below trend. This is especially noticeable for the morning peak period with an estimated 20% drop below trend in April and 14% in May followed by the daytime (11% and 9%) and early morning (13% and 10%). The evening peak was a relative laggard (9% and 7%). These reductions tended to reduce in magnitude over time so that values for June trend back towards expectation but are still lower than would be expected from the underlying trend alone.

MONTH IN 2020	EARLY MORNING	MORNING PEAK	DAYTIME	EVENING PEAK	LATE EVENING
January	–1.4	–2.8	–3.2	–2.4	–2.6
February	–1.1	–1.7	–1.8	–2.9	–3.0
March	–0.4	–1.7	–1.8	–0.6	–1.8
April	–13.5	–19.6	–10.8	–9.0	–9.4
May	–9.6	–14.2	–8.8	–7.3	–6.5
June	–4.1	–6.2	–4.6	–3.7	–3.5

Table 4: Percentage above/below the expected mean half-hourly GWh by month.

Note: Percentages are based on central (point) estimates and are rounded to reflect the uncertainty represented in Figure 2.

Figure 3 shows the overall de-seasoned trend in mean half-hourly GHG emissions in tonnes (tCO_{2e})/month over the period split by the peak period. This plot therefore represents the combination (multiplication) of the patterns of demand and carbon intensity. As would be expect, there has been a substantial decline in mean half-hourly GHG emissions (about 480–710 tCO_{2e}/year) since 2017 depending on the period. Again, given relatively carbon intense peak periods (***Table 2***), one would expect these to have fallen from a relatively higher level and to a greater degree, and this is indeed the case. However, daytime GHG emissions have also fallen substantially potentially due to the rise in solar.

Table 5 shows the results of using the above/below-trend method to estimate the extent to which UK Covid-19 lockdown decreases emissions from electricity consumption. While the largest below-trend fall was during the morning peak periods in April and May, both January (evening peak) and February (morning peak) also showed large below-trend reductions well before lockdown. Although both April and May showed large below-trend reductions, especially during the day reflecting sunny weather conditions (see Section 3.1), these had reversed by June which had largely returned to trend, as ***Figure 3*** demonstrates.

MONTH IN 2020	EARLY MORNING	MORNING PEAK	DAYTIME	EVENING PEAK	LATE EVENING
January	1.3	−6.0	−4.1	−15.4	−3.8
February	−6.1	−12.5	−5.2	−6.4	−3.6
March	1.3	−1.9	−2.3	−5.3	−2.0
April	−7.9	−18.0	−15.3	−9.2	−5.7
May	−8.6	−16.2	−13.9	−8.3	−6.0
June	−0.7	0.9	4.3	3.6	2.4

Table 5: Percentage above/below the expected mean half-hourly total CO_2e by month

Note: Percentages are based on central (point) estimates and are rounded to reflect the uncertainty represented in Figure 3.

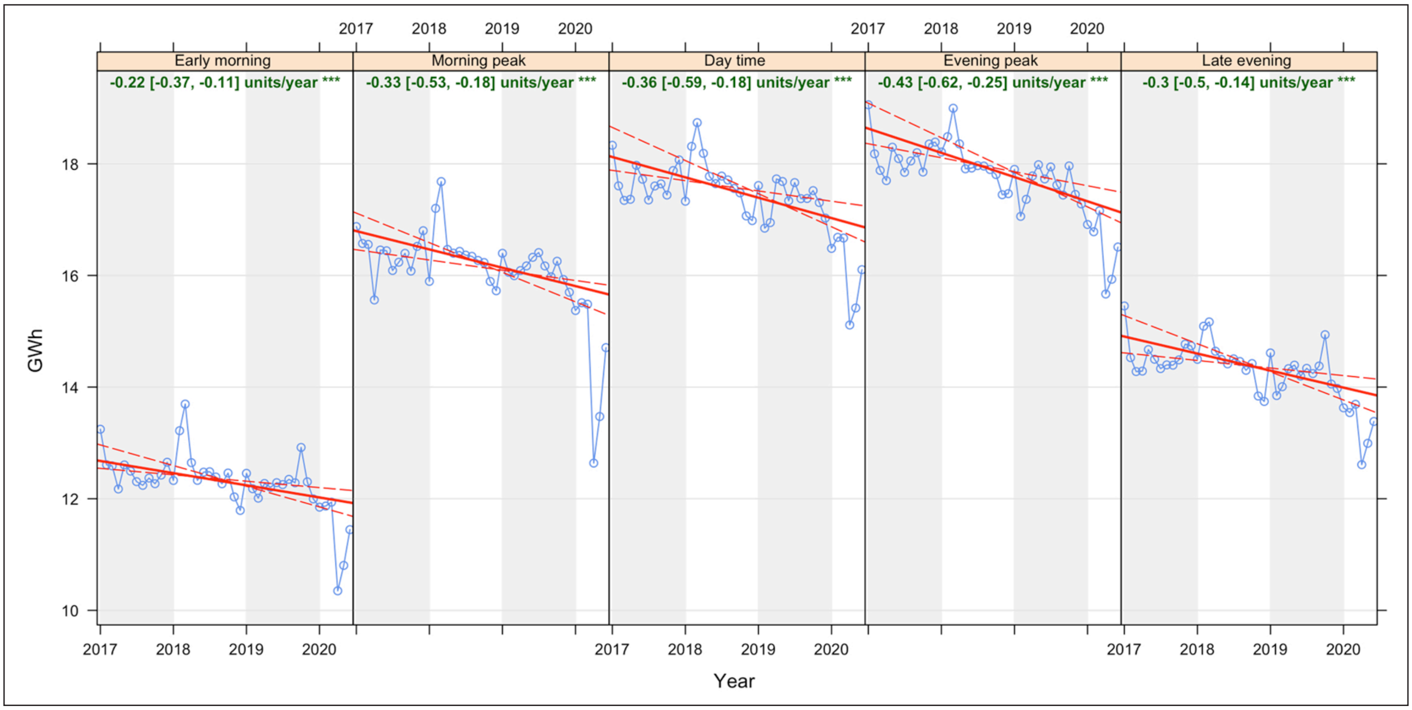

Figure 2: Theil–Sen plot of de-seasoned mean half-hourly GB electricity generation, 1 January 2017–30 June 2020.

Source: Authors' calculations. Solid lines are the median trend; dotted lines are bootstrapped 95% confidence intervals.

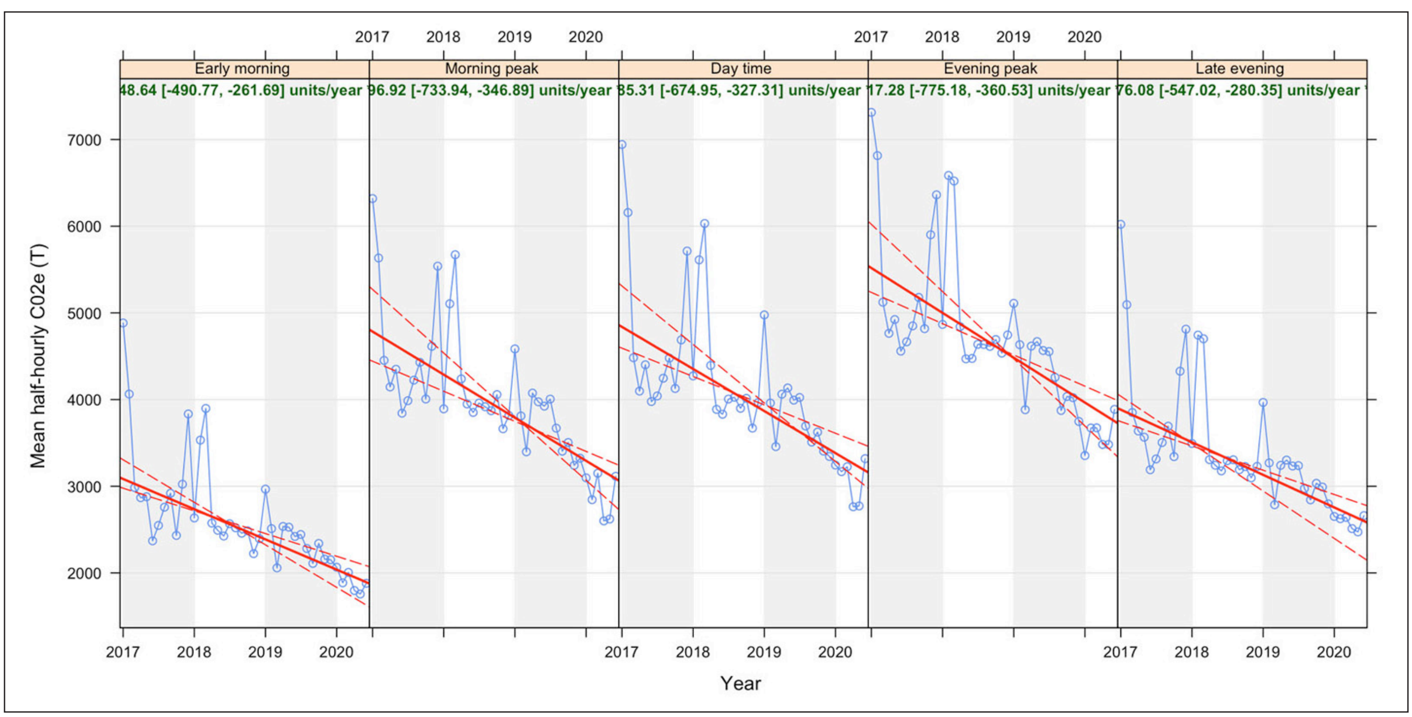

Figure 3: Theil–Sen plot of de-seasoned mean half-hourly GB TCO_2e, 1 January 2017–30 June 2020.

Source: Authors' calculations. Solid lines are the median trend; dotted lines are bootstrapped 95% confidence intervals.

4.2 VARIATION FROM EXPECTATION: DAILY ANALYSIS

This section uses the 'date aligned' data to compare adjusted-date days in 2017–19 with the 'same' day in 2020 over the period since the start of February 2020 using the Covid-19 periods defined in ***Table 3***. As noted above, per-day 'reductions below expectation' values were not estimated due to the wide range of potentially confounding effects, including bank holidays and daily weather conditions.

Figure 4 compares the mean half-hourly generation per day for 2020 with the 2017–19 reference period. The plot shows that generation in early February was already lower than the mean of the previous years, but the two converged at the start of March before diverging again just before lockdown. The lockdown effect is clearly visible with generation through late March, April and May substantially lower on most days and with much greater day-to-day variation. Nevertheless, the distinctions between weekdays and weekends are still visible, although 2020 weekdays do indeed appear comparable with 2017–19 weekend days in terms of levels of consumption (Wilson *et al.* 2020). The effects of the Easter, VE Day and Spring Bank Holiday public holidays are also clear with Monday, 25 May recording the lowest half-hourly consumption in the entire data set of 8.4 GWh at 03:30 hours. Sunday, 24 May recorded both the lowest carbon intensity of 54–55 g CO_2e/kWh from 12:00 to 13:00 hours *and* the lowest half-hourly CO_2e emissions of 714 T at 06:30 hours. However, it is clear that the depression in consumption in April and May eased in June (see also ***Table 4***) with the 2020 and 2017–2019 reference lines converging as one moves towards the start of July.

Again, ***Figure 5***, which shows mean half-hourly TCO_2e/day, incorporates features of the preceding plot mediated by trends and variations in half-hourly carbon intensity (see Figures S5 & S6 the supplemental data online). Overall, GHG emissions were already lower in 2020 than the reference period, and they declined through the early stages of lockdown, as would be expected. In contrast to pre-lockdown, some weekdays in mid-April and mid-June showed lower emissions, but in general weekends were still low-emissions days compared with weekdays. Half-hourly GHG emissions increased through June 2020 and indeed weekdays almost exactly match the reference period values between the 4th and 18th. Given the underlying trend, this does not represent a 'return to normal' but, as ***Table 5*** shows, it indicates substantially more emissions than might be expected.

4.3 VARIATION FROM EXPECTATION: TIME-OF-DAY ANALYSIS

Finally, having established monthly and daily variations from 'normal', the paper considers variation by time of day to reveal how the shape of consumption may have changed in the three lockdown periods. ***Figure 6*** shows the percentage difference in half-hourly consumption between the 2020 lockdown periods and the same periods in the 2017–19 reference years. It shows a relatively constant about –1% difference between 2020 and 2017–19 during the pre-lockdown period, reflecting ongoing underlying demand reduction (***Table 1***). Percentage reductions in other lockdown periods that are substantially below this line can therefore be interpreted as lockdown-correlated below-trend reductions.

In contrast, Period 1 was characterised by a substantial reduction in demand in the morning periods on all days of the week. For weekdays this 'peaked' at about –4% at 06:00 hours on Fridays, but by about 2–3% at 08:00 hours at weekends, with the least reduction seen on Sundays. Daytime demand was substantially depressed on all weekdays, but the reduction was of less magnitude around mealtimes (12:00–13:00 and 17:00–19:00 hours), as would be expected. Sundays deviated from this pattern with very little demand reduction compared with pre-lockdown. Demand was least suppressed in the evening on all days except around 20:00 hours on Sundays.

Period 2, when outdoor activities were extended, had a distinctly different profile to Period 1 on all days except Tuesdays. In general, the level of demand suppression was reduced compared with Period 1, although this was not seemingly the case for Monday afternoons. However, overnight demand was comparable with pre-lockdown on all days except Tuesdays and Wednesdays, and appeared relatively higher overnight on Friday–Sunday than pre-lockdown, potentially indicating increased home media appliance use.

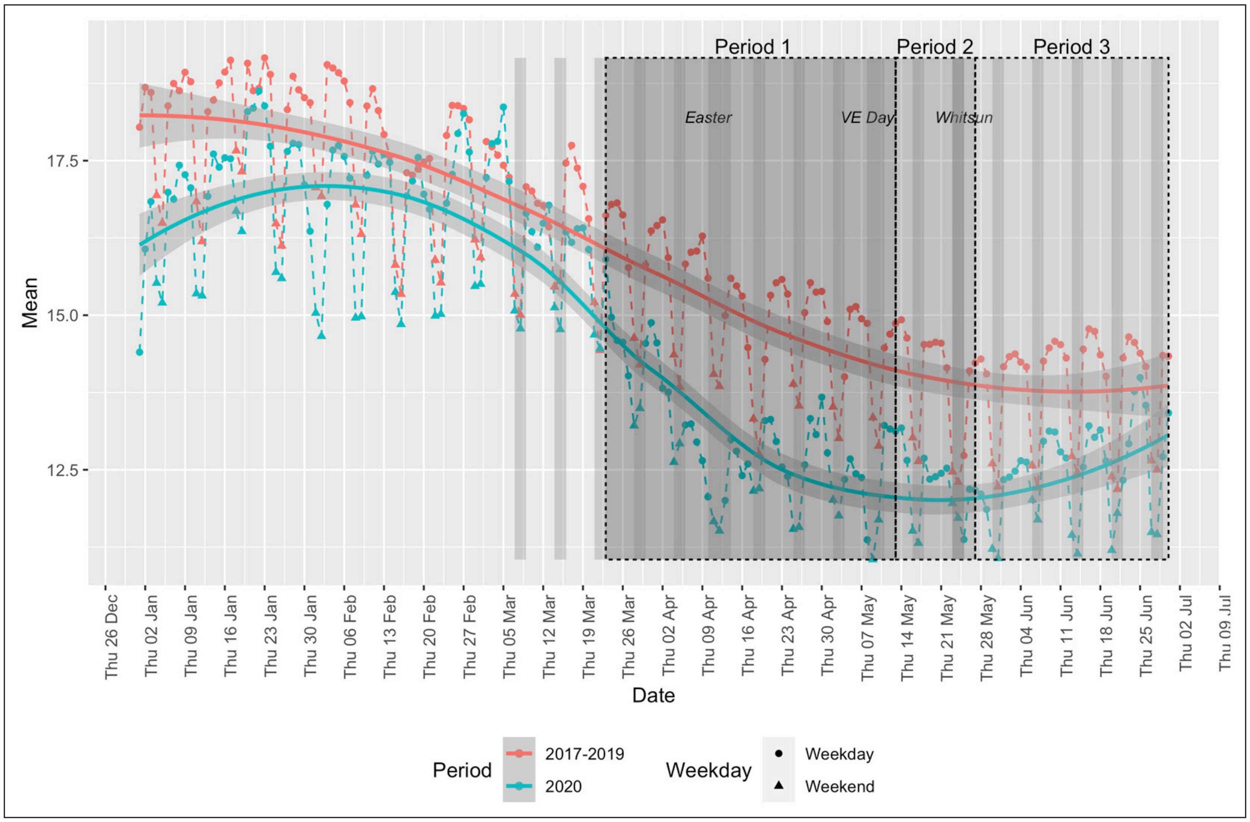

Figure 4: Mean half-hourly electricity consumption (GWh)/day, 1 January–30 June for 2017–19 (mean) and 2020.

Note: Box = UK Covid-19 lockdown to date.

Source: Authors' calculations.

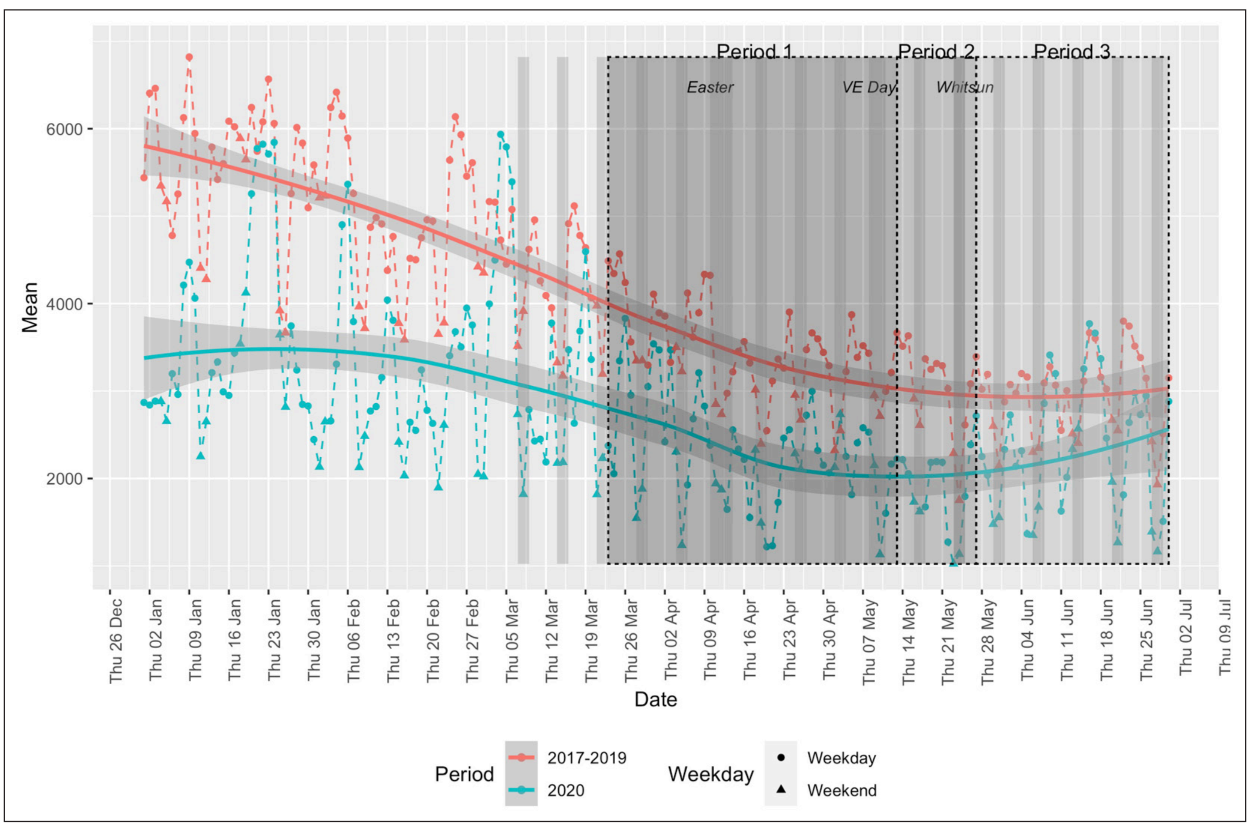

Figure 5: Mean half-hourly emissions (TCO_2e/day, 1 January–30 June for 2017–19 (mean) and 2020.

Note: Box = UK Covid-19 lockdown to date.

Source: Authors' calculations.

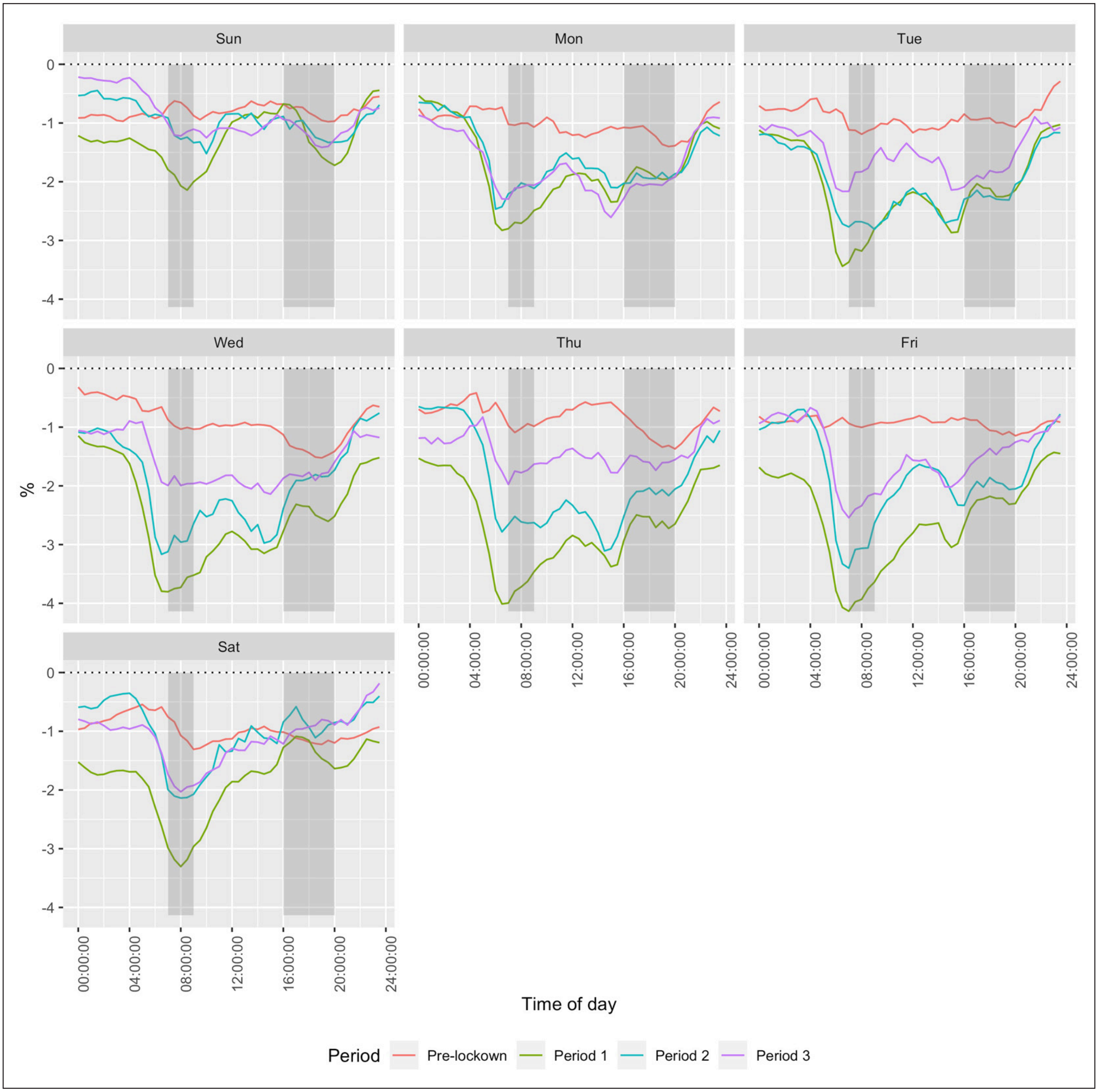

Figure 6: Percentage change in half-hourly GB electricity consumption (GWh) by day of the week and time of day from 1 January to 30 June for 2017–19 *versus* 2020 by lockdown period.

Note: Normal 'peak' demand periods are shaded. The dotted line = 0% reference.

Source: Authors' calculations.

Period 3, when workplaces started to reopen, continued the trend towards normal demand profiles on Tuesdays–Thursdays, but was little different from Period 2 on Mondays and at weekends. Fridays saw least early evening suppression with demand returning to close to trend (a 1% reduction), although this could not have been due to the reopening of pubs and restaurants, which was not until the 4 July. As with Period 2, Period 3 showed relatively higher demand overnight on Friday–Sunday compared to pre-lockdown.

Similarly, ***Figure 7*** shows the percentage change in total half-hourly CO_{2e} emissions for the year/month/day combination. Although clear patterns are difficult to discern, in general the results follow the overall pattern reported in ***Table 5***. Thus, 'baseline' emissions in the 2020 pre-lockdown period are 20–40% below the 2017–19 reference period. Periods 1 and 2 show emissions reductions relatively close to those of the pre-lockdown periods, with the exception of most overnight periods. There were notable reductions on Sundays, Mondays, Fridays and Saturdays in Period 2, which may

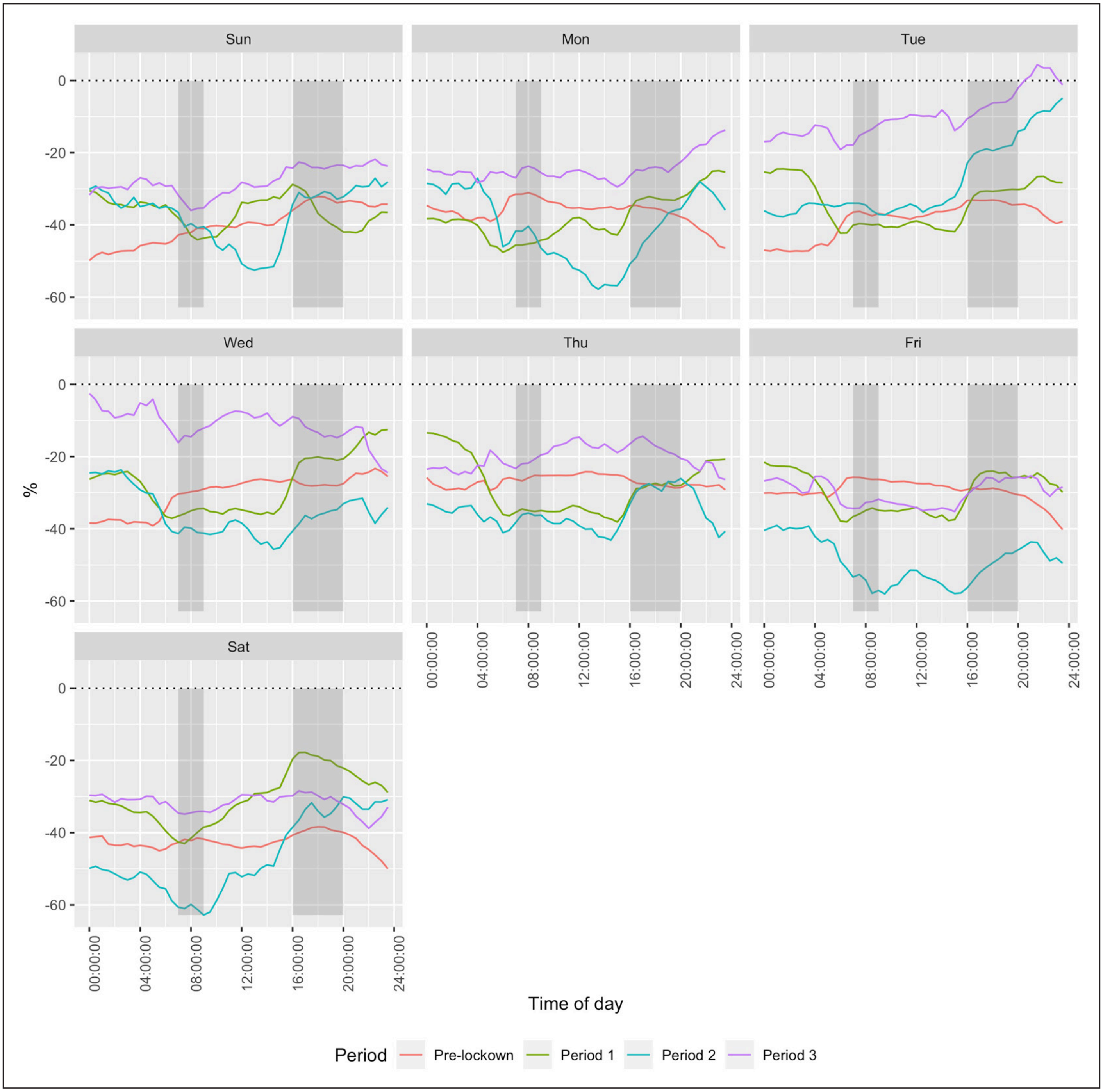

Figure 7: Percentage change in mean half-hourly emissions by day of the week and time day from 1 January to 30 June for 2017–19 *versus* 2020 by lockdown period.

Note: 'Peak' demand periods are shaded. The dotted line = 0% reference.

Source: Authors' calculations.

be due to the Whitsun long weekend at the end of May (*cf.* ***Figure 5***). In general, Period 3 showed a notably lower magnitude of reduction, especially on Tuesdays and Wednesdays, potentially reflecting the different weather conditions in June.

5. DISCUSSION

Well-known underlying downward trends in both overall consumption and carbon intensity mean that consumption and emissions in 2020 would be expected to be lower than the corresponding period in previous years, even in the absence of Covid-19 restrictions. The results reported here suggest that the effects of the initial Covid-19 lockdown on GB's electricity consumption were generally to suppress daily weekday demand below trend so that weekdays and weekends became relatively similar in terms of overall demand levels. Further, as would be expected given the increased weather dependence of GB's generation (Staffell & Pfenninger 2018), there is no simple relationship between reductions in demand and reductions in electricity generation-driven emissions. Indeed, in some periods and at certain times of day in Period 3, emissions were notably above trend (***Table 5*** and ***Figure 7***).

Even though weekdays did, to some extent, become weekends, the weekday/weekend cycle of variation did not vanish during lockdown periods with weekdays and weekends still discernible (***Figure 4***). The suppression of demand on bank holidays in Periods 1 and 2 is very clear, and it is known that this created a difficult grid management period where demand was unusually low and renewable generation unusually high (National Grid ESO 2020b).

The below-trend monthly reductions presented in ***Table 4*** showed that the Covid-19 lockdown periods in GB reduced overall electricity consumption by up to 20% in April (morning peak period) and 14% in May (morning peak), before reducing in magnitude to 6% in June (morning peak). However, these patterns of consumption do not necessarily lead to lower GHG emissions. As a result, while morning peak emissions fell by 18% in April, this reversed in June which had 1% above-trend emissions (***Table 5***). Daytime emissions fell in April and May, representing both a decrease in daytime consumption and an increase in embedded solar generation during the sunniest month on record (MetOffice 2020), but were 4% above trend in June. Evening peak emissions were only about 8–9% below trend and reached 4% above trend by June.

Figure 6 shows in more detail that morning peak-period consumption reduced substantially in both lockdown Periods 1 and 2 and to some extent in Period 3 when schools and many workplaces remained closed. Unfortunately, this paper cannot explain why this was the case as the data used do not have per sector consumption profiles, or disaggregation by household type or appliance use. There has been speculation that those no longer commuting to work consequently rose later and delayed morning energy-demanding practices. However, given the uses to which electricity is put in GB (see Section 2), other explanations must also be considered, such as the potential reduction in industrial and commercial heating or cooling, or reductions in electrified transport.

On the other hand, the evening peak period appeared to be resistant to change with a 9% reduction in April falling to 7% (May) and 4% (June) (***Table 4***), a pattern reflected in the detailed time-of-day change plot (***Figure 6***). Given that demand in this period is more heavily driven by household rather than commercial or industrial demand (see the supplemental data online: electricity load profiles by Elexon class), this provides evidence to support the hypothesis that activities undertaken during the evening period are highly time-of-day dependent and thus unlikely to shift even if other constraints on the timing of daily life are relaxed (Torriti 2017).

Finally, late evenings in Periods 2 and 3 were also notable not only for resisting change but also on some evidence (***Figure 6***) for increasing above trend, especially on Fridays and Saturdays. This could plausibly be attributed to a switch to in-home food preparation and leisure which does not benefit from economies of scale and so might be expected to more than compensate for the energy consumption reduction caused by the closure of the sector.

6. CONCLUSIONS

Clearly the aggregated data used in this paper cannot determine per sector consumption patterns, nor can it provide evidence of specifically which electricity services and energy-using practices changed during the UK's Covid-19 lockdown. This must wait for more detailed analysis of per sector electricity consumption data and especially in-home appliance data as a proxy for energy-using practices (Durand-Daubin 2013; Palmer *et al.* 2013a; Suomalainen *et al.* 2019).

In general, reduced commercial and industrial activity is likely to have led to lower-than-trend electricity consumption during the day due to reductions in process heat and heating/cooling demand. At the same time, the unusually sunny April and May (see Section 3.1) would have increased embedded solar generation which is not visible to this data source and may have led to apparent additional midday demand suppression. However, neither of these processes is likely to have caused demand reductions at other times of the day.

This is reflected by the large below-trend reductions in demand in April corresponding to lockdown Period 1, especially in the morning and daytime periods. These reductions were of lower magnitude in May (mainly corresponding to Period 2) and less substantial still in June (corresponding to Period 3). The morning reduction was particularly clear and centred around 06:30–08:00 hours on weekdays and Saturdays, suggesting that they were caused by the closure of schools, retail and commercial premises, and non-essential workplaces. There is little evidence in these data that this demand was shifted to other periods of the day as there are no clear new 'above-trend' periods (*cf.* ***Figure 6***). This suggests that the practices that usually happen at this time were either discontinued or became desynchronised. The only exception to this was late on Friday and Saturday evenings as social leisure activities become almost wholly home based. If this trend continues into winter restrictions, which include the closure of most hospitality venues, then evening weekend demand is likely to return to these levels.

The relative resistance of evening demand to substantial change compared with the morning period is not surprising given that evening demand is more strongly driven by domestic activities and the multiple factors that constrain when things are done (Anderson & Torriti 2018; Torriti 2017; Walker 2014). Some of these, related to school and work-related travel, as well as work itself for those furloughed, were relaxed during the lockdown period. However, the data do not suggest that this enabled a large-scale shifting (or reduction) of evening energy-using activities compared with that seen in the early morning.

From a system management perspective, it seems unlikely that Covid-19 lockdown periods in GB provide much of a view of the future of a low-emissions electricity system. The forecast increases in electricity consumption due to the decarbonisation of heat and transport (CCC 2019) are absent as, conversely, are potential decreases in energy demand for heat/cooling due to substantial post-Covid-19 energy-efficiency retrofit programmes. However, in this respect the conditions observed during the Period 1 lockdown bank holidays, with unusually low demand and unusually high renewable generation, may pertain in the future as the National Grid ESO (2020c) has observed.

From an emissions perspective, the increased relevance of weather to electricity-generation carbon intensity (Staffell & Pfenninger 2018) means that reductions in demand do not straightforwardly translate into reductions in emissions. Indeed, it is possible that Covid-19 lockdowns have prevented continued on-trend emissions reductions by increasing late evening demand, which must be met by fossil fuel generation on less windy days (*cf.* ***Figure 7***).

Looking to the future, there is increasing evidence that home-working is becoming an accepted and embedded norm in the UK with a large number of employees in the service sector avoiding, or being encouraged not to return, to centralised office-based work (Jack 2020). In this respect, some of the patterns observed in May–June are likely to be sustained and, with the advent of more stringent localised lockdowns in response to localised outbreaks, the patterns observed for April and May are also likely to be repeated in specific locations.

However, perhaps of more concern are the implications of local or national restrictions that are likely to persist during the 2020–21 winter heating season. With increased household occupancy due to the incomplete return to pre-Covid-19 work patterns, but with schools open, it is unlikely that the morning-demand reductions reported here will be sustained at least for those with children at school. On the other hand, there is likely to be increased demand in the 5% of homes that use electricity for heat at the same time as industrial and commercial demand rebounds. In this respect, further analysis of household level data is crucial to understanding the potential implications for localised energy and heat poverty in the coming 2020–21 winter months.

This will be of particular interest to local authorities that face localised restrictions and which also have higher rates of electric heating, such as the City of London (47.9% of 4300 households), Isles of Scilly (39.5% of 990), Tower Hamlets (23.77% of 101,000) and Southampton (19.5% of 98,200).[2] It will also be of interest to local electricity network operators managing constrained networks in small areas with much higher rates of electric heating (***Table 6***), and which will need to meet both increased daytime domestic heat and rebounding commercial and retail demand. Where these correlate with areas of high deprivation, such as central Birmingham, Leicester city centre, and Cathedral & Kelham in Sheffield (***Table 6***), local authorities may need to explicitly intervene to prevent winter under-heating and consequential health and other disadvantages.

AREA	LOCAL AUTHORITY	NUMBER OF HOUSEHOLDS	% WITH > 1 DEPRIVATION DIMENSION	DEPRIVATION QUANTILE	% WITH ELECTRIC HEATING
Central	Birmingham	3433	67.78%	25% most deprived	82.32%
Castlefield & Deansgate	Manchester	3087	52.74%	Other	81.63%
Pier Head	Liverpool	2782	51.47%	Other	81.45%
Leeds City Centre	Leeds	3569	63.80%	Other	78.40%
Piccadilly & Ancoats	Manchester	3885	63.40%	Other	76.42%
Cardiff Bay	Cardiff	3654	48.41%	Other	74.44%
Leicester City Centre	Leicester	2961	74.47%	25% most deprived	70.01%
Cathedral & Kelham	Sheffield	3270	73.64%	25% most deprived	64.86%
City Centre North & Collyhurst	Manchester	3368	68.59%	25% most deprived	60.84%
Central & Islington	Liverpool	3201	66.26%	25% most deprived	59.39%

Table 6: Top 10 English and Wales local areas (middle layer super output areas—MSOAs) by the percentage of households with electric central heating and percentage with at least one dimension of deprivation

Source: Census 2011, QS415EW and QS119E.

In summary, while this analysis can provide some insight, understanding exactly how different sectors have responded to 2020 Covid-19 lockdown restrictions and what the implications might be for national and local energy system management under future regional or national lockdowns requires significantly disaggregated data. Analysts will then be in a position to understand the electricity and wider energy system that will need to be managed through a Covid-19 winter to ensure minimal impact on vulnerable households that use electric heating and who are least able to meet energy bills. Given that the UK is unlikely to 'send this virus packing' (Prime Minister's Statement on Coronavirus 2020b) for some months to come, we will then at least have a better idea of how to live with it.

NOTES

1 The term 'Great Britain' denotes England, Wales and Scotland (and not Northern Ireland). Data for Northern Ireland electricity demand were not used in this research.

2 Census 2011: QS415EW; *https://www.nomisweb.co.uk/census/2011/data_finder*.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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SUPPLEMENTAL DATA

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