The impact of the UK’s COVID-19 lockdowns on energy demand and emissions

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Keywords: COVID-19, GHGs, air pollution, energy, electricity, gas

Abstract

Around the world, efforts to contain the COVID-19 pandemic have profoundly changed human activity, which may have improved air quality and reduced greenhouse gas emissions. We investigated the impact of the pandemic on energy demand and subsequent emissions from electricity and gas throughout 2020 in the UK. The daily pattern of electricity demand changed in both lockdowns, with weekday demand shifting to that of a typical pre-pandemic weekend. Energy demand in 2020 was modelled to reveal the impact of the weather and the pandemic. The first lockdown reduced demand by 15.6% for electricity and 12.0% for commercial gas, whereas the second lockdown produced reductions less than half. Domestic gas demand did not change during the first lockdown, but increased by 6.1% in the second, likely due to increased domestic heat demand. The changes in demand for gas resulted in little change to overall gas consumption emissions during the pandemic. For electricity, large emission reductions occurred during the two lockdowns: up to 22% for CO$_2$, 47% for NO$_x$, and 29% for PM$_{2.5}$. Yet, the largest CO$_2$ emission reduction for electricity in 2020 (25%) occurred before the pandemic, which happened during a warm and stormy spell with exceptional wind generation. These observations suggest that future similar changes in activity may result in little change for gas demand and emissions. For electricity, emission reductions through changes in energy demand are made possible by the generation mix. To enable further emission reductions in the future, the generation mix should continue to decarbonise. This will yield emission reductions in both times of lowered energy demand, but more importantly, during times of high renewable output.

1. Introduction

The COVID-19 pandemic has impacted daily life all around the world with enforced lockdowns restricting typical human activities in the effort to contain the virus. These changes in human activities have had profound immediate impact on the production of air pollutants and greenhouse gases, resulting in observed improvements in air quality around the world (Berman and Ebisu 2020, Venter et al 2020, Wang et al 2020).

The largest energy vectors by fuel in the UK are petroleum (44%), natural gas (31%), and electricity (18%) (BEIS 2019). Petroleum is primarily used for transportation, gas is primarily for domestic heating and some industrial use, and electricity is used in roughly equal share by the domestic, industrial, and commercial sectors. All these energy vectors have been impacted by the changes in activity brought on by the COVID-19 pandemic. This study investigates how natural gas and electricity, which comprise half of the UK’s total energy demand, were impacted by the changes in activity brought on by the measures employed in the UK to combat the pandemic, and the resulting impacts on emissions of carbon dioxide and air pollutants.

Some recent studies have observed the impacts of COVID-19 restrictions on electricity demand. Bahmanyar et al (2020) and Cicala (2020) investigate hourly electricity demand patterns in Europe and...
the US respectively. Prol and Sungmin (2020) model electricity demand from March to August in 2020 in a counterfactual scenario with no pandemic restrictions to show the reductions across several countries and US states. Here we use similar methods to model counterfactual demand in the UK for all of 2020 for electricity and, additionally to these studies, for natural gas. We cover the UK’s two national lockdowns in 2020 and periods where measures to combat the pandemic were localised, revealing how the different levels of restriction had corresponding different levels of impact on energy demand and emissions.

Gillingham et al (2020) went beyond demand to estimate the emissions reductions due to changes in several energy vectors in the months after lockdown commenced in the United States. However, the authors warn how the socioeconomic impact of the pandemic in the long-term could delay policies to mitigate emissions, which may then outweigh the reductions seen in the short run. Here we provide the first estimate for the changes in CO$_2$ and air pollutant emissions caused by the UK’s lockdowns.

Finally, we contextualise these emissions savings by comparing them to the influence of weather on energy demand (due to heating) and electricity supply (due to renewable output).

2. Methods

Our approach consists of four steps outlined in the following subsections:

(a) Collect data on electricity and natural gas consumption;
(b) Estimate emissions of CO$_2$, NO$_x$ and PM$_{2.5}$ from final energy demand and secondary/mid-stream conversion of fuels into electricity;
(c) Develop demand regression models to correct for changes in weather, allowing 2020 to be compared to previous years;
(d) Correct for changes in renewable capacity between 2020 and previous years using marginal emissions factors.

With this approach, we first make a direct comparison between demand and emissions in 2020 with those from the previous three years (2017–19). We then generate counterfactual scenarios for demand and emissions in 2020 if both the weather and electricity generating infrastructure were held constant, thus allowing the impact of the pandemic to be separated from that of differences in temperature and renewable energy production.

Throughout 2020, the response in the UK to COVID-19 took on different levels of severity. We have condensed the range of responses to a period of either national lockdown or local measures. The timeline of 2020 using these categories is given in Table 1. We use these date periods to later frame our findings.

2.1. Data collection

Data on UK electricity generation was taken from Electric Insights (Staffell 2020). The data included the generation output of each powerplant type at a half hourly time resolution, including embedded generation sources, and overall electricity system metrics such as the carbon intensity of electricity. The method to produce this data is documented by Staffell (2017). Data on daily gas use was taken from the National Grid’s online database (2020). Gas consumption in the UK is split between categories:

(a) Power stations, gas consumed in the generation of electricity, connections directly to the National Transmission Systems (NTS).
(b) Industrial offtake, gas consumed by industrial sites with a direct offtake from the NTS.
(c) Daily metered (DM), gas consumed by smaller scale industry and larger commercial locations.
(d) Non-daily metered (NDM), mostly domestic gas consumption and smaller commercial buildings, where consumption is not monitored daily. Both DM and NDM offtake from Local Distribution Zones.
(e) Storage, gas taken off from the NTS for storage.

To avoid double counting gas consumed in power stations, the fuel demand and resulting emissions for gas power stations were included this study, but were exclusively allocated to the electricity domain. Only final demand (combustion) was considered in this analysis and so natural gas storage was not used. A full description of the data items taken from the database is given in the supplementary material (available online at stacks.iop.org/ERL/16/054037/mmedia).

2.2. Estimating emissions

Emissions of CO$_2$, and air pollutants NO$_x$ and PM$_{2.5}$, from electricity and natural gas consumption were estimated using emissions factors for each general powerplant technology. CO$_2$ emissions were based on the emissions factors derived in Staffell (2017) for the British power sector. For NO$_x$ and PM$_{2.5}$, the UK National Atmospheric Emissions Inventory (NAEI)
was used to derive emissions factors (NAEI 2018). Emission factors were assumed to be constant within each powerplant type, as Britain does not have an equivalent to the US Continuous Emissions Monitoring System, and so plant-level emissions data do not exist. However, Britain’s fleet consists of relatively homogenous technologies built in consolidated phases (e.g. combined-cycle natural gas turbines from the 1990s and 2000s, biomass conversions from the 2010s), and generation efficiencies across the fleet are similar within these technologies (Ward et al 2019). The emission factors for both electricity and gas are given in the supplementary material.

To calculate emissions from gas combustion, emissions factors were derived from the NAEI (2018) for CO₂ and air pollutants. The NAEI contains more granular sources of natural gas combustion than the National Grid data, and so required pooling of the NAEI sources to align with the National Grid categories. However, as NDM, DM and Industrial Offtake contain overlapping NAEI categories, assumptions were made to accommodate the discrepancy. The key assumption was to allocate 2/3 of NDM as the NAEI source: domestic combustion. The 2/3 fraction was determined by comparing the total NDM demand with the value for domestic combustion given in the Digest of UK Energy Statistics (BEIS 2019). This observation agrees with similar observations by Wilson et al (2013). The remaining NAEI sources were pooled together, corresponding to 1/3 NDM, DM and Industrial Offtake. Finally, emission factors were derived by diving the NAEI emissions by the corresponding activity data.

2.3. Demand regression models
Demand for electricity and gas follow a strong weather dependant relationship in the UK, as a large proportion of this energy is used for heat. A shared axis energy diagram of electricity and gas demand are given with average daily temperature in figure 1, which illustrates this relationship.

We created models of demand for electricity and gas as a function of weather-based variables to enable the modelling of two counterfactual scenarios of demand in 2020. Following the methods of Staffell and Pfenninger (2018) we derive population-weighted heating degree days (HDDs) and cooling degree days (CDDs) for Britain based on gridded temperature data from NASA’s MERRA-2 reanalysis (Gelaro et al 2017).

Historical demand for electricity and natural gas was modelled using ordinary least squares (OLS) regressions against these HDDs and CDDs, with separate regressions performed for weekdays versus weekends and holidays. The regressions were based on data from 2017 to 2019, where overall energy demand for both energy vectors has not significantly changed. The derived regression functions with predictor coefficients are given the supplementary material.

Models were derived for electricity and the two weather dependant gas categories: DM and NDM. Industrial offtake does not follow a temperature or seasonal relationship, and so, no model was derived.

Using the OLS demand models, two scenarios for 2020 were modelled:

(a) Actual Weather Scenario: demand predicted using actual CDDs and HDDs from 2020.
(b) Typical Weather Scenario: demand predicted from CDDs and HDDs representing the typical weather conditions. Typical weather conditions were produced by taking the mean values of CDDs and HHDs from the last decade and smoothed using a two-week rolling average.
2.4. Controlling for renewable generating capacity

As emissions in 2020 are compared to previous years, the generation mix in 2020 was controlled for the increase of installed renewable capacity over the period from 2017 to 2020. The installed capacity of biomass, wind, and solar generation increased by 23%, 18%, and 2% respectively between the 2017–19 average and 2020 (using end of year capacity values) (Staffell 2020). We therefore linearly reduced their output in 2020 by these values to synthesise what they would have produced with infrastructure of the historical period. There was no change in hydro capacity over this period, so it was unchanged.

This reduction in renewable generation meant more supply had to come from other powerplant plant types. This increased supply was distributed between other powerplant types based on the marginal impact of renewables on their output during 2019 and 2020. Following Gissey et al (2018), we performed linear regressions on the first differences (change between each half-hour period) for output from renewables as a function of output for each other powerplant technology in turn. From this, we found that gas, imports, and coal provided the largest share of the increase: 84%, 12%, and 4%, respectively. The method and results of the regressions are given in detail in the supplementary material.

By amending the generation mix in this way, the confounding effect of increased installed capacity of renewables was removed. This change isolated the impacts of the pandemic and of the weather on the generation mix and resulting emissions. More extensive controls for the generation mix, such as to accommodate changes in fossil fuel generation or in the hour-to-hour output of renewables, were not used as these would make our counterfactual scenario deviate more widely from actual outcome. Our marginal analysis is valid when applied at the margins (Gissey et al 2018), so the aforementioned mix of powerplants would likely be responsible for adapting to small changes from realised renewable output. Larger changes (e.g. upwards of 20 GW) could be expected if other factors were controlled for, and so would potentially be accommodated for by a very different mix of technologies. Understanding this would require use of an electricity system model to replicate the changes in conditions between 2017 and 2020, and so would risk revealing more insights about the assumptions and workings of the model than about the impact of the pandemic (Ward et al 2019).

3. Results and discussion

First, energy demand in 2020 is compared to the previous three years is given on daily and yearly time-scales. Next, to determine how the pandemic and the weather conditions of 2020 impacted energy demand we present two counterfactual scenarios investigating these two factors. Lastly, we observe how emissions in 2020 has changed from previous years, using the generation mix to illustrate the electricity emissions reductions.

3.1. Demand

3.1.1. Comparing 2020 to the previous three years

Throughout most of 2020, the daily pattern of electricity demand (referred to as the demand profile) was markedly different from the last three years. Before the first national lockdown, demand on both week-days and weekends were consistently lower throughout the day than in previous years, as shown in figure 2. During both national lockdowns, weekday and weekend demand fell, particularly at peak times in the morning and evening. In the first national lockdown, weekday demand experienced the largest decrease, falling to that of a typical weekend. The change in the demand profile corresponds to the observed change in behaviour by the UK population, with most people staying at home, mimicking the conditions of
a weekend throughout the week. Weekends in lockdown remained lower than weekdays, as some essential workplaces likely still followed a traditional work week schedule. During the period of local measures, where changes to human activity to combat the pandemic were localised, saw the smallest change during the pandemic.

Demand before the first national lockdown was reduced compared to the previous three years, as evident in figures 2 and 3. The role of weather conditions during this period and its impact on demand and subsequent emissions are investigated in sections 3.1.2 and 3.2 respectively.

During the first lockdown, demand fell for DM gas and electricity, both exhibiting a step reduction in demand which tended back towards the three-year average during the local measures period. No observed change in industrial offtake could be attributed to changes in activity due to lockdown.

3.1.2. Scenarios of 2020
Two counterfactual scenarios were modelled to disaggregate the effect of the pandemic and the weather on energy demand in 2020. The resulting daily energy predictions of these scenarios are shown in figure 4.

Using these predictions, the impact of the weather on demand was determined from the difference between the typical and actual weather scenarios (A and B from figure 4). Next, the effect of the pandemic can be determined by the difference between the demand predicted by the actual weather and the real demand (B and C from figure 4). These differences are given in figure 5, averaged across the different periods of restrictions during 2020.

The weather reduced demand for all energy vectors at the beginning of 2020, as shown in figure 5, explaining the previous observations of lowered demand occurring before the pandemic. The weather continued to impact demand throughout 2020, mostly affecting NDM gas. There were small changes in activity due to the pandemic before the first national lockdown commenced, these restrictions in activity produced a small reduction in demand for electricity and DM gas.

The first national lockdown had the greatest impact on electricity and DM gas, with the restrictions causing demand to fall by 15.6 ± 1.8% and 12.0 ± 0.8%, respectively (±95% prediction intervals). The second national lockdown produced a reduction less than half of the first, with electricity and DM gas falling by 6.3 ± 2.3% and 4.1 ± 1.1%, respectively. This discrepancy in demand reductions between the lockdowns corresponds to the observed difference in restriction measures. In the first lockdown only essential work was permitted, whereas in the second more economic activity was allowed to continue (Hale et al 2021). This discrepancy also explains the earlier differences between the lockdowns on the daily electricity demand profile, shown in figure 2.

The second national lockdown occurred during a cold period with substantial heat demand. During this period, NDM gas demand increased due to the lockdown by 6.1 ± 1.6%, the only increase in
demand observed due to lockdown. This observation could correspond to the shift of heat demand from the workplace to the home, where majority of heat is provided by domestic combustion. These societal shifts may correspond to redistribution of demand between the energy vectors, from electricity and DM to NDM. As typical daily working patterns are expected to change as the result from this pandemic, but also due to larger socioeconomic trends, the relationship between the different energy vectors requires further research.

The mean reduction in DM gas demand during the pandemic was found to be $8.9 \pm 0.4\%$, whereas NDM gas was observed to have a small increase of $1.2 \pm 1.0\%$. As DM demand consists of about a 5th of NDM demand, there was no change in overall gas demand during the pandemic. Throughout the pandemic, the restrictions caused electricity to reduce by $9.2 \pm 0.8\%$. Prol and Sungmin (2020) observed an $11.4\%$ reduction in electricity demand in the UK, over the same period as their study we observe an $11.7 \pm 1.2\%$ reduction, confirming their findings. The observation that electricity and DM gas demand was significantly reduced by changes in human activity due to pandemic measures agrees with previous findings, such as Gillingham et al (2020).
3.2. Emissions

All emissions were reduced at the start of 2020 before the first national lockdown, this follows the earlier observations that demand for all energy vectors was reduced due to weather during this period. This can be seen in figure 6, which shows daily emissions for 2020 and the mean daily emissions for 2017-19. These results are summarised in table 2 for specific periods in 2020, the values are given as the relative percentage of mean daily emissions in 2020 to that from 2017-19. Before the pandemic, CO$_2$ emissions from natural gas combustion (the sum of NDM and DM emissions) were reduced by 7% compared to the previous three years. During this period, for electricity we find a large relative CO$_2$ emission reduction of 25%, the largest relative reduction for any period for all of 2020. This reduction is partly due to the reduction in demand due to mild weather conditions and partly due to high share of wind in the generation mix.

In both national lockdowns there were significant emission reductions for electricity, and smaller reductions for gas as expected from the previous changes in demand. Whereas during the periods of local measures there were smaller emission reductions for electricity and a small increase for gas.

3.3. Electricity generation mix

The capacity of installed renewables was controlled in 2020 to match the previous three years, isolating the effects of weather and deployment of different generators to determine emissions. Despite this, during the start of 2020 low carbon sources made up a larger share of the mix and overall output than in the previous three years. This can be seen in figure 7, where both the renewable-adjusted generation mix and sum of low carbon sources are given. Of the low carbon sources, wind contributed far more than in previous years, this was due to exceptional weather producing extreme wet and windy conditions (Staffell 2020). Figure 7 is replicated for the unadjusted generation mix in the supplementary material, where wind was shown to break its relative and absolute generation records due to the weather and due to the increase in installed capacity.

The reduction in CO$_2$ emissions was greater in the period before the pandemic than during any of the
lockdowns. Combining this result with the generation mix for the same period, we can conclude that the reductions in emissions were enabled by the combination of installed renewables and by the mild weather conditions. These somewhat surprising results highlight how sensitive electricity generation emissions have become to seasonal variation in weather and the amount of installed renewables. It is important to state that the installation of more renewables capacity throughout 2017–20 meant emission reductions in this period were larger than this.

During the pandemic, low carbon sources were consistently lower than in the previous three years, with gas providing the flexibility to accommodate for changes in demand brought on by the pandemic. These reductions in demand and subsequent reductions in gas-fired electricity generation led to CO₂ emission reductions of 14% for the pandemic. The largest emission reductions during the pandemic occurred under national lockdown.

During the period of local measures, nuclear decreased to its lowest output for over a decade. A variety of factors lead to this low output, partly due to planned plant maintenance and repair, but also crucially due to the pandemic. The largest single generating unit on the grid, nuclear generator Sizewell B, was limited to half its normal output between May and September. This reduction was not to intended as long-term demand side response to the pandemic but implemented to reduce the risk of a system blackout (Gosden 2020). Werth et al (2021) similarly observed that nuclear output was reduced throughout Europe in response to the lowered demand during this period. The resulting generation mix for this period saw low carbon sources significantly lower than in the previous three years. The result of the opposing factors: reduced demand and reduced low-carbon generation, on emissions were largely negated, producing small reductions (2%) of CO₂ emissions.

4. Conclusions

During the UK’s first COVID-19 national lockdown in the spring of 2020, demand for gas and electricity was drastically reduced. Daily patterns in electricity demand shifted, with weekday demand reducing to that of a typical weekend before lockdown, reflecting the societal changes with more people remaining at home throughout the week, mimicking a weekend. Electricity demand fell by 15.6% and commercial gas (DM gas) by 12.0%, confirming earlier research on the impact of national lockdowns on demand. The second national lockdown in November 2020 produced reductions in demand less half that of first as the restrictions were less severe. Domestic gas (NDM gas) did not change in the first national lockdown and increased in the second by 6.1%. This increase is likely due to more heat demand in homes as this lockdown occurred during a typically cold period.

During the two national lockdowns daily gas emissions of CO₂, NOₓ, and PM₁₀,₅, fell when compared the same periods from the previous three years. However, on average over the duration of the pandemic there was no net change in daily gas consumption emissions. This lack of change came from the balance between the reductions in commercial gas and the lack of change at the start and then increase in demand for domestic gas. During both national lockdowns, electricity emissions were reduced by a much greater extent than gas. The reductions were produced by lowered fossil generation (coal and gas), despite low carbon generation below normal levels for
these periods due to low nuclear output. The lowered nuclear output throughout 2020 may have limited the emission reductions.

Mild winter conditions at the start of 2020 produced lowered demand and subsequently lowered emissions for both gas and electricity. This effect was greatest for electricity, where the CO₂ emission reductions for this period were the largest seen throughout all of 2020. The mild winter temperatures and exceptional wind generation, enabled by abnormal weather conditions, produced this reduction. This episode demonstrates the importance of low carbon sources’ ability to opportunistically reduce the emission intensity of electricity.

There is significant interest in learning from how the changes in activity during the pandemic affected energy demand and emissions. The conclusions from this work and further research on the pandemic can inform future policies aiming to reduce emissions, such as incentivising working from home. Changes in activity mimicking that of national lockdown will not likely change emissions from gas, as the reductions in commercial gas will be offset by the increase of domestic gas, as seen during the second lockdown. However, significant electricity generation emission reductions were observed for both before and during the pandemic. In both cases the generation mix, and in particular the contribution of low carbon sources, determined the scale of the emission reductions. Highlighting how both technological improvements and changes in activity are important for reducing future CO₂ and air pollutant emissions.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

D M was funded by the Natural Environment Research Council under Grant NE/S013350/1.

I S was funded by the EPSRC under Grant EP/R045518/1.

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