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Building energy use in COVID-19 lockdowns: did much change?

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ABSTRACT

The lockdowns introduced to prevent the spread of COVID-19 had huge impacts, as people were largely confined to their homes. It could be expected that residential energy use would increase while non-residential decreased, however the picture is not so clear. Here three complementary datasets on different scales are used to explore changes in building energy use during two UK lockdowns: the complete building stock of Great Britain, a sample of approximately 1000 residential buildings, and one of about 24,000 residential boilers. Energy-signature analysis was used for the building data to estimate the changes in demand for space heating and other uses, with the boiler data able to separate space and water heating and explore changes in these. In the 2020 lockdown residential energy consumption for water heating and appliances increased, with decreased use for space heating, resulting in a reduction in total energy use during the heating season. In the 2021 lockdown total energy consumption changed little, however a decrease in the use of gas space heating was observed. The residential changes counteracted non-domestic changes, resulting in little difference in national energy consumption. These results highlight how longitudinal datasets enabled by Internet of Things-enabled devices can be crucial as an evidence base for research.

POLICY RELEVANCE

The impacts on national energy consumption of increased time spent at home provide an important context for the pursuit of net zero targets, particularly with the rise in flexible working seen since 2020. That little change was seen overall could be due to the energy use in non-domestic buildings not decreasing proportionately to their decrease in use during national lockdowns, and thus seeking to lower non-domestic energy use to account for lower utilisation of spaces could deliver carbon and cost savings. This could be achieved through measures such as automated switch-off services, demand controlled heating and ventilation, and reduction in space. The finding that drastic changes were not made to home heating behaviours could have implications for future demand-side response schemes, indicating that perhaps occupants are happy to adapt to cooler conditions by achieving comfort in other ways.

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1. INTRODUCTION

The UK COVID-19 lockdowns, introduced to curb the spread of the virus in 2020 and 2021, produced nationwide natural experiments: what happened to our energy use when we were restricted in spending time outside of our homes? This research compares data from lockdowns and selected comparison periods to address this question. The findings from this have implications for future policy regarding behavioural change advice in the pursuit of net zero (Barrett *et al.* 2022), and possible impacts of changing work patterns on the energy system.

People in the UK were instructed to stay at home other than for essential purposes from 23 March to 11 May 2020, referenced here as lockdown 1. All non-essential high street businesses were closed, and schools were only open to children of key workers (Office for National Statistics (ONS) 2020a). Similar restrictions were imposed in early 2021 between 5 January and 8 March (here referred to as lockdown 3), with variable restrictions in different regions between these periods (Brown 2021).[1] During these lockdowns people were not allowed to leave their homes without a 'reasonable excuse', such as purchasing food, medical reasons or solo exercise (Brown 2021); in lockdown 3 it was also permitted to meet one other person outside for exercise, to attend a place of worship, and 'bubbles' were in place to enable anyone who lived alone to be considered part of another household, or for childcare arrangements (Brown 2021). In a survey of 2250 UK residents conducted in lockdown 1, around 87% indicated they were complying with lockdown rules, however only just under half were supportive of the government's response to COVID-19 with 44% instead suffering under lockdown measures (Duffy & Allington 2020).

Burdett *et al.* (2021) compare park mobility data (the frequency and duration of visits to parks) from January–early February 2020 to mid-February–August 2020. A sizeable decrease from the baseline period was found during lockdown 1, with large increases in mid-May when restrictions on outdoor recreation were lessened (Burdett *et al.* 2021), corroborating that the restrictions on leaving homes were largely followed during this period and more time was spent in domestic buildings. A review of studies of changes to physical activity and sedentary behaviour across multiple countries during lockdowns found that the former decreased, whilst the latter increased (Stockwell *et al.* 2021), again indicating compliance with lockdown restrictions and increased time spent at home. The increase in sedentary behaviours may increase electricity demand associated with appliance use, as well as increased demand for space and water heating in the domestic sector due to more time within homes.

During lockdown 1, 36.6% of UK businesses were operating from their normal place of work, with much higher (> 50%) percentages for industries associated with health and social care, manufacturing, transportation, and waste management (ONS 2021). Reduced occupancy of non-domestic buildings is expected to be associated with a decrease in their energy use, however some automated systems may have continued to run during lockdowns and it is possible that buildings with a reduced in-person workforce may have continued to operate as normal, with only 24.3% of businesses temporarily closed (*i.e.* ceased trading) during lockdown 1 (ONS 2021). There was less of an impact on businesses in lockdown 3, with only 12.3% temporarily closed and 44.2% operating at their normal place of work (ONS 2021), with the remainder operating with remote working.

All full UK lockdowns occurred during the space heating season as defined by the UK Standard Assessment Procedure (SAP) for predicting domestic energy use (BRE 2014) (Figure 1), although heating into May could be less usual in reality (BRE & DECC 2013).

The temperature and solar conditions are shown in Figure 1 from January 2019 to the end of May 2021; this period covers the lockdowns and pre-lockdown comparisons analysed and highlights that solar radiation and external temperatures were unseasonably high during lockdown 1, with spring 2020 the sunniest spring on record for the UK (Kendon *et al.* 2021) with an average of 133.7 Wm^{-2} in comparison with 105.1 Wm^{-2} for the same dates in the previous year. The average external temperature in lockdown 1 was 9.4°C in comparison with 8.6°C during the same period in 2019, with average temperatures across the UK between 1991 and 2020 of 5.7°C in March, 7.7°C in April and 10.2°C in May (World Climate Guide 2024).

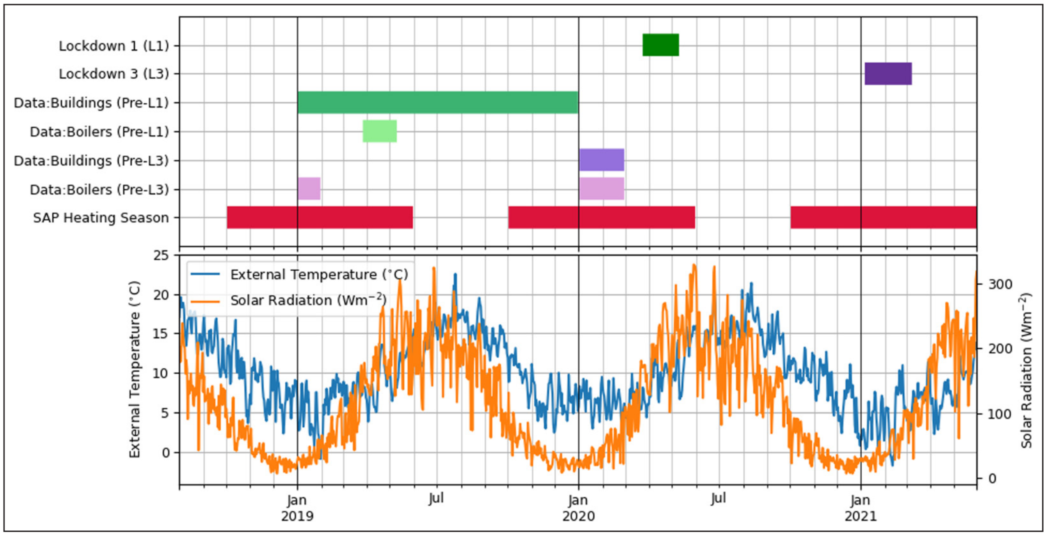

Figure 1: Temperature and solar conditions, January 2019–end of May 2021.

Note: The top plot shows the timeline of lockdowns 1 and 3, the pre-lockdown comparison periods used for the analysis of both boiler and buildings datasets, and the space heating season as defined by the Standard Assessment Procedure (SAP); with a plot of the daily average external air temperature and solar radiation for the UK on the bottom.

Restrictions to activities outside the home led us to predict a series of consequent outcomes for energy use during lockdowns. First, electricity consumption in homes would increase, resulting in additional free heat being contributed to them, and lowering the external temperature at which active space heating would turn on (the balance temperature). Second, estimates of the thermal performance (*i.e.* heat loss and heating system efficiency) of domestic buildings would either remain unchanged (as it would be unlikely for many retrofits to occur), or the effective heat loss would increase if more rooms were heated due to occupants using more of their homes whilst largely confined to them during lockdown. Third, more time spent at home was predicted to increase demand for space and water heating on the assumption that households typically only heat whilst at home, and would use additional hot water due to, for example, taking showers at home that previously occurred in workplaces and gyms.

Various data sources (BEIS 2020, 2021; IEA 2021) indicate that while total UK energy consumption and carbon emissions decreased during lockdowns, these increased for the residential sector, reflecting the increased time spent at home—despite warmer weather than previous years presumably contributing to a reduction in space heating demand during heating hours (BEIS 2020, 2021; IEA 2021). Erias & Iglesias (2022) used data from 15 European countries to explore the impact of lockdowns on gas use, finding the largest recorded downturn in natural gas demand overall, but with an increase in residential demand. Tubelo *et al.* (2022) studied the impact of lockdown 1 on electricity consumption from a small sample of 21 gas-heated dwellings, finding an average increase of 17% over a year likely due to increased time at home; however, analysis was not adjusted for weather conditions. Timing of use also changed; UK national electricity data were analysed at peak times by Anderson & James (2021) for lockdown 1 compared with the period 2017–19, who estimated a morning peak decrease of 20%, a daytime decrease of 11% and no change in the evening. This change in electricity consumption patterns during lockdowns was also found in other European countries and New York (Bahmanyar *et al.* 2020; Li *et al.* 2021; Santiago *et al.* 2021) with weekday profiles appearing more like weekend profiles from pre-pandemic data.

Mehlig *et al.* (2021) analysed electricity and gas data from the UK, finding that in lockdown 1 total domestic and non-domestic electricity demand decreased, as in other studies, whilst domestic gas was unchanged. In lockdown 2, however, domestic gas was found to have increased by 6.1%, which is attributed to the cooler weather in November. Similar conclusions were found by Zapata-Webborn *et al.* (2023), where counterfactuals for 508/326 (electricity/gas) households covering two years since the start of the lockdowns were produced through machine-learning techniques. In lockdown 1, electricity was found to have increased by 9%, with gas unchanged. Electricity use again was found to increase in lockdown 3 by 9%, with gas use also increasing by 12% in this cooler lockdown period. The changes were found to vary with household type, with the greatest electricity increases in homes with children, whilst the greatest gas increases were in households with no children or adults in work.

Although the increases in gas consumption have largely only been found in the cooler lockdown periods, changes in gas use cannot be attributed to space heating alone; Alda-Vidal *et al.* (2020) reported a 35% increase in UK domestic water use (hot and cold) from the start of lockdown 1 until the end of October 2020.

The results of a survey of around 1000 households commissioned on occupant behaviour changes in lockdown are presented by Huebner *et al.* (2021), with conclusions that align with the studies of the energy data outlined above. Appliance usage increased in duration and spread over a day; 59.5% of respondents reported no change in space heating hours, and 86.9% reported no change in the number of rooms heated, although it was found that window opening increased on cold days during lockdown. Among this sample the proportion of adults working from home tripled during the first lockdown, however the sample was biased towards wealthier households which were potentially more likely to be able to work from home. It is perhaps surprising that self-reported home energy-use behaviours did not change much given the increased time spent at home; however, with around half the sample not in work, this could be less important to energy-use behaviours, or it could reflect the uncertain reliability of self-reported behaviours (Huebner *et al.* 2021). Hampton (2017) found that those working from home would tolerate lower temperatures than otherwise and were willing to adapt for comfort in other ways, which would align with the lack of changes reported by Huebner *et al.* (2021).

The above results indicate changes in electricity and gas consumption in homes during the lockdowns, however this paper presents an analysis using both physical models to enable the estimation of the separate impacts of space and water heating changes, and new data from boiler transducers[2] and national data covering all buildings.

This paper explores the impacts of lockdown conditions on gas and electricity use in buildings (residential and other) by analysing three datasets, specifically looking at changes in space and water heating. The analyses of the datasets are here named GB Building Stock, Residential Buildings and Residential Boilers for simplicity. (As the label 'GB' implies, the data are only from England, Wales and Scotland, and not Northern Ireland.) GB Building Stock analysis used National Grid gas and electricity data (ESO, National Grid 2023) aggregated across domestic and non-domestic buildings; Residential Building analysis used data from about 1000 homes which are part of the Smart Energy Research Lab (SERL) Observatory (Webborn *et al.* 2021); and Residential Boilers analysis used data from about 24,000 homes with a UK boiler maintenance service contract (a total of about 150,000).

2. METHODS

This research utilised three datasets of varying scales and two analysis methods to explore the impacts of lockdowns on energy use and to investigate the hypotheses stated in the introduction from multiple perspectives.

2.1 DATA

As mentioned above three datasets across different scales and containing data to investigate different aspects of energy use were used in this study to investigate the impacts of COVID-19 lockdowns on building energy consumption; in this section they are described in more detail. As all data are secondary, ethical approval was not required for this study.

2.1.1 GB Building Stock (National Grid)

The National Grid data consist of historic electricity and gas demand data from all buildings (non-domestic and domestic) on a half-hourly (electricity) or daily (gas) basis, downloaded from the National Grid website (ESO, National Grid 2023) for the period January 2017–August 2021. For the purposes of analysis, these were matched with temperature and solar data from the Copernicus/ECMWF ERA5 hourly reanalysis dataset (ECMWF 2022), averaged across the UK. All data were converted to daily averages for the analysis presented here.

2.1.2 Residential Buildings (SERL Observatory)

The SERL Observatory dataset, described by Webborn *et al.* (2021), consists of half hourly and daily smart meter electricity and gas data, household survey responses, public Energy Performance Certificate (EPC) data, and climate data. The analysis presented here utilised a sample of around 1000 homes within the observatory that were suitable for the planned analysis (*i.e.* had sufficient data present during the lockdowns and comparison periods). For these homes, the half hourly smart meter and the climate data were averaged to daily values.

2.1.3 Residential Boilers (connected devices—combination boilers)

This dataset consists of data from individual combi-boilers (boilers that provide instantaneous hot water rather than 'system boilers' which have a separate hot water tank) rather than from the entire stock of GB buildings in the National Grid and individual metered buildings in the SERL Observatory datasets. Gas-fired combi-boilers are the dominant form of space heating in the UK. The data are collected by an internet-connected device on the boiler which logs multiple data points across sensors each time the boiler switches between the supply of hot water for space heating or direct hot water, with logged data transmitted to the cloud for analytics and storage. The data were supplied to the researchers as daily data aggregated from the raw time series feed for the period 2018–22, allowing comparison before, during and after lockdown restrictions. This detailed on-board boiler data enable novel analysis into domestic energy use during lockdowns.

The insights are considered to be from an unobserved cohort; the device is provided for the purpose of pre-emptive maintenance using the same sensors. The sample has known limitations in representation due to the cost of purchasing the device and subscribing to the service to which the device logs data, resulting in a higher proportion of more affluent occupants compared with a random sample.

2.2 ENERGY SIGNATURE ANALYSIS

Both the GB Building Stock and Residential Buildings datasets were analysed using an energy signature method called power temperature gradient (PTG), described in Section 2.2.2. This method, as used in this paper, uniquely examines how energy use (predominantly for space heating) changes with external temperature, which drives the heat loss of the building, and solar radiation which impacts the incidental heat gains. This paper therefore accounts not only for differing external temperature but also for unseasonal levels of solar radiation such as those in lockdown 1.

2.2.1 Data preparation

The PTG analysis of buildings used daily average total power—daily total energy consumption of electricity (Wh day^{-1}) plus gas (Wh day^{-1}), divided by 24 hours per day—external temperature and solar radiation data. Dwellings in the Residential Buildings dataset were removed if their contextual data from the EPC or SERL survey responses indicated that they had any unmetered energy use, such as solar panels or solid fuel heating. A simple linear regression of data where the daily average external temperature was below 12°C was used in conjunction with Chauvenet's (1863) outlier criterion to exclude erroneous data points.

2.2.2 Model

The PTG method is one of a family of methods utilising the energy signature of a building. The energy signature is a plot of the power against the external temperature, which can be modelled in several ways (Fels, 1986; Summerfield *et al.* 2010). It has been used to estimate the energy savings made by retrofitting properties (Fels, 1986); to estimate the heat loss coefficient (as here) (Chapman *et al.* 1985); and for policy evaluation (Elwell *et al.* 2015). The method is simple and thus has significant implicit assumptions making it more suitable for analysis of a large sample of buildings simultaneously than individual assessment (Hollick 2020). The analysis estimates four parameters: the in-use heat power loss coefficient (HPLC), representing the combined fabric and systems efficiency of a building; the baseline power (P_{base}), the daily average power outside of the heating season for appliances and water heating; the balance temperature (T_{bal}), the external temperature below which space heating is required if no solar gains were available; and an effective solar aperture (g), reflecting the average contribution of solar radiation to the heating of the dwelling. The PTG model is given as:

$$\begin{cases} P = HPLC\left(T_{bal} - T_{ext}\right) + P_{base} - gS & T_{bal} > T_{ext} \\ P = P_{base} & T_{bal} < T_{ext} \end{cases} \tag{1}$$

where T_{ext} is the external temperature, and P is the total electricity and gas consumption.

A simplified version of this model was applied to lockdown 3 data, given the low levels of solar radiation and lack of non-heating season data, and is given as:

$$P = \text{HPLC}\left(T_{bal} - T_{ext}\right) \tag{2}$$

This model does not directly incorporate occupant behaviours such as rooms heated or hours in the home, and as such assumes that factors such as these are constant between periods of data to which the model is applied, reflecting regular use of the building. As the building fabric was highly unlikely to change between these times, this assumption enables changes to energy consumption and use of buildings to be investigated as changes to the estimates of these parameters during the different time periods can only be due to behaviour changes.

2.2.3 Bayesian optimisation

The data were optimised to the PTG model using Bayesian techniques, resulting in estimated distributions for parameters rather than single values. Markov chain Monte Carlo (MCMC) sampling was employed to simulate the joint posterior parameter distribution, and thus obtain estimates for the parameters from the median values of the marginalised distributions.

The emcee Python module was utilised, which implements the affine-invariant ensemble sampler proposed by Goodman & Weare (2010). A total of 1000 walkers of 10,000 iterations were produced with a burn-in of 1000. For the SERL Observatory analysis the chains were initialised at an HPLC based on the outlier analysis and the priors specified as a uniform distribution within the limits specified in Table 1. For the National Grid analysis the chains were initialised at values estimated from an initial plot of the data, with the prior limits also specified in Table 1. A Gaussian likelihood function was assumed for all analyses.

PARAMETER	PRIOR RANGE FOR RESIDENTIAL BUILDINGS	PRIOR RANGE FOR THE GB BUILDING STOCK
HPLC (WK^{-1})	0–1500	0–10 × 10^{10}
T_{bal} (°C)	–5 to 35	–5 to 35
P_{base} (W)	0–3000	0–5 × 10^{12}
g (m^2)	0–50	0–10 × 10^{8}

Table 1: Limits of the uniform priors set on the parameters for Bayesian optimisation of the data to the power temperature gradient (PTG) model.

2.3 RESIDENTIAL BOILERS ANALYSIS

The Residential Boilers dataset enabled analysis of the impact of lockdowns on mains gas combi-boiler-heated homes, with data collected from internal sensors within the appliances. Data were cleaned and filtered to include only homes with a boiler rated as 30 kWp capacity and those clearly occupied during the analysis period as defined by Section 2.3.4. Residential Boilers data have no contextual location data so were only corrected for external temperature, not solar radiation given that solar radiation varies substantially based on locality and the national average would be unlikely to reflect the exposure of the sample homes. For temperatures, local discrepancies are less pronounced.

2.3.1 Data preparation

Exploratory data analysis (EDA) was undertaken on all periods to understand how energy use changed when a building was unoccupied, using the number of hot water tappings (see Section 2.3.4) as a proxy for occupancy, alongside review of data coverage across the study periods. The same boilers are studied within each lockdown and corresponding comparison period, but not across lockdowns due to limitations of data coverage across all years. The same data-cleaning methodology was applied to all analysis periods.

To understand the limitations of the sample, the mean is compared with the known population mean as reported by Energy Consumption in the UK (ECUK) (ONS 2020b).

2.3.2 Data cleaning and outlier handling

The supplied data went through an extract, transform, load (ETL) procedure which included data cleaning. Data cleaning was limited to removing observations through two criteria (physically improbable values and data quality), as listed in Table 2.

PHYSICALLY IMPROBABLE	DATA QUALITY
Maximum energy (space heat kWh) should not exceed the stated boiler power × 24 h	Sample period provided by logger > 98.9% of a day
Hot water runtime should not exceed 12 h	Only analyse boilers free from null values in the study period for the variables of interest
Mean hot water flow should be between 0 and 75°C	

Table 2: Criteria for Residential Boilers data cleaning.

Note: The data quality criterion of > 98.9% of a day was selected due to a natural break in the data at this level.

2.3.3 Normalisation for external temperature

Observed demand for space heating was normalised using a degree-day method (EEA 2019) with a 15.5°C base temperature, as is typical in the UK. There are no metadata that would allow locating homes, so temperature data were taken from a population-weighted value using the national grid method, as in Watson *et al.* (2019).

2.3.4 Calculating periods of home occupation using hot water data

Every time hot water is drawn via outlets from the combi-boiler (a boiler that provides instantaneous hot water and space heating), this is recorded in the Residential Boilers dataset as a 'tapping'. For each study period, the year before lockdown was used to analyse typical occupancy values. Homes with more than two days unoccupied within a month were removed from the sample to ensure a like-for-like comparison on occupancy.

3. RESULTS

3.1 GB BUILDING STOCK

National Grid data were analysed with the PTG method to assess the impact of lockdowns on energy use from all buildings (residential and non-residential). Pre-lockdown data from 1 January 2017 to 23 March 2020 were compared with the available data at the time since the start of lockdown 1, 23 March 2020–31 August 2021 (Figure 2).

The estimated baseload decreased by 4% compared with pre-lockdown), and the balance temperature increased by 0.3°C. The estimated HPLC decreased, indicating that 4% less energy per degree drop in external temperature was consumed within the UK building stock, potentially due to the decrease in occupancy of non-domestic buildings. However, all changes are within the standard deviation of the power prediction and the similarity of the slopes in Figure 2 indicate that the patterns of consumption of the whole building stock remained approximately constant; any changes across the domestic and non-domestic stock appear to cancel each other out.

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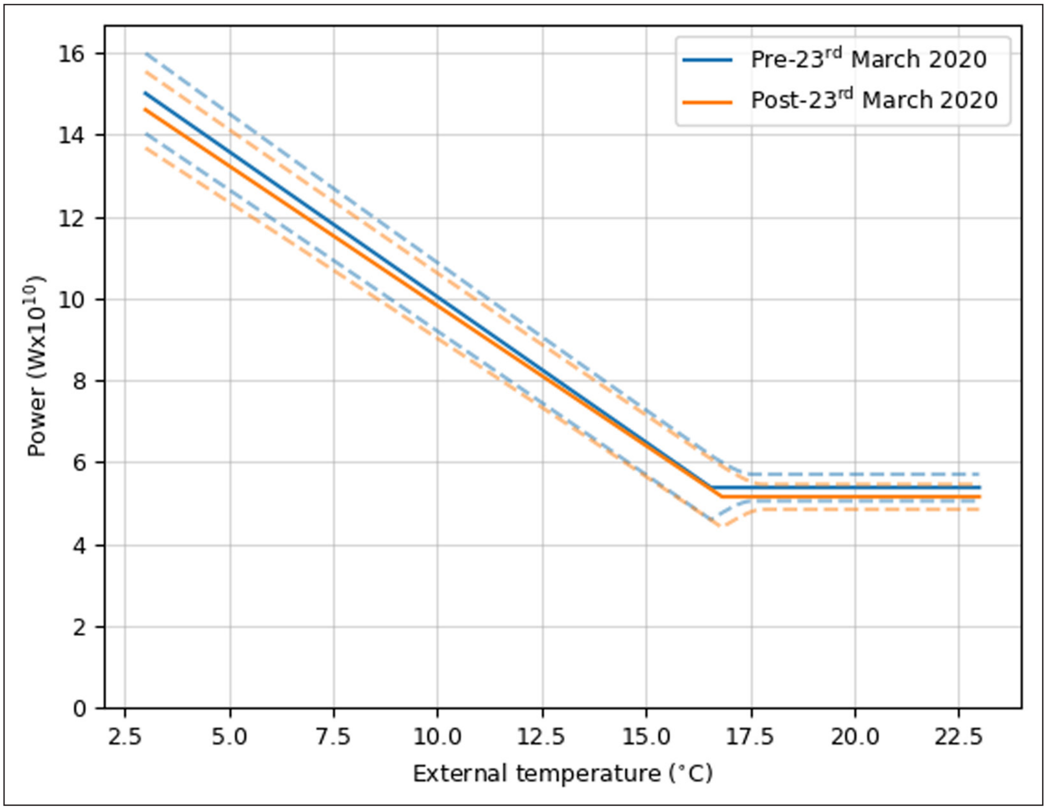

Figure 2: Estimated relationship between the daily average external temperature and power (rate of electricity and gas consumption) based on power temperature gradient (PTG) analysis of the GB Building Stock both before and since the start of lockdown 1, plotted at zero solar radiation.

Note: The gradient of the slope is the heat power loss coefficient (HPLC); the power of the flat section is the baseline power; and the temperature at the changepoint between these sections is the balance temperature given zero solar radiation. The dotted lines reflect 1 SD (standard deviation) of the posterior distribution of the power prediction.

3.2 RESIDENTIAL BUILDINGS

Lockdowns 1 and 3 were investigated for the Residential Buildings dataset; the former in comparison with data from 2019, and the latter with data from January–February 2020 (Figure 1). Recruitment to SERL took place in waves; here analysis of all 2019 data was compared with lockdown 1 to maximise the number of households with data from both periods, as the ideal comparison period of exactly one year before contained insufficient households. As the energy signature analysis considers the external temperature and level of solar radiation, these variables do not need to be matched for a valid comparison period; however, the time of year affects the daylight duration and the shading around buildings which will likely affect the dwelling's energy consumption in turn. Data from a full calendar year will incorporate the full range of these effects and therefore data from all 2019 are a reasonable comparison period. Lockdown 3 was compared with data from January–February 2020, before restrictions due to the spread of COVID-19 began to take place, but after COVID-19 was first reported in the UK media, some habits could potentially have started to change.

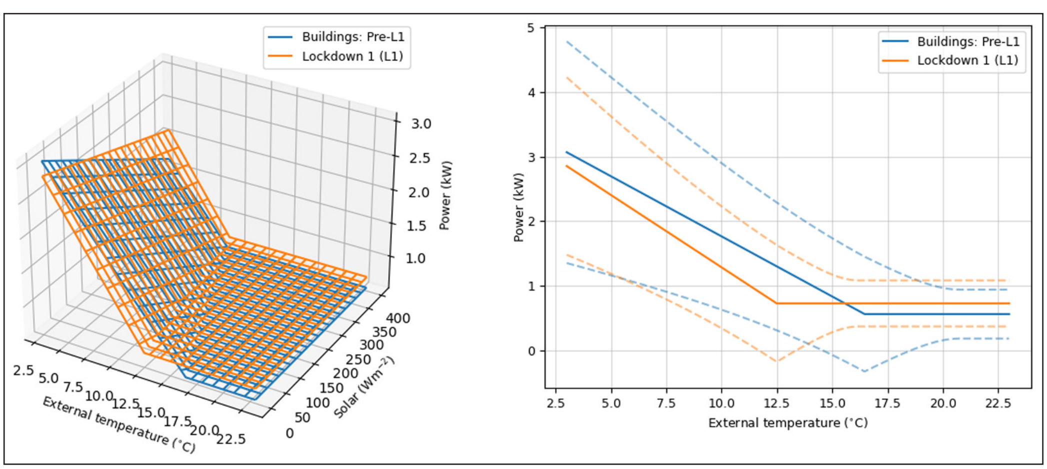

Figure 3: Mean estimated daily average power (rate of electricity and gas consumption) per building in the Residential Buildings dataset at different external temperatures in 2019 and during lockdown 1: (left) the full model and (right) at zero solar radiation.

Note: These are produced from the results of individual household power temperature gradient (PTG) analysis averaged across 914 households analysed. Unlike in Figure 2, here the dotted lines reflect the combined errors in each estimated parameter across all households in the datasets and as such are larger. In particular, the contribution of error in the balance temperature is clearly shown in the lower-bound line, reflecting the transition between the two segments of the model.

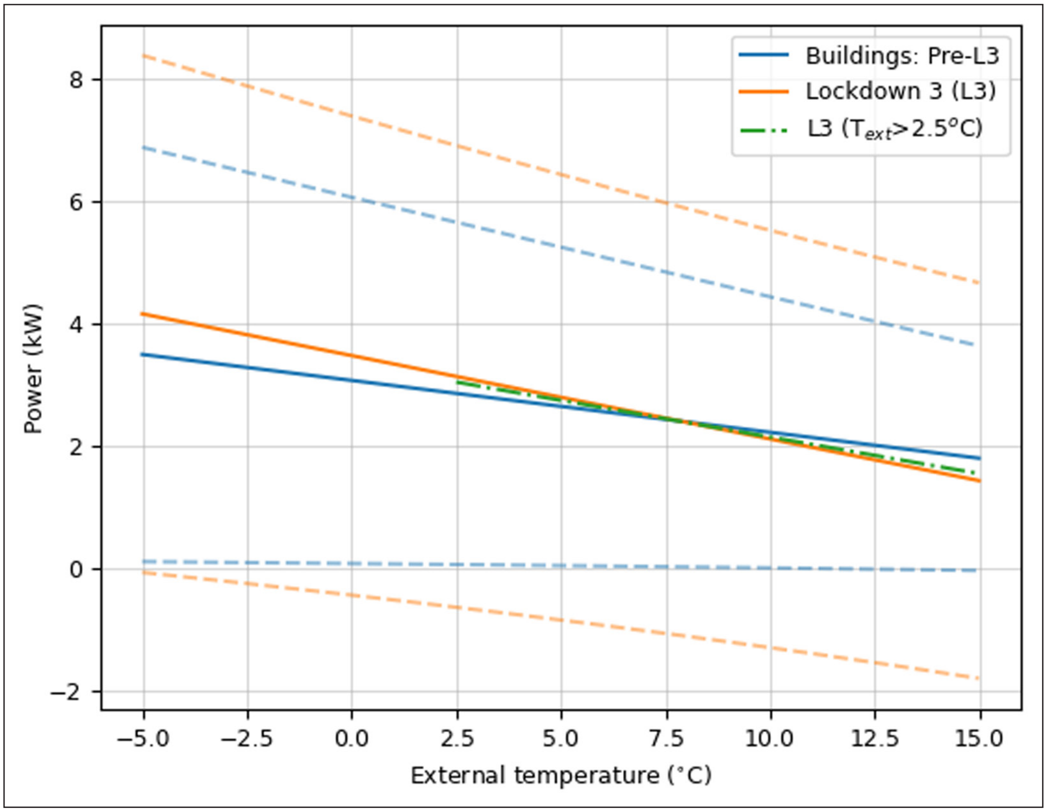

Figure 4: Mean estimated daily average power (rate of electricity and gas consumption) per residential building in early 2020 and lockdown 3.

Note: As in Figure 3, these are produced from the results of individual household power temperature gradient (PTG) analysis averaged across 1406 households analysed. The green dot–dash line corresponds to the analysis of data from lockdown 3 at daily average temperatures above 2.5°C to provide a closer comparison due to the lack of these temperatures in the January 2020 dataset. As boilers can fail to achieve their setpoints at lower temperatures, creating a complex non-linear relationship between energy use and external temperature, excluding such temperatures avoids such issues skewing results.

Figure 3 shows that in lockdown 1 during the heating season (sloped section of the graph) homes would use less energy at a given external temperature and more energy outside of the heating season (baseline power). Around 30% (±2%) more energy per degree temperature drop was used on average during lockdown 1, with the mean HPLC changing from 186 to 223 WK^{-1}, which is a significant difference: $t(1826) = 7.71$, $p < 0.001$, $d = 0.29$. For lockdown 3 (Figure 4), which only includes heating season data, there is again a significant difference in the gradients of the plot shown in Figure 4 for lockdown 3 and the comparison period, however the with larger confidence bands than for lockdown 1. The mean change in HPLC is 53% (±3%) in lockdown 3, with the average increasing from 85 to 136 WK^{-1} (Figure 5c), and is also significant: $t(2810) = 14.93$, $p < 0.001$, $d = 0.50$. An additional dash–dot green line again shows data from households in lockdown 3, but only where the average daily temperature was > 2.5°C to more closely align with the temperature range of the comparison period. Here the mean change is smaller, at 41% (±2%) with a 'before' HPLC of 120 WK^{-1}, but still significant: $t(2810) = 9.81$, $p < 0.001$, $d = 0.40$. That this line is closer to the comparison period suggests that during lockdown 3 there was an increase in the HPLC at lower temperatures; this is a surprising result, implying that homes used more energy per degree temperature drop below 2.5°C.

Figure 5a demonstrates that the PTG method results in high variance of parameter estimates on an individual property level, but reveals insights about the whole sample. Most changes in HPLC are small, in agreement with survey responses (Huebner *et al.* 2021), indicating that little change was made to the hours and areas of homes in which space heating was used. The balance temperature decreased in lockdown 1, by 20% (±6%) or around 4°C (Figure 5b), in part because of the increase in baseline power of 50% (±4%) (Figure 5d), reflecting the assumed increased heat gains from lights, appliances and hot water use offsetting the need for space heating. For lockdown 3, baseline power and balance temperature were either not estimated or with insufficient certainty due to the low external temperatures during this lockdown and the consequently simplified model (equation 2) applied.

Analysis of the SERL Observatory highlights that the domestic sector had increased baseload demand in lockdown in contrast to other sectors, and also that some behavioural changes may have led to changes in the rate of increased energy consumption at decreasing temperatures. The increased baseload demand of households during lockdown will have contributed to the relatively small change seen in the National Grid data for the GB stock.

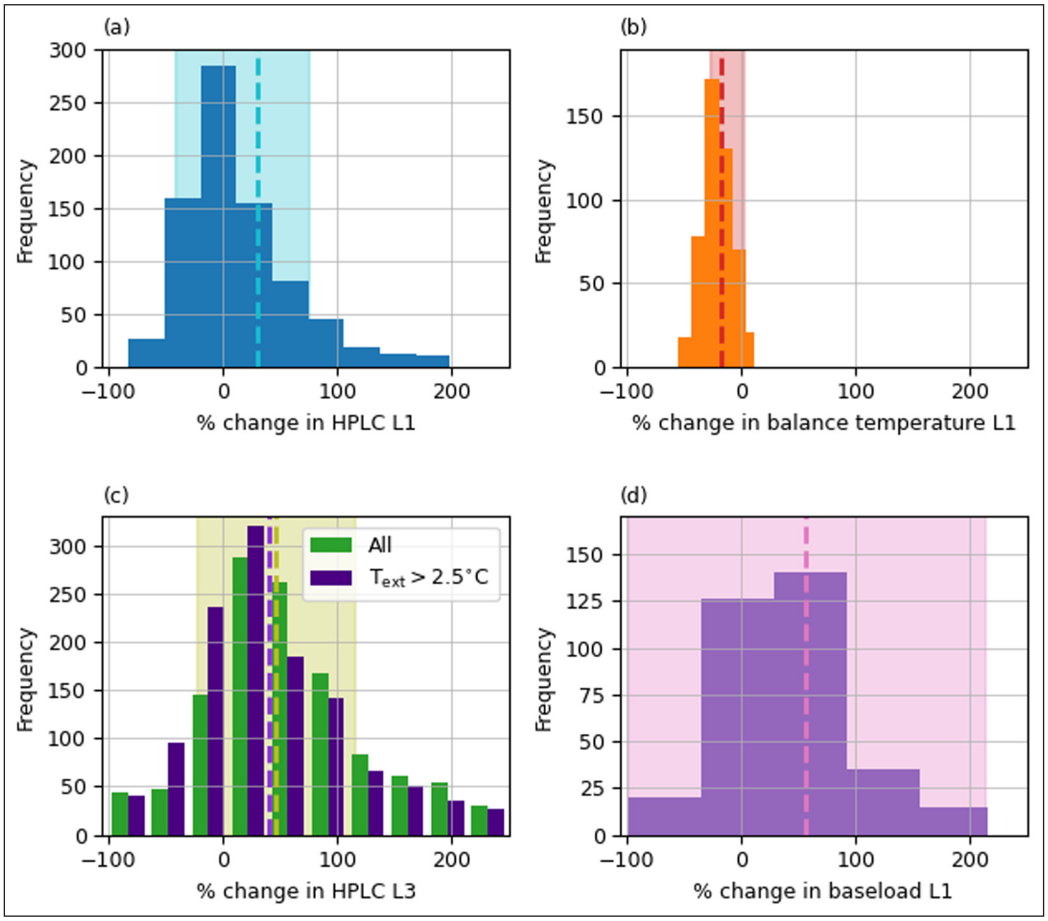

Figure 5: Distributions of the percentage changes for each individual property across the Residential Buildings dataset in three estimated parameters for lockdown 1 from 2019, and in the heat power loss coefficient (HPLC) alone for lockdown 3 from January and February 2020.

Note: The mean and standard deviation of these differences are indicated by vertical sections. **(a, c)** Most changes in the HPLC were small for lockdowns 1 and 3, respectively, with a trend towards a decrease in efficiency, particularly in lockdown 3; **(b)** the decrease in balance temperature in lockdown 1 is at least partially attributed to the increase in baseline power **(d)**.

3.3 RESIDENTIAL BOILERS

The Residential Boilers dataset enabled analysis of the impact of lockdowns on mains gas combi-boiler-heated homes. The number of hot-water tappings was used as a proxy for occupation; the number of days without a hot water tapping decreased significantly during lockdown, implying that the number of days occupied increased. Such changes in occupancy would be expected to impact energy use in the home. As Figure 6 illustrates, there was a significant increase in total number of hot water tappings, 36% in lockdown 1, from 18.9 (SD = 16.2) to 25.7 (SD = 19.7), and 11% in lockdown 3: from 19.1 (SD = 15.8) to 22.7 (SD = 17.8). Despite the far smaller change in the later lockdown, both changes are significant: $t(16075) = -57.9$, $p < 0.001$, $d = 0.2$ for lockdown 1; and $t(19131) = -76.8$, $p < 0.001$, $d = 0.2$ for lockdown 3.

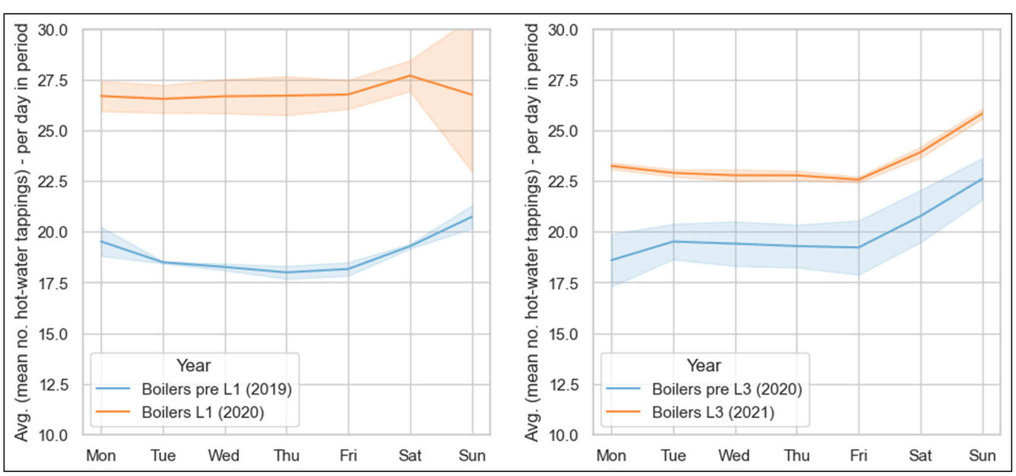

Figure 6: Comparison of the number of hot water tappings per weekday across lockdowns 1 and 3, with a 1 SD (standard deviation) error band.

Alongside an increase in the number of hot water tappings, the total observed hot water use (mean daily litres) significantly increased in lockdowns 1 and 3 (Figure 7), with a greater difference in lockdown 3. The mean total daily hot water use for lockdown 1 is 131.35 L (SD = 111.1 L), and in the comparison period 113.8 L (SD = 106.1 L). This change is significant: $t(16075) = -52.8$, $p < 0.001$, $d = 0.2$.

The mean total daily hot water use for lockdown 3 was 127.3 L (SD = 110.1 L), compared with a mean 114.7 L (SD = 101.5 L) in the previous year. This difference too is significant, $t(19131) = -44.4$, $p < 0.001$, $d = 0.1$.

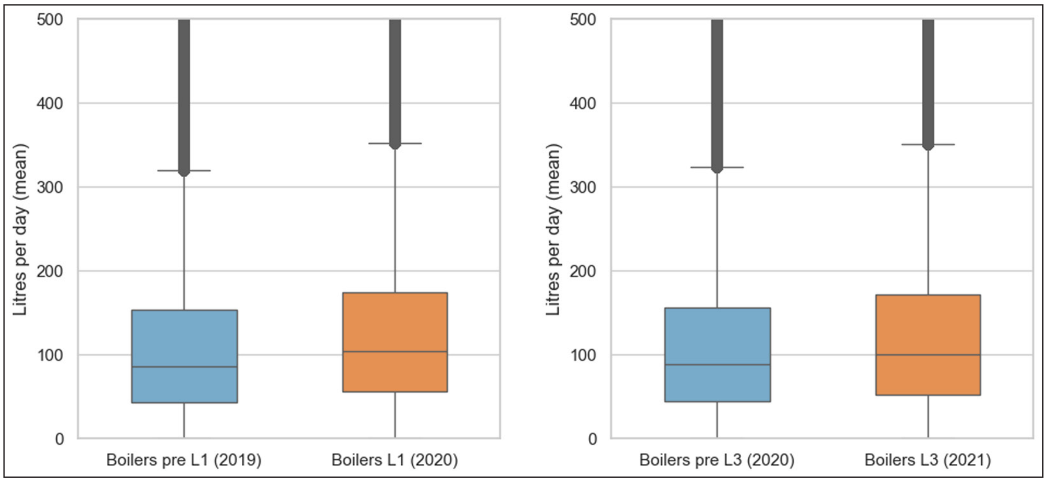

Figure 7: Daily residential hot water demand (litres) in lockdowns 1 (2020) and 3 (2021).

Figure 8 shows the change in degree-day-normalised space heating demand for the sample of homes with boiler data. In lockdown 1, the demand decreased by 10.2%; and in lockdown 3, by 6.4%. A paired samples *t*-test was run for both changes and showed that the decreases in degree-day-normalised space heating demand were statistically significant; $t(16075) = 41.9$, $p < 0.001$, $d = -0.2$ for lockdown 1 and $t(19131) = 61.9$, $p < 0.001$, $d = -0.1$ for lockdown 3. The means for lockdown 1 and the preceding year are 4.2 kWh (SD = 3.1 kWh) and 4.7 kWh (SD = 2.9 kWh) respectively, with figures for lockdown 3 and the preceding year of 5.7 kWh (SD = 2.4 kWh), 6.1 kWh (SD = 2.6 kWh). As there are no further contextual data for the homes (*e.g.* reported changes in the number of rooms heated or thermostat setpoints), this change cannot be attributed to any particular heating behaviour.

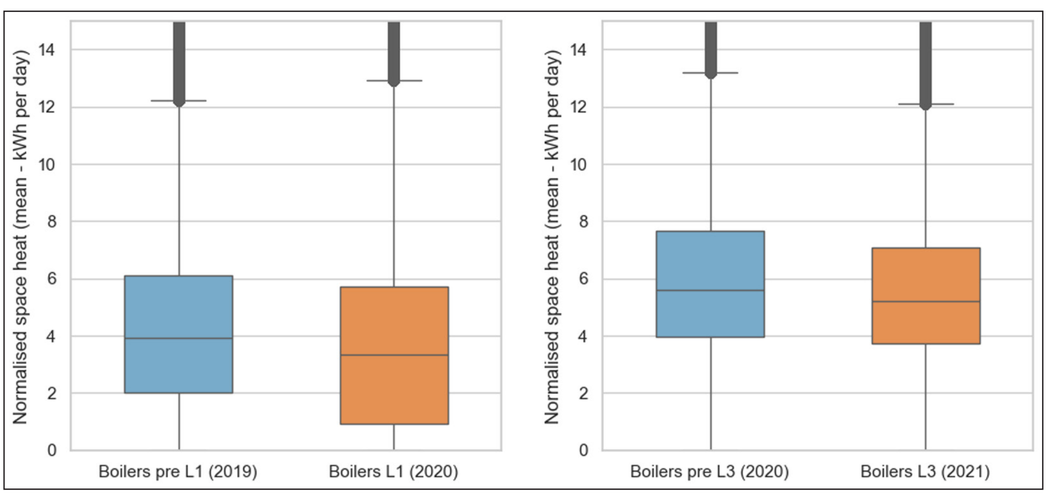

Figure 8: Normalised daily space heating demand (kWh) in lockdowns 1 (2020) and 3 (2021).

4. DISCUSSION AND CONCLUSIONS

Did COVID-19 lockdowns cause building energy use to change? The evidence in this paper suggests a complex answer to this simple question; however, a consistent and perhaps surprising narrative emerges.

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The impact of lockdown restrictions during the COVID-19 pandemic was investigated in this research by analysing three energy datasets recorded at complementary scales: gas and electricity consumption in the complete building stock and in a sample of about 1000 homes; and a sample of boilers from about 24,000 homes. Lockdowns imposed huge restrictions on leaving home and working conditions and were consequently expected to significantly impact energy use in domestic and non-domestic properties; however, only small changes in energy demand were observed.

Analysis of the GB Building Stock data including domestic and non-domestic buildings indicated that lockdown restrictions and a switch to working from home had very little impact on the national building energy consumption. In the analysis of individual residential buildings, predicted energy consumption was found to increase in lockdown 1 when not using space heating, but to decrease otherwise, with increased energy consumption during lockdown 3. Findings from the Residential Boilers dataset indicated increases in gas-fired water heating, aligning with the buildings results, however with decreases in gas-fired space heating, although the latter is a very small effect, and could perhaps indicate increased use of electricity-based heating, such as portable fan heaters or heated blankets, in homes during lockdowns. The estimated energy use per degree temperature drop of the homes in the Residential Buildings dataset decreased in both lockdowns, which could be caused by increased window opening or heating previously unheated spaces and hence increasing the surface area for building heat loss; however, occupants did not self-report this latter activity (Huebner *et al.* 2021). This change was larger in lockdown 3, with much cooler external temperatures than in the comparison period. This is likely due to the decreased temperatures during this lockdown, with the smaller change in HPLC when only days > 2.5°C were analysed, suggesting that the estimated HPLC changes at extremely low temperatures, disagreeing with the PTG model which assumes a linear relationship with external temperature. This could perhaps be due to increased heating hours or additional rooms being heated at these lower temperatures. Hampton (2017) found that when working from home people were willing to use measures such as hot water bottles to keep warm, and it may be that these become insufficient below around 2.5°C, resulting in the increased space heating demand.

Santos & Azhari (2022) estimate an increase (0.11–0.6%) in total UK greenhouse gas emissions in their scenario of increased homeworking across all sectors, based on an assumption on increasing domestic demand for electricity and gas through increased hours at home (where 62% of domestic demand is for space heating), and this is also raised as a concern by Erias & Iglesias (2022). However, with space heating here not found to hugely increase, or indeed increase at all, this may be an overly pessimistic view. Analyses of both residential buildings and residential boilers found that electricity use and water heating did increase in lockdown, with increased free heat gains from this likely contributing to the lower heating season consumption. The increase in hot water demand could be due to increased occupancy of domestic homes and demand displaced from leisure activities such as showering elsewhere and eating outside the home.

The increases in residential energy consumption could perhaps explain the small changes seen at the national, both domestic and non-domestic, level, and could indicate that increased working from home will not have a large impact on overall energy consumption going forward. However, it is also true that consumption in the non-domestic sector appears to have decreased less than initially assumed, with many businesses operating as normal during the lockdown periods (ONS 2021). To achieve an overall reduction in demand it would be necessary to have variable operation of workplaces to enable reactions to lower levels of occupation (Hampton 2017).

The future implications of the changes in lockdown energy use have been explored by Trask *et al.* (2021), considering the uptake of electric vehicles and the pursuit of net zero, with changes to residential demand not found to be impactful on these goals. Studies of China, Italy, Europe and the US have also explored changes in national energy consumption during lockdowns, with similar findings to the UK (IEA 2021; Krati & Aldubyan 2021; Honoré 2020).

Homes were occupied more during pandemic lockdowns, which is supported by increased hot water and electricity use. However, around a third of adults in the UK were classified as key workers (ONS 2020c), continuing to work outside of their homes, with children of key workers attending school. A detailed survey on the impact of COVID-19 on occupant practices, using the same cohort as the Residential Buildings data, reported a majority (61.4%) of the sample having no change to how many adults worked from home during the lockdown in 2020. The increased non-space heating energy use observed in this study is consistent with reported increases in home cooking, washing, watching television and online meetings (Huebner *et al.* 2021). Surprisingly, space heating demand did not hugely increase, which is partly attributable to increased indirect heating from cookers and other appliances. We might have expected the space heating to be on for longer and more rooms heated because of the increased occupancy hours; however, space heating is indirectly controlled by programmers and thermostats that are often poorly understood and challenging to change (Huebner *et al.* 2013). The survey conducted by Huebner *et al.* (2021) supports this finding, with occupants reporting little change to heating zones, timing and setpoints. Occupants may have dressed warmer or otherwise adapted to cooler internal temperatures during times when their houses were previously unoccupied.

The potential adaption of occupants to cooler temperatures in occupied but unheated periods has implications for behavioural change expectations and demand-side management. Did occupants not adjust their space heating because they retained habits around heating system operation? In such a case, a demand-side response, to balance supply and demand, may have poor uptake or low effectiveness if it is needed to be initiated by the home occupants. Direct load control was found to be surprisingly acceptable by Fell *et al.* (2015), so it may be that a remotely managed demand-side response with electric heating would be more effective than self-managed. Does the lack of change instead demonstrate occupants' adaptability in dressing warmer or otherwise adjusting to their environment, which could support the implementation of a demand-side response? A limited ability to adjust space heating settings could also contribute. Further research is required to explore this possibility.

When people were spending more time at home and were forbidden to visit many buildings, it would be thought that the energy use in non-domestic buildings should have reduced. However, analysis of all buildings connected to the National Grid showed that total building energy use changed minimally. Analysis of households in the SERL Observatory showed an increase in energy use outside of the heating season and a decrease otherwise, suggesting increased appliance use throughout which could have masked a decrease overall in non-domestic buildings. However, much energy use in non-domestic buildings is automatically controlled and set regardless of occupation—even lighting is sometimes set permanently to 'on' for security—so perhaps this could explain the small nature of the changes found (Erias & Iglesias 2022). This suggests that improvements to automation arrangements and systems, in addition to reappraising space requirements, could result in greater demand reduction with increased working from home than was achieved during COVID-19 lockdowns.

The small change to national building energy demand during the lockdowns could be seen as an argument against behavioural change as a contributor to reaching net zero. However, a major contributor to the small scale of the change could be widescale uptake of adaptive comfort measures by occupants to avoid increasing their energy use when working from home. This adaptability could contribute to future energy demand reductions in support of achieving net zero. Occupants appear to have either chosen to adapt to cooler temperatures in their homes at certain times of the day, or have been unwilling (or unable) to adjust their heating schedules. Decarbonisation of heating through the widespread adoption of heat pumps may benefit from these findings. First, heat pumps are most efficient with a relatively constant space heating schedule (Crawley *et al.* 2023) compared with gas boiler operation during constrained hours in a morning and evening period, as common in the UK (Huebner *et al.* 2013); a switch to heat pumps may bring significant improvements to thermal comfort during occupied but currently unheated hours, a potentially attractive proposition to occupants. Second, a demand-side response of heat pumps may be required to support grid management (Crawley *et al.* 2023) and the potential for occupants to adapt their practices to accommodate lower temperatures during certain times may support its implementation. Further research is required to explore these issues in detail.

The above narrative has used three very different datasets in terms of contextual data and consistent sample, none of which was collected explicitly to answers questions about the impact of COVID-19 on building energy use. In consequence, a range of different analytical techniques have been used to unpick what might have happened. However, the analysis does highlight how innovations in smart meter data and Internet of Things-enabled devices (residential boilers in this case) could in future be used to provide more coherently the evidence base for future research, for example, into changes in energy use during the net zero transition. In the UK, an observatory of residential energy use is being established that plans to use this combination of smart meter and other transducers to track future changes in energy use (EPSRC 2022).

NOTES

1 Lockdown 2 (November 2020) is not considered in this paper due to it short length (four weeks) and the varying restrictions across the country.

2 Boiler transducers are input sensors within the boiler, monitoring temperatures and flow rates of hot water within the system along with one on the diverter that monitors demand source.

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FH: data curation, formal analysis, methodology, software, visualisation, writing—original draft preparation; DH: data curation, formal analysis, methodology, software, visualisation, writing—original draft preparation; TO: supervision, writing—review and editing; CE: supervision, writing—review and editing; GMH: conceptualisation, funding acquisition, project administration, supervision, writing—review and editing.

COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

All data used in this paper are secondary datasets. National Grid data as used for the GB Building Stock dataset can be accessed at ESO, National Grid (2023), and details of how to apply for access to the SERL Observatory used for the Residential Buildings dataset are in Webborn *et al.* (2021). The Residential Boilers dataset cannot be shared.

ETHICAL APPROVAL

Ethical approval was not required as no new data were collected and all secondary datasets used were pseudo-anonymised or anonymised.

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