

Impacts of COVID-19 on the Energy System



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Table of Contents

	LIST OF ACRONYMS	4			
	EXECUTIVE SUMMARY	5			
1	INTRODUCTION	8			
2	CHANGES IN ELECTRICITY USE AT NATIONAL-SCALE	9			
2.1	Changes in consumption patterns	9			
2.2	Electricity generation mix	10			
2.2.1	Pricing of power	11			
2.2.2	Carbon emissions	11			
2.3	Observations outside of GB	11			
2.4	Summary	13			
3	IDENTIFICATION OF COVID-19 POLICY INFLUENCES ON ELECTRICITY USE	14			
3.1	The impacts of government policy in response to COVID-19 on electricity demand	14			
3.2	Methodology	14			
3.2.1	Policy data	15			
3.2.2	Weather correction	16			
3.3	Results	17			
3.4	Discussion	18			
3.4.1	Stringency and consumption	18			
3.4.2	Policy considerations	19			
3.4.3	Workplace closures	19			
3.4.4	Teleworking	19			
3.4.5	Economic implications	20			
3.5	Limitations	20			
3.5.1	Quantifying policy data	20			
3.5.2	Electricity only	20			
3.6	Summary	21			
4	CHANGES IN ELECTRICITY USE AT HOUSEHOLD SCALE	22			
4.1	Behavioural changes	22			
4.2	Current literature on household consumption	22			
4.3	Evidence from UK lockdown	23			
4.3.1	Data Collection	23			
4.3.2	Methodology & results	25			
4.3.3	Limitations	26			
4.3.4	Discussion & conclusion	26			
4.4	Willingness to telework and social implications	27			
4.4.1	Commute characteristics	27			
4.4.2	Work environment	29			
4.4.3	Social impact of teleworking	29			
4.5	Activity-based agent demand models	29			
4.5.1	Activity-based agent demand simulator for household electricity consumption	30			
			4.5.2	Demonstration of the activity-based agent demand simulator with work-from-home and electric vehicle adoption scenarios	32
			4.5.3	Simulation results	34
			4.5.4	Conclusions and limitations	36
			4.6	Summary	36
			5	CHANGES IN ELECTRICITY SYSTEM OPERATIONS	38
			5.1	Maintaining grid stability and ancillary services	38
			5.1.1	Conditions for grid stability	38
			5.1.2	Balancing the grid: tools and processes implemented by the ESO during COVID-19	40
			5.2	Future trends	41
			5.2.1	Methodology	41
			5.2.2	Results & discussion	42
			5.3	Applicability to other countries	43
			5.4	Summary	43
			6	CONCLUSIONS AND RECOMMENDATIONS FOR DECARBONISATION OF THE GB ENERGY SYSTEM	44
			6.1	The rise of teleworking	44
			6.2	Coordinating policy approaches	44
			6.3	Systems-based change	45
			6.4	Enhanced frequency response	45
			6.5	Market considerations	45
			REFERENCES		46

List of Acronyms

ABM	Agent-Based Model(ling)
BEIS	Department of Business, Energy and Industrial Strategy
BM	Balancing Mechanism
CfD	Contracts for Difference
EFR	Enhanced Frequency Response
ESO	Electricity System Operator
EV	Electric Vehicle
GB	Great Britain
GDP	Gross Domestic Product
ICT	Information and Communications Technology
IEA	International Energy Agency
ODFM	Optional Downward Flexibility Management
ONS	Office for National Statistics
OXCGRT	Oxford COVID-19 Government Response Tracker
PFR	Primary Frequency Response
RES	Renewable Energy Sources
RoCoF	Rate-of-Change-of-Frequency
WFH	Work(ing) from Home

Executive Summary

This Briefing Paper explores the impact the COVID-19 pandemic had on the UK's energy sector over the course of the first government-mandated national lockdown that began on 23 March 2020. Research from several aspects of the Integrated Development of Low-carbon Energy Systems (IDLES) programme at Imperial College London is presented in one overarching paper. The main aim is to determine what lessons can be learnt from that lockdown period, given the unique set of challenges it presented in our daily lives and the changes it brought about in energy demand, supply, and use. Valuable insights are gained into how working-from-home policies, electric vehicles, and low-carbon grids can be implemented, incentivised, and managed effectively.

The closure of businesses, industry, and schools under lockdown led to a fall in national electricity demand by up to 19% in Great Britain (GB) (Staffell *et al.*, 2020b, p.4; IEA, 2020b). This trend was also witnessed around the world, most notably in Italy where electricity demand fell by up to 28% in late-March 2020 (IEA, 2020b). Renewable penetration reached record highs due to suppressed demand and favourable weather, in turn lowering the cost of wholesale electricity and the carbon intensity of the grid.

COVID-19 has given the power system in GB a unique glimpse into the future (Staffell *et al.*, 2020a) with grid conditions that were not expected for several years (National Grid ESO, 2020g). With the difficulty that comes with balancing inherently intermittent renewables, additional services to support these variations had to be invented and implemented at a fast pace to ensure stable supply. Given the short time frame under which National Grid, the Electricity System Operator (ESO), had to act, the services put in place were effective in preventing any major outages. However,

between May and July 2020, the additional services cost approximately three times more than the previous year; £302 million compared to £101 million (National Grid ESO, 2020h; Badesa *et al.*, 2021). Simulations conducted by Strbac *et al.* (2017) and Badesa *et al.* (2021) highlight the importance of cost-effective ancillary services that anticipate low-inertia instability in the future, with fast frequency response mechanisms found to significantly reduce expected costs of ancillary services.

The effect lockdown policy could have played in this national decline in consumption is explored by Auvermann (2020), with workplace closure being the factor that showed the strongest correlation with suppressed demand. These closures had several consequences for businesses and their employees, as redundancies increased faster in 2020 than during the 2008/9 financial crisis and workers were placed on furlough as a part of the Coronavirus Job Retention Scheme (ONS, 2021a). A pattern that emerged, which has potential for long-term implementation, was the uptake in working from home. Hook *et al.* (2020) and O'Brien & Yazdani Aliabadi (2020) both found that a majority of studies they assessed in regards to teleworking saw a reduction in energy consumption and/or emissions with its uptake, highlighting it as an area of discussion in light of the coronavirus lockdown.

Containment and closure policies restricted travel and leisure activities outside of residences, so with more time spent watching television, cooking, and working from home, household energy consumption increased (Morales Rodriguez, 2020; Cheshmehzangi, 2020). Smart meter and questionnaire data examined by Coutellier *et al.* (2021) found weekly residential electricity consumption increased by 10.4% in 2020, compared to the same time period in 2019. Despite this increase, there was a 6.7% decline in related emissions, predominantly due to high renewable grid content and partly through a shift in household activities to

less carbon-intensive hours. With such interest surrounding teleworking, this factor was isolated, and it was found that there was a 6% increase in weekly electricity consumption per day spent teleworking under lockdown. However, when computing household emissions by accounting for decreased commute and including both electricity and gas usage, working from home one day a week is found to have reduced weekly household emissions by 5%.

Understanding willingness to work from home and the social implications of doing so is crucial to guiding policy design and effective implementation. Benefits of working from home identified in the literature include flexibility during the working day, reduced commutes, lower overhead costs, and increased productivity (Bloom, 2014). However, there remains some scepticism as this practice may lead to social isolation as well as unpaid employee overtime, negatively influencing wellbeing (Mann & Holdsworth, 2003). Morales Rodriguez (2020) provides insight into how mode of transport, commute distance, office size, and previous experience with teleworking all influence an employee's propensity to telework. Whilst those who commute to larger offices, over longer distances, via public transport, and those who worked from home under lockdown are more inclined to keep doing so post-pandemic, the opposite is true for employees who walk short distances to work in smaller offices.

With commuting mode playing both a crucial role in the inclination to telework and energy expenditure, the interaction between a work-from-home policy and electric vehicle (EV) ownership is also considered. This allowed for a better understanding as to how two ongoing drivers of energy consumption have the potential to influence residential electricity consumption. Based on scenario analysis using an agent-based demand simulator created by Pawlak *et al.* (2021), modelling undertaken for the purpose of this report found teleworking increases daily household

electricity consumption by 2 – 5%, which is much lower than the impact of EV uptake with the consequent increase in electricity demand ranging from 22% – 43%.

Recommendations for decarbonisation of the GB energy system based on experiences during COVID-19

With these findings in mind, recommendations are made that may be relevant for the transition towards a net-zero energy system, with the following factors identified as the most significant:

- Teleworking emerged as a key trend in 2020 that may have staying power, with analysis presented here indicating its potential to reduce national electricity demand. On a residential level, although contributing towards slightly higher electricity consumption, overall energy consumption and emissions per household fell as working from home eliminated the need to commute. Two office days a week would be preferred by workers in the future. However, an opt-in scheme is recommended rather than a mandated approach, despite not being as influential on reducing national electricity demand, since teleworking may not be beneficial or appropriate for all employees.
- Coordination between two drivers of future electricity demand discussed in this paper, teleworking and EV roll-out, is recommended. Observations from EV adoption and work-from-home policies suggest the need for aligning these two interventions, as they are inevitably intertwined through the activity-travel behaviour patterns of the household members. For example, policies and incentives could be designed to encourage people who need to commute to adopt and use EVs rather than incentivising people who will work from home to purchase EVs.

- Higher electricity consumption does not necessarily mean resultant emissions will increase as this depends on renewable penetration and, to a lesser effect, demand flexibility i.e., carbon content of the grid at times during which electricity consumption increases. A systems-based approach is vital in achieving a net-zero grid with low-carbon supply being pertinent in achieving this goal. Behavioural changes may not achieve the same success alone.
- In relation to grid dynamics, whilst the remedial steps taken by National Grid ESO were highly effective given the need to respond quickly to a combination of increased renewable generation and reduced demand, long-term strategies that anticipate high renewable penetration will ultimately be more cost-effective. To aid this transition, developing enhanced frequency response capacity is required to help stabilise a low-inertia grid. New technologies such as electric vehicles and synthetic inertia from wind farms could be key for this purpose.
- With no market for inertia, it is important to understand how to make current energy-based financial support mechanisms for certain generators (e.g. Contracts for Difference) appropriate for the provision of inertia and frequency response. This has the potential to create market conditions more relevant to high renewable penetration and avoid compensation for curtailing renewable generation.

With the unique challenges it presented to the energy system in the UK and around the world, the experience of COVID-19 provides valuable insight in progressing toward, and managing, a net-zero grid.

1. Introduction

The outbreak of the COVID-19 virus in 2020 initiated not just a health crisis but also caused unprecedented economic and social disruption around the globe. Effects have been widespread with a significant impact also seen on energy systems worldwide, the repercussions of which have continued into 2021. Partial or total lockdowns were imposed by governments when the virus initially took hold, with measures including forbidding citizens from leaving their homes except for essential activities, closure of schools and workplaces, and restrictions on internal and international travel. With these measures, more time spent at home and less time travelling altered our daily routines, activities, and resultant energy consumption.

In Great Britain (GB), the electricity demand was seen to drop by up to 19% compared to levels in the same period in previous years (IEA, 2020b). Suppressed demand coupled with large renewable output at times created conditions that were not expected for some years, as renewable capacity continues to grow to meet Greenhouse Gas (GHG) emissions targets legislated by the UK government. Electricity System Operators (ESOs) faced several practical challenges to maintain grid stability, as a result of the emergent imbalance between electricity supply and demand. The impacts and rapid changes observed across the energy system throughout this health crisis remind us that energy is inextricably connected at multiple points to society and the economy.

The pandemic, and resultant lockdown, present a unique set of circumstances that continue to evolve. Two distinct patterns in electricity consumption emerged with the onset of the first national lockdown; whilst overall national consumption declined, household consumption increased. Reports such as Cheshmehzangi (2020) and Cicala (2020) identify the impact on household energy consumption, with central focuses placed upon China and Texas, respectively. An overview of how national and international electricity demand was affected is given by López Prol & O (2020), with the influence on grid dynamics and the potential issues associated with renewable penetration within the EU discussed by Werth, Gravino & Prevedello (2021).

This Briefing Paper gathers research from a wide range of working groups at Imperial College London and assimilates their findings in a series of demand- and supply-side perspectives detailing conditions specific to GB. National context is provided before delving into the ramifications of lockdown policy on electricity demand. How this extended to household level consumption is then discussed in detail with particular reference to teleworking and behavioural changes under lockdown. The paper also presents one of the very first applications of an IDLES activity-based demand simulator, used to predict a range of work-from-home scenarios and their intersection with electric vehicle ownership to help better understand what role these two factors may play in the future and how they interact. The supply-side issues encountered by ESOs conclude the research topics of interest and combine with the discourse from the demand-side to extrapolate lessons learnt during the pandemic. Emphasis is placed upon the first set of lockdown measures implemented on 23 March 2020, with a broader commentary out to the end of 2020.

The main benefit of this research is the unique collaboration of working groups from diverse backgrounds to provide a narrative reflecting the multidisciplinary impact lockdown has had on the energy system. The contents compiled in a manner such as this provides an overview of the conditions COVID-19 imparted on GB and how best to learn from the adverse challenges presented during the health crisis.

2. Changes in Electricity Use at National-Scale

The collective closure of office buildings, schools, and industry meant that national demand decreased overall from mid-March 2020 as weekdays under lockdown began to resemble weekend consumption (Staffell *et al.*, 2020b). This had an impact on the wholesale price of power and carbon intensity of the grid. This chapter summarises the changes seen in Great Britain (GB) electricity consumption data and compares the trends to previous years and those seen in other countries. Transformations seen in the GB energy supply, energy prices, and carbon emissions from that point onwards are also discussed.

2.1 Changes in consumption patterns

» BOX 1: Weather correcting energy data

The amount of energy a household consumes on a daily basis depends on multiple variables, with one key influence being outside air temperature. For example, energy use in GB in August is lower compared to December given the heating requirements during winter months, which themselves can be milder or harsher than previous seasons. This complicates the ability to attribute energy consumption changes to an external measure, such as a policy change, or lower electricity cost.

Comparisons of energy consumption over time therefore need to account for temperature fluctuations, and there must be caution when drawing conclusions on consumption at different times of the day, month, or year. The weather correction process eliminates weather as a variable, allowing for comparative assessment of energy consumption independent of temperature differences.

On 23 March 2020, the UK government implemented a national lockdown. Under these measures, individuals were instructed to remain at home unless they were classed as critical workers or fulfilled a strict criterion, such as shopping for food or attending a medical appointment. These regulations meant that non-essential businesses and venues such as pubs, libraries, and places of worship were closed in a bid to limit the spread of the virus. (Cabinet Office, 2020)

As a result of the lockdown, weekday electricity demand in GB fell by 13% in the first quarter of the year (Staffell *et al.*, 2020b). This is demonstrated in Figure 1, where there is a noticeable difference between pre- and post-COVID lockdown demand. Levels fell to those witnessed at the beginning of the 1980s when there were approximately 10 million fewer people in GB, and the nation was still recovering from a recession (ONS, 2020d).

This downward trend continued throughout April 2020. At its lowest, GB's demand was approximately 19% lower than in prior years (IEA 2020b). As restrictions began to ease, demand recovered incrementally throughout the third quarter until restored to pre-COVID levels at the beginning of November. Overall, COVID-19 is thought to have reduced GB electricity demand by an average of 6% throughout 2020 (IEA 2020a).

2. Changes in Electricity Use at National-Scale

2. Changes in Electricity Use at National-Scale

2.2 Electricity Generation Mix

COVID-19 has given the power system in GB a unique glimpse into the future (Staffell *et al.*, 2020a). Favourable weather for solar generation, reduced demand, and low generation costs contributed towards the higher-than-average utilisation of renewable energy sources (RES). For example, between 1 April and 1 July 2020 on average 39% of power supply was provided by renewables compared to 30% over the same period in 2019 (Electric Insights, 2021).

A plethora of milestones in 2020 were achieved in regard to electricity output; April set record highs for solar power, May became the first month in GB's history in which no coal was used for electricity generation, and, on average, 46% of electricity came from low-carbon sources in June (National Grid ESO, 2020b, 2020c, 2020d). This high share of renewables on the grid and low demand also had consequential effects on power pricing and electricity driven emissions.

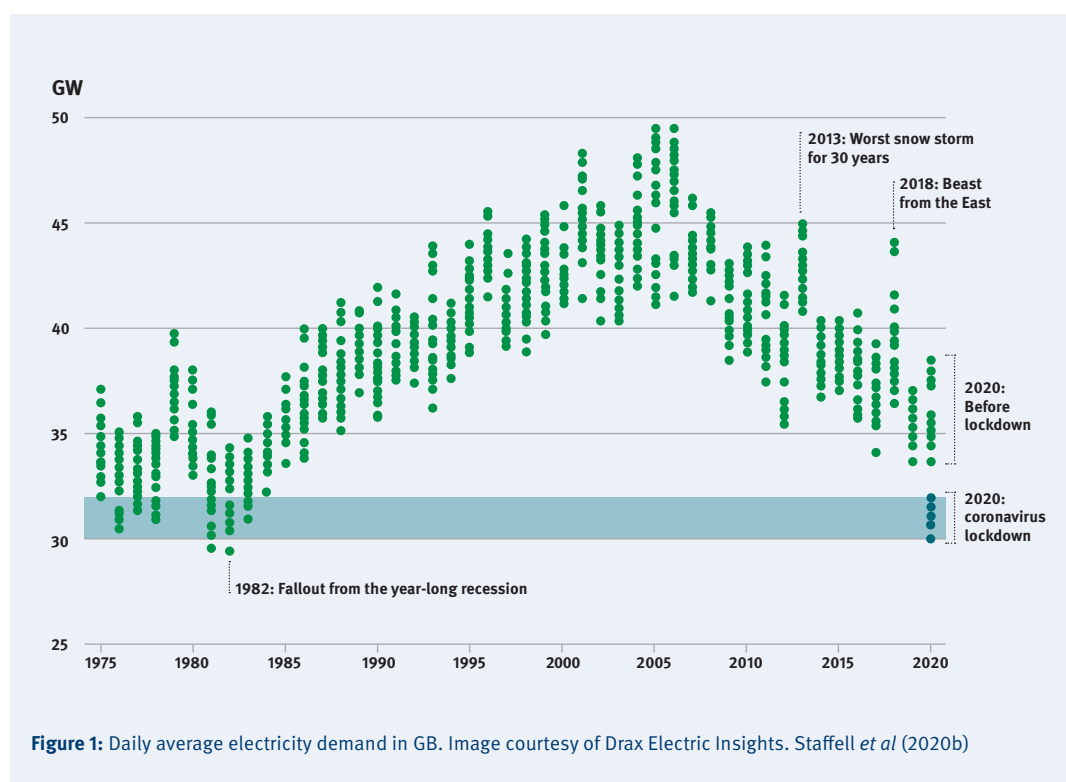


Figure 1: Daily average electricity demand in GB. Image courtesy of Drax Electric Insights. Staffell *et al* (2020b)

2.2.1 Pricing of power

The reduced need for fossil fuelled generation due to lockdown combined with falling international gas prices pushed electricity prices down (Staffell *et al.*, 2020b). Over the course of lockdown, electricity prices proved to be the lowest in almost two decades, with May averaging £22/MWh and £24/MWh for day-ahead and real-time prices, respectively (Electric Insights, 2021). Additionally, reduced generation costs meant that £1.3bn was saved in supply costs over the course of the second quarter. (Staffell *et al.*, 2020a)

Conversely, in January 2021, UK power prices surged with real-time prices averaging at £78/MWh throughout the month, and day-ahead market exceeding £1000/MWh, which is in stark contrast to the aforementioned lows in May 2020 (Electric Insights, 2021; Matson & Gogna, 2021). With lockdown restrictions in place at the time of this high pricing period, it is important to note that the main driver behind these increases is thought to be unrelated to high demand or low output from renewables, rather attributed to the outages of conventional power plants (Matson & Gogna, 2021).

2.2.2 Carbon emissions

With augmented renewable generation and low demand, the carbon intensity of the grid declined. Between April and June 2020, the carbon intensity of the grid averaged at 153 g/kWh compared to 194 g/kWh during the same period in 2019, with lows of 18 g/kWh recorded during the Spring bank holiday in May (Electric Insights, 2021; Staffell *et al.*, 2020c, p.3–7). This exceptionally low figure was further aided by the lack of coal electricity generation (see 2.2).

The average carbon emissions from electricity generation during the 1st and 2nd national lockdowns were 22% lower than during the previous three years. This fall was reported after correcting for the weather and growth in renewables capacity (Mehlig *et al.*, 2021), as the mild spring and having more wind farms

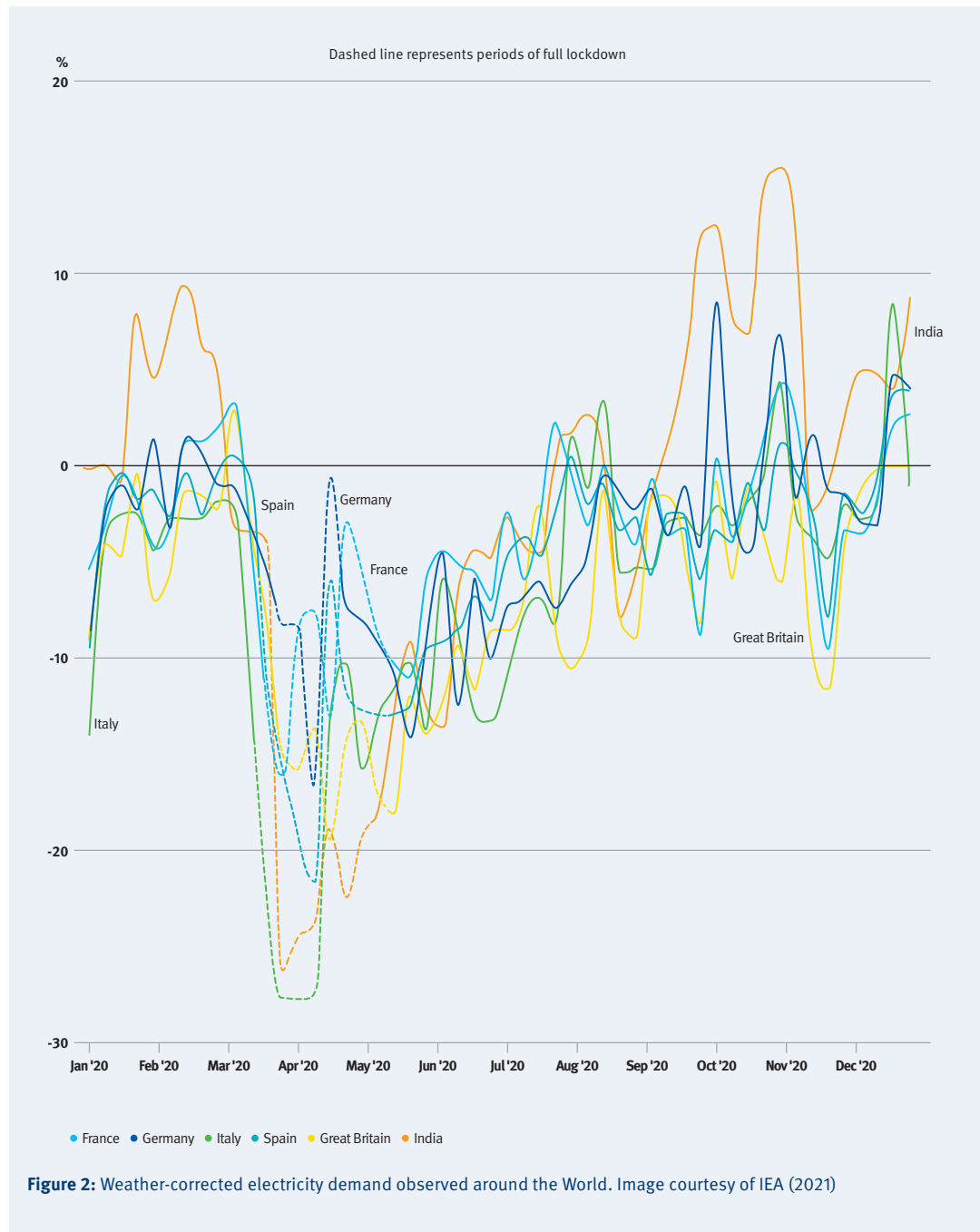
both reduce the need to consume fossil fuels, and so would mask the effect of lockdown on emissions. Reduced output from fossil fuelled power stations also meant particulates (PM 2.5) and nitrogen oxides (NOx) were 20-35% lower during the lockdowns.

2.3 Observations outside of GB

The same pattern was witnessed across many other countries, with the majority of governments implementing some sort of economic and societal restrictions to reduce virus propagation. Figure 2 shows the weather-corrected year-on-year change in weekly electricity demand in 2020 for six different countries (IEA, 2021).

Within the EU, Italy and Spain both witnessed percentage declines greater than that of GB, with the former experiencing one of the most dramatic reductions in electricity demand (28% decline in late March). As restrictions began to ease in mid- to late-April, electricity demand began to recover. This trend continued through May and into June and July where levels were maintained within 10% of 2019 demand. Recovery was most pronounced in India where industrial and commercial sectors drove demand, until Diwali and strikes in the agriculture sector led to a short decline in November (*ibid.*).

2. Changes in Electricity Use at National-Scale



2.4 Summary

National electricity demand declined in GB and around the world as a consequence of restrictions implemented in response to the COVID-19 pandemic. Demand fell by up to 19% in GB and did not recover until December 2020. The same situation was observed across many other countries, as governments went to extraordinary lengths to mitigate virus propagation.

Favourable weather and suppressed demand resulted in an increase of RES on the grid, with record highs and lows set with respect to the use of solar, wind and coal and the carbon intensity of the grid. Chapter 3 disentangles how specific policy interventions during lockdown may have been related to the suppressed demand witnessed in the UK and abroad.

3. Identification of COVID-19 Policy Influences on Electricity Use

The COVID-19 lockdown provided insight into the relationships between specific policy interventions and electricity demand. This chapter focuses on the first set of lockdown restrictions imposed in the UK from 23 March 2020 and draws on analysis conducted by Auvermann (2020). The aim is to determine which, if any, of the policies implemented influenced electricity demand, to what extent, and to assess which might have staying power post-crisis.

3.1 The impacts of government policy in response to COVID-19 on electricity demand

Over the past decade, the energy sector has contributed towards 45%¹ of fossil carbon dioxide emissions with heat and electricity production being the primary sources (Peters *et al.*, 2020). Whilst improved energy efficiency and reduced demand are usually cited as key influences in attaining net-zero targets, there is limited analysis regarding the influence policies have on energy demand (Sorrell, 2015). With COVID-19 presenting such drastic declines in national electricity demand, a unique opportunity is available to analyse how lockdown policy interventions played a role in this.

3.2 Methodology

In order to determine the relationship between COVID-19 mitigation policies and electricity demand, a regression analysis was carried out (see Box 2). This process first entailed gathering data, then weather correcting it, before being able to calculate the difference in electricity usage prior to, and during, lockdown. In this case, details concerning policy implementation and electricity demand were required for regression, and temperature and population data for the purpose of weather correction. Auvermann (2020) details the full list of data sources and sorting required for its use.

» BOX 2: What is regression analysis?

Regression analysis allows us to understand how different independent factors correlate with an outcome. The outcome you are trying to understand or predict is called the dependent variable and the factors that influence it, the independent variables.

A relationship between them can be established to determine: Which independent variables are most influential? Are there factors that we can ignore? How confident are we on the relationship?

Understanding the connection between an outcome and the factors that influence it allows us to interpret data and predict future scenarios.

¹ This figure does not include emissions from industrial (e.g. metals production, chemicals), land transport, shipping, aviation or agricultural sectors

3.2.1 Policy data

The Oxford COVID-19 Government Response Tracker (OxCGRT) from Hale *et al.* (2020) details the date policies were implemented in an attempt to mitigate the effects of the COVID-19 pandemic. These policies are arranged into four main groups based on their respective areas: Containment and Closure (C), Economic (E), Health System (H), and Miscellaneous (M). These groups are subdivided into specific policy indicators such as C3 – Cancel Public Events or H3 – Contact Tracing and, in most cases arranged on an ordinal scale and assigned a number pertaining to whether recommended or required actions were put in place, referred to as ‘levels’ in this paper. This enables differentiation between the influence of government-mandated policies or opt-in schemes to be made. For example, C3 consists of three levels ranging from 0 – 2, whereby

0 refers to ‘no measures’, 1 to recommended cancelling, and 2 to required cancelling. Levels are assigned to all policies in the database except E3, E4, H4, H5 which are represented by monetary contributions in USD (US Dollars), and M1, which is qualitative.

Separate to these levels, stringency of the containment policies (C1-8) were also supplied, ranked from 0 – 100 based on the strictness of their enforcement, whereby 100 represents the most stringent of measures. An overview of policy indicators and their subdivisions, given in the dataset and used in the regression, are provided in Table 1. The Containment & Closure indicators are most relevant to energy use and will be discussed in detail.

Policy Group	Policy Indicator
Containment & Closure (C)	C1: School Closure C2: Workplace Closure C3: Cancellation of Public Events C4: Restrictions on Gatherings C5: Closing of Public Transport C6: Stay at Home Requirements C7: Restrictions on Internal Movement C8: International Travel Controls
Economic (E)	E1: Income Support (for households) E2: Debt/contract relief (for households) E3: Fiscal Measures E4: International Support
Health System (H)	H1: Public Information Campaigns H2: Testing Policy H3: Contact Tracing H4: Emergency Investment in Healthcare H5: Investment in Vaccines
Miscellaneous (M)	M1: Wildcard (flagging of ‘unusual or interesting interventions’ made by governments)

Table 1 Policy groups and indicators tracked by the OxCGRT

3. Identification of COVID-19 Policy Influences on Electricity Use

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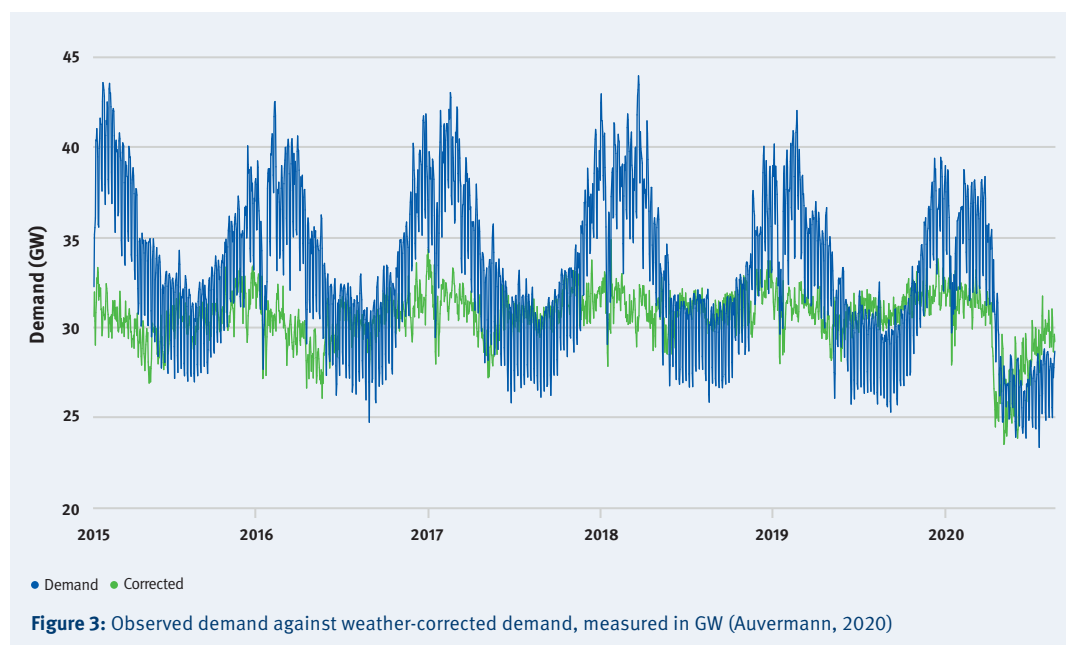
3.2.2 Weather correction

As discussed in Chapter 2, weather correcting energy data is required to make valid comparisons between daily, weekly, monthly, or yearly shifts in demand. To carry out this procedure, corresponding temperature data was first modified and weighted by population density. As more populous regions demand more electricity, this was done to account for regional fluctuations in weather and limit the influence high density areas experiencing the same weather would have. The diminishing effect that ambient temperatures have on interior temperatures over time was also considered with the use of a half-life function.

In research, heating degree days (HDD) and cooling degree days (CDD) are used to quantify the energy demand required to heat or cool buildings. If the ambient temperature is below the HDD threshold then heating would be required to maintain a comfortable interior temperature and similarly, if above the CDD threshold, air conditioning would be necessary. By comparing daily temperature averages from the dataset to the HDD and CDD thresholds (determined from an iterative process) an estimation was made for the additional energy

consumed due to the weather, thus eliminating it as a variable. This approach of removing all heating and cooling demand was taken instead of the more usual approach of estimating demand for a 'typical meteorological year' to highlight how electricity demand for non-thermal purposes is reasonably constant throughout the year with the sole exception of the Christmas and New Year holiday period. Figure 3 demonstrates the actual and weather-corrected demand profiles in the UK.

Given the fluctuations in daily demand profiles, one-week moving averages were used in the final model. These averages omitted weekend data as weekday transformations witnessed greater differences. Absolute and relative changes in electricity demand between pre- and post-COVID-19 conditions were then calculated. With the difference in consumption now weather corrected, any correlations between electricity demand during lockdown and policies implemented at that time can be investigated and compared to years prior. The stringency of the measures was also examined for containment policies to establish if stricter enforcement had any influence on demand.



3.3 Results

Two models were run for the UK regression: a complete and a trimmed model. The complete model comprised of all listed indicators and respective levels in Table 1, whilst the trimmed model comprised of statistically significant policy indicators with a p-value ≤ 0.05 . In Table 2, the listed policies and respective levels all returned a p-value less than, or equal to 0.05, indicating there is a 5% chance (or less) that the correlation was produced by chance.

Policy Indicator	Level	Effect on Electricity Demand
C2 – Workplace Closure	Level 1* Recommended closing (or recommended work from home)	3% decrease
	Level 2 Required closing (or work from home) for some sectors or categories of workers	18 – 20% decrease
	Level 3 Required closing (or work from home) for all-but-essential workplaces	18 – 20% decrease
C7 – Restrictions on internal movement	Level 1 Recommend not to travel between regions/cities	3% increase
C8 – International travel controls	Level 1 Screening Arrivals	3% increase
*only significant in trimmed model		

Table 2 Policy indicators that correlated with changes in demand

3. Identification of COVID-19 Policy Influences on Electricity Use

3. Identification of COVID-19 Policy Influences on Electricity Use

3.4 Discussion

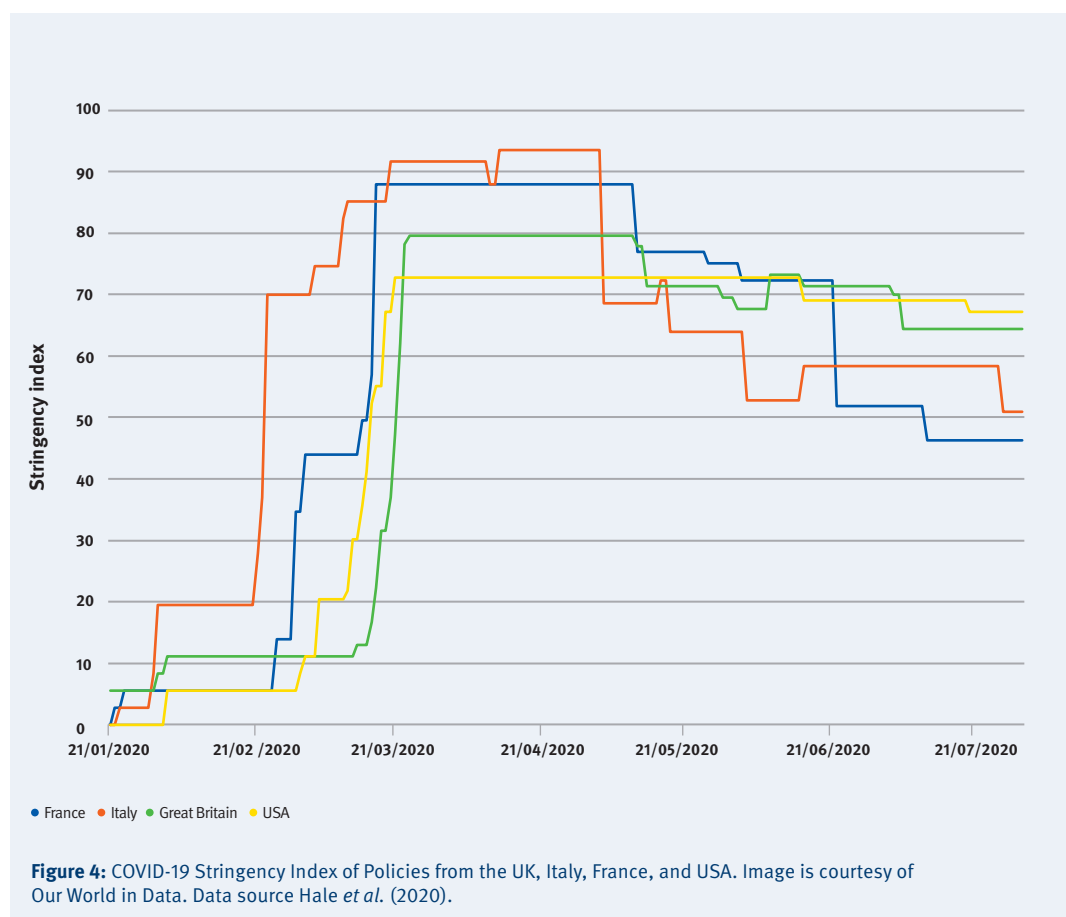
3.4.1 Stringency and consumption

For all containment policies (C1 – 8) that were assigned stringency measures between 0 – 100 (where 100 = strictest response), Auvermann (2020) found that, on average, a 0.22% decline in electricity demand was witnessed in the UK, per additional level of stringency. This means that tighter restrictions reflected larger reductions in demand.

This is a finding also shown by López Prol & O (2020) who investigated the influence of COVID-19 measures on short-term electricity consumption in a variety of European

countries and US states including Italy, New York, France and Florida. Their investigation determined a non-linear relationship between stringency and electricity demand. Changes in daily consumption reached just below -20% at a stringency of 100, which agrees with the findings presented here, where a 22% decline in demand would be expected with a stringency level of 100.

In Figure 4, the stringency indexes of the UK alongside Italy, France and the USA are presented to give context to the strictness of legislation implemented under COVID-19. The most severe restrictions were seen between the end of March up until the end of April within the UK, coinciding with the 19% decline in electricity demand discussed in Chapter 2.



3.4.2 Policy considerations

Further to the analysis conducted using UK data, regressions were also carried out for other countries alongside an overall ‘World’ model². Policy indicators that were significant in reducing demand mostly lined up with containment measures such as C1 – School Closures, C2 – Workplace Closures, and C6 – Stay at Home Requirements. This is unsurprising given the discussions in Chapter 2 where national demand in the UK and abroad declined dramatically following strict lockdown measures.

Whilst C1 was most influential in the Netherlands, with 15 – 24% change in demand estimated at Levels 1 & 2 (recommended closing & required closing for some), Level 3 measures requiring all schools to close correlated with suppressed demand in seven country-wide models (Austria, Estonia, Italy, the Netherlands, Norway, Poland, and Australia).

Although these containment and closure policies showed correlations with lower electricity demand, school closures or actions such as restrictions on internal and international movement are not considered plausible policies in the pursuit of reducing electricity demand. With this, and the aims of this chapter in mind, workplace closure (C2) will be discussed in greater depth.

3.4.3 Workplace closures

The closure of workplaces has had several consequences for businesses and their employees. Compared with the 2008/9 financial crisis, the number of redundancies increased faster in 2020 and Gross Domestic Product (GDP) contraction more than doubled, declining by 9.9% (ONS, 2021a, 2021b).

According to Tera, Canal & Hunt (2020), between 3–19 April 2020, over just half of those aged 16–64 in the UK remained in work either as normal or remotely. This is comparable to a norm of 75% where the discrepancies in these values mainly constituted of furloughed workers

(approximately 20%), but also of those off-sick, isolating due to COVID-19, or recently unemployed. As of the 14 August 2021 a cumulative total of 11.6 million jobs had been furloughed across 1.3 million different employers (Clark, 2021).

In the final model, all levels of C2 - Workplace Closures were seen as statistically significant, providing negative correlation with electricity demand. This indicates that the transition to working from home alongside furlough and office closures could have contributed towards the decline in national electricity demand. Out of these variables, however, working from home is the only one that has potential to be implemented long-term, as such it is considered in more depth.

3.4.4 Teleworking

Teleworking refers to participation in work-related tasks using information and communications technology (ICT) in a remote location that is separate to a central office (O’Brien & Yazdani Aliabadi, 2020; Graizbord, 2015). With regards to this paper, teleworking will be referred to interchangeably with “working from home” and in specific reference to employees who would otherwise work at a central office.

Teleworking has previously been investigated as a means to reduce overall energy consumption and greenhouse gas emissions (Matthews & Williams, 2005; Roth, Rhodes & Ponoum, 2008; Larson & Zhao, 2017). Most literature on the topic indicates a decline in energy use and/or emissions as uptake of teleworking increases. For example, Hook *et al.* (2020) found that 26 out of 39 studies in their scope suggested a decline in energy consumption and/or emissions whilst O’Brien and Yazdani Aliabadi (2020) found this true for 26 out of 30 reports.

² Full list of countries tested: Japan, Austria, Belgium, Switzerland, Czechia, Germany, Denmark, Estonia, Spain, Finland, France, Greece, Italy, Lithuania, Latvia, the Netherlands, Norway, Poland, Portugal, Romania, Sweden, Austria, and the USA.

3. Identification of COVID-19 Policy Influences on Electricity Use

Given the breadth of variables that influence consumption throughout the working day, the findings are often dependent on the context of the study, the study boundaries (which uses of energy are considered) and the inclusion of so-called ‘rebound effects’ (O’Brien & Yazdani Aliabadi, 2020). These effects refer to variations in energy use that arise as a consequence of teleworking. For example, an employee who works from home may lower their energy consumption by eliminating their commute but, as a result of heating or air conditioning their house or increased reliance on personal electronic devices, could offset these savings.

Over the course of April 2020, 46.6% of employees in the UK were recorded as doing some work from home, 86% of those reportedly as a consequence of COVID-19 (ONS, 2020a). Teleworking options were more likely to be offered to occupations that required higher qualifications and more experience, as opposed to manual labour and entry level positions (*ibid.*). It is perhaps unsurprising to note then, that the share of remote working opportunities corresponds to a country’s GDP per capita (Dingel & Neiman, 2020). The consideration of long-term teleworking is therefore an approach that may favour post-industrial economies such as the UK, in relation to national electricity demand. The implications this has at a household level is discussed further in Chapter 4.

3.4.5 Economic implications

It is important to highlight that the aforementioned declines in electricity demand were due to reduced activity rather than improved efficiency, so were not beneficial for economic growth. Between January and November 2020, Administrative & Support Services, Arts & Entertainment, and Accommodation & Food Services were the industries that suffered the greatest number of redundancies (ONS, 2021a).

Further to this, conditions in the UK may have exacerbated these issues as public health restrictions and voluntary social distancing reportedly had more influence on the UK economy, which experienced the largest contraction in volume GDP, relative to other G7³ countries (ONS, 2021c).

3.5 Limitations

3.5.1 Quantifying policy data

The qualitative nature of policies means that translating their level of strictness into a numerical scale from 0 – 3 could result in slight discrepancies between the apparent and actual influence on demand. In this way, continuous quantitative measurements would enhance the regression. For example, if the average (or total) number of hours worked from home was reported for C2 – Workplace Closure, the relationship between teleworking and demand could be evaluated more accurately, with percentage change in electricity demand per additional hour worked from home provided.

3.5.2 Electricity only

Data assessed in this regression relates solely to electricity data, so whilst determining correlation between policies, how these may influence the energy sector as a whole requires further evaluation. The ambiguity teleworking studies present on energy savings (Hook *et al.*, 2020) reflects its multiple influences on home, office and transport energy use, over the short and long term. As such, any measures taken should be carefully considered, a matter discussed in further depth in Chapter 4.

³ Canada, France, Germany, Italy, Japan, United Kingdom, United States

3.6 Summary

The analysis provides valuable insight into how lockdown policy interventions could have influenced electricity demand and allows attribution of changes in demand to the arrival of particular policies at different levels of strictness. Workplace closures was identified as a major influence, which led to an increase in reported teleworking. With the ability of teleworking to persist into the future it is important to consider the benefits it may be able to provide regarding lowering electricity demand.

In contrast to national demand, household electricity consumption increased under the first lockdown. Before conclusions are drawn from this chapter, teleworking's influence on household consumption must first be analysed with respect to behavioural changes witnessed throughout the pandemic.

3. Identification of COVID-19 Policy Influences on Electricity Use

4. Changes in Electricity Use at Household Scale

The national decline in electricity consumption was noted throughout Chapter 2 and analysed in respect to policy interventions in Chapter 3. Workplace closure was identified as a significant contributor to this decline, however, at the household level, this influence caused electricity consumption to rise. Behavioural shifts under lockdown influenced how and when electricity was consumed throughout the day. This chapter will focus on why, and by how much, residential demand varied in the UK, with a wider discussion placed upon teleworking and resultant emissions.

Willingness to telework post-lockdown is assessed through survey data that reveals mode of transport and commute distance play a pivotal role in preference. Commuters who travel via public transport are more likely to want to telework, whilst those who walk are more likely to want to work at a central office. Privately owned petrol and diesel car owners made up the majority of respondents, but they are almost equally split when their willingness to work from home is assessed.

With this willingness to telework even with respondent access to a private vehicle, how a shift in electric vehicle (EV) ownership could intersect with teleworking policies post-lockdown and the influence it would have on household electricity consumption is an open question. Charging EVs from home would mean a rise in the daily usage of household electricity, estimated to be around 22–43% higher when compared to a baseline scenario (no teleworking, no EVs). Such an observation suggests the importance of a coordinated approach between EV ownership, public transport investment and teleworking initiatives. This is an area explored in Section 4.5 through the first application of an activity-based model under the IDLES programme.

4.1 Behavioural changes

Under lockdown, restrictive measures meant that adults spent on average less time travelling each day and, whilst at home, increased the time spent on activities such as gardening, cooking, and watching TV (Cheshmehzangi, 2020; ONS, 2020c). The number of people who reported doing at least some work from home increased from 5% in 2019 to 47% in 2020, with 86% of those being a result of the pandemic (ONS, 2020a; 2020b).

Flexible working hours and home schooling meant that the usual morning peak in demand prior to school runs and commutes elongated throughout the day and resulted in flatter consumption levels, with morning electricity demand declining by 18% (Wilson *et al.*, 2020; National Grid ESO, 2020a). Despite this, weekly residential consumption increased under lockdown with more time spent at home throughout the remainder of the day.

4.2 Current literature on household consumption

Although numerous studies have examined the effect of lockdown on national electricity consumption as discussed in Chapter 2 (López Prol & O, 2020; IEA, 2021; Bahmanyar *et al.*, 2020; Mehlig *et al.*, 2021) limited research has been carried out on a disaggregated,

household level as of the time of writing. This is especially true when it comes to examining the role of teleworking in consumption patterns and the environmental implications associated with higher household demand in lockdown.

One study that demonstrates the different patterns in residential and non-residential energy consumption under lockdown is García *et al.* (2021). Their results found that energy consumption in Manzanilla, Spain, fell by an expected 38% for non-residential customers, whilst residential customers increased their usage by approximately 15%. Further literature that utilises smart meter data to analyse lockdown's influence on residential electricity or energy consumption includes Cicala (2020) who found, on average, a 10% increase in Texan households electricity consumption, with a 16% rise noted during working hours. Meanwhile, closer to home, Octopus Energy (UK energy supplier) found a 4% increase in energy consumption amongst UK households (Sykes, 2020).

The aforementioned research acknowledges the role of teleworking, but only Cicala (2020) estimated that the increase in households' electricity consumption was 3% greater in areas with higher potential homeworking. However, no additional consideration is given to the carbon emissions associated with this rise in working from home. The following study will attempt to fill this gap in literature in carbon emission analysis and demonstrate how residential energy consumption varied in lockdown with specific reference to teleworking.

4.3 Evidence from UK lockdown

The grid conditions surrounding COVID-19 (high renewables, low aggregate demand) coupled with behavioural changes that affected demand present a unique case study. By understanding how these physical and behavioural dynamics influenced carbon emissions under lockdown new insight may be gained as to how we can

better reduce them. Research conducted by Coutellier *et al.* (2021) in collaboration with Octopus Energy provides understanding as to how customers' behavioural changes influenced energy consumption in comparison to the same period in 2019. It was conducted using two anonymised data sources from energy customers: distributed questionnaires and respondents' smart meter data.

4.3.1 Data Collection

Questionnaire Data

A survey was designed to measure respondents' experiences of teleworking throughout lockdown and prior to it: commuting routines, size of workplace and company, willingness to telework, and activity changes during lockdown. It aimed to fill the gaps in literature on rebound effects discussed in Chapter 3 and in O'Brien & Yazdani Aliabadi (2020). Non-work travel, although listed as a rebound effect, was not considered within the questionnaire due to the study taking place under lockdown (Morales Rodriguez, 2020)

To reduce bias, the questionnaires were distributed to customers who were on fixed price tariffs as opposed to flexible options with half-hourly price adjustments. This meant that the respondents would be more representative of the overall population. Of the 9,000 questionnaires issued by email, 1,164 households authorised the use of their energy data and 452 returned the questionnaire. As each survey enabled the inclusion of five adults per household the total number of teleworkers represented was 1,126.

Transportation choices and commuting distances among respondents were consistent with recent figures released by the Department of Transport with most adults reportedly using private petrol/diesel cars or public transport: DfT estimates that around 68% travel to work by car and less than 20% used either rail, trams, subway or bus (DfT, 2019a).

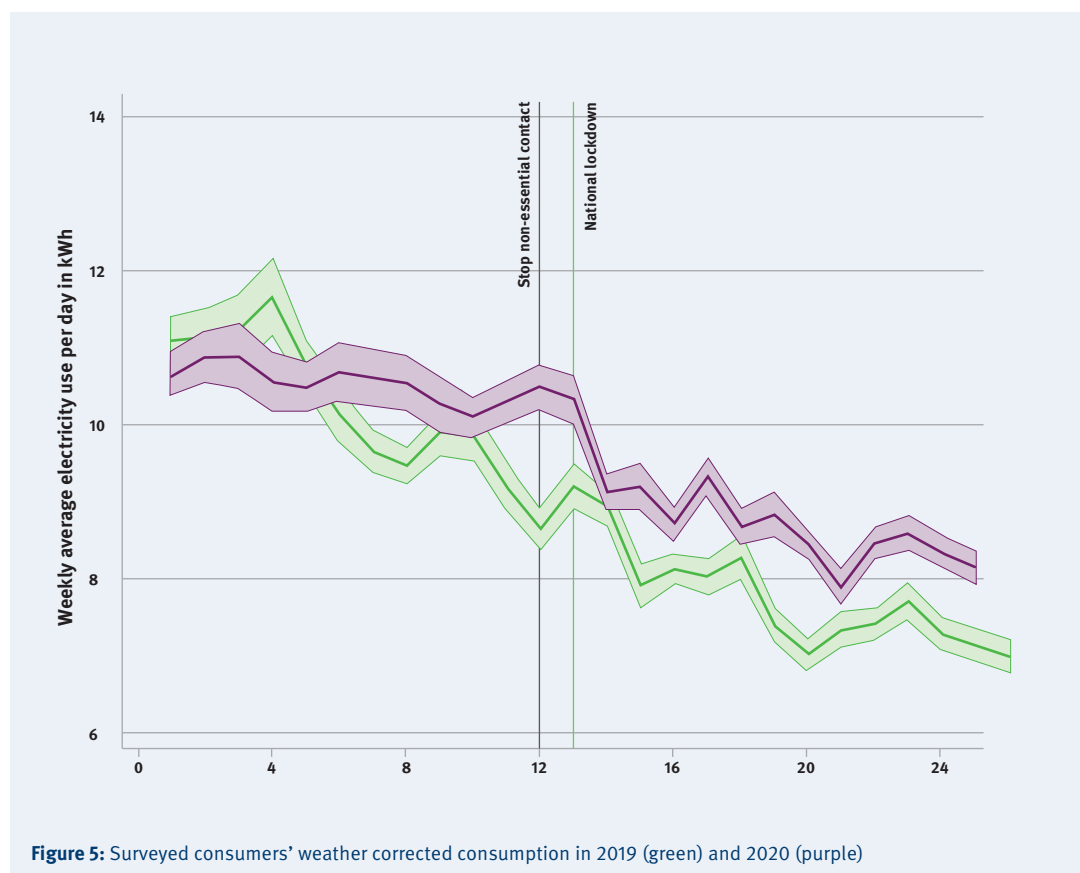
4. Changes in Electricity Use at Household Scale

Smart Meter Data

Smart meter data of survey participants between Weeks 1 and 26 of 2020 was provided to compare to a 2019 baseline. This was then combined with questionnaire results to allow for the unique alignment of consumers' energy usage with behaviours that directly influenced their consumption during lockdown.

To control for the influence of weather on the consumption of electricity, hourly temperatures from the weather station closest to each household, based on the first three digits of their postcode, were collected and included in the regression analysis weekly variations of weekly average electricity usage per day among surveyed customers, with temperature

corrections. From Week 12 onwards, when strong restrictions to movement were advised, and Week 13, when lockdown started, electricity consumption in 2020 exhibits a lower seasonal drop than 2019, providing evidence that lockdown had a significant effect on households' electricity consumption within the UK.



4.3.2 Methodology & Results

Lockdown effect on household electricity consumption

A multivariate regression analysis was used to assess the impact of lockdown on electricity consumption. Weekly electricity consumption was found to have increased by 10.4% as a result of the lockdown, relative to 2019. The trend witnessed in electricity demand was higher during the working week (12.1%) compared to weekends, where it increased by 8.2%. In addition, Figure 6, below, details how electricity profiles of surveyed households varied throughout the day, during and outside of lockdown. Demand is seen to peak later in the morning and is sustained at a higher level until the afternoon, where a small peak is seen around lunchtime. Relative to the average hourly consumption, the evening peak was earlier during lockdown.

Lockdown effect on electricity emissions

Carbon emissions resulting from electricity consumption can be calculated by multiplying half-hourly electricity consumption by the carbon intensity of the grid in that half-hour. These half-hourly values were summed up to obtain weekly emissions from electricity. Despite the large increase in electricity consumption, weekly household emissions decreased by 6.7% (compared to the same period in 2019). This decline is due to two main factors: the lower carbon intensity of the grid in 2020 (discussed in Section 2.2.2) and behavioural changes that altered electricity demand (Figure 6), shifting consumption to lower carbon intensive hours and avoiding peak demand.

To understand whether the behavioural changes were significant in and of themselves in reducing emissions, 2019 half-hourly carbon intensities were applied onto 2020's demand

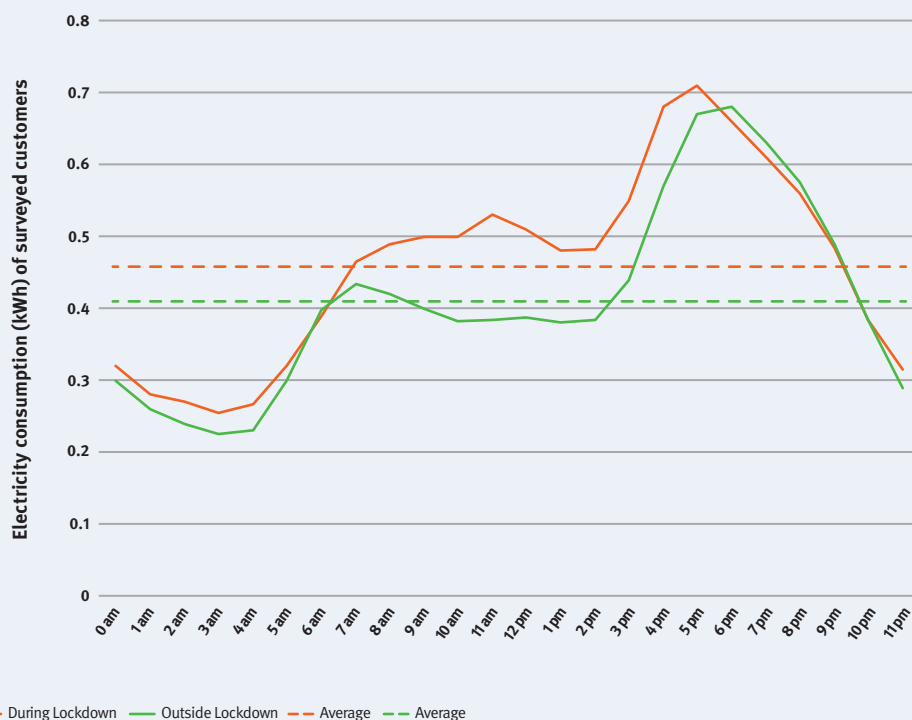


Figure 6: Weather corrected daily electricity consumption profiles for the participating households during and outside of lockdown

4. Changes in Electricity Use at Household Scale

4. Changes in Electricity Use at Household Scale

profiles. This process effectively isolates behavioural change as a factor as it eliminates the “greener” grid of 2020 as a potential influence on lower emissions. When this was carried out, the outcome was an increase in carbon emissions by 7.1% (3.3% lower than reported increase in electricity consumption). These results show that residential flexibility and time of use can deliver reductions in carbon emissions, independent of policy interventions or pricing.

Lockdown effect on teleworking and household emissions

To understand the impact of teleworking on households’ carbon emissions, one needs to go beyond electricity use. In this study, household carbon emissions were computed by combining three sources: electricity usage (using the same method above), gas usage, and data on each participant’s commute from the survey. With respect to gas consumption, the carbon emissions were computed from energy profiles using a 203.36g CO₂/kWh conversion factor, in accordance with the 2020 estimates by the UK government⁴. Weekly household emissions from commuting were derived from the survey results. Each inhabitant reported their transportation choices, commuting distance, and the number of days they commuted to work on a weekly basis. Once combined, this gives commuting emissions per inhabitant, which are then summed at household level. Carbon emissions from other activities, such as non-home-based leisure, offices’ energy use, non-commute travel, could not be included here due to measurement limitations.

On average, the weekly carbon footprint of a household decreased by 33% during lockdown. Further analysis into the drivers behind this outcome, which considered how often members of the household reported being at home during the week, frequency of teleworking, and whether or not children were

present revealed that teleworking one day per week decreased household emissions by 5%. So, whilst electricity consumption was seen to increase by 6%, a teleworker would still decrease their overall carbon footprint due to reductions in commute-related emissions.

Behaviours that most affected electricity consumption

In line with literature, the questionnaire revealed that there were significant declines in the use of transportation, with greater falls witnessed in public transportation than in private car usage (Cheshmehzangi, 2020). Most notably, household activities such as gardening, online shopping and leisure, cooking, and housekeeping witnessed the sharpest increase in frequency in agreement with the Office for National Statistics (2020c).

4.3.3 Limitations

The above study only accounts for direct energy usage from household consumption and commuting and does not take office energy consumption into consideration when calculating emission and energy differences in teleworking. Therefore, further investigations could be conducted to solidify the findings here. Furthermore, it should be noted that systemic increases in teleworking could in the long-run lead to public transport capacity and hence emission reductions.

4.3.4 Discussion & Conclusions

The study by Coutellier *et al.* (2021) derived several key findings around household consumption, emissions, and habits over the course of the 2020 lockdown. The increase in household electricity demand witnessed is in contrast to the nationwide decline caused by the closure of workplaces, schools, and industry.

⁴ <https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020>

Behavioural changes altered the way in which electricity was consumed throughout the day, flattening demand profiles and shifting consumption to less carbon intensive hours. This, combined with the high levels of renewable penetration discussed in Chapter 2, meant that despite a 10.4% increase in weekly electricity consumption the resultant emissions were 6.7% lower compared to the same period in 2019. Although both factors were significant in disentangling the growth of consumption from its emissions, the greener grid of 2020 had a much higher influence than demand flexibility, reinforcing the fact that achieving net-zero grid emissions relies heavily on a low-carbon electricity supply.

Along with energy data, the questionnaire, detailing consumers' commute patterns and frequency of teleworking allowed for the assessment of direct household emissions, which were found to have declined by 33% during lockdown. Teleworking one day per week was shown to decrease weekly carbon emissions by 5%, with the 6% increase in electricity consumption per day being outweighed by the lack of commute. The increase in electricity consumption reported is near agreement with the agent-based model (ABM) results in Section 4.5 under the scenario most akin to lockdown conditions (Scenario 2) and is similar in magnitude to the IEA's lower estimate, who found that a day working at home could increase household energy consumption by 7–23% (IEA, 2020c).

With these findings, greater clarity has been provided around how teleworking influenced residential demand under lockdown. If this practice is to be considered for longer-term implementation, however, it is important to first understand what influences a person's willingness to telework, and how shifting transport patterns could potentially affect household electricity consumption under such a policy.

4.4 Willingness to telework and social implications

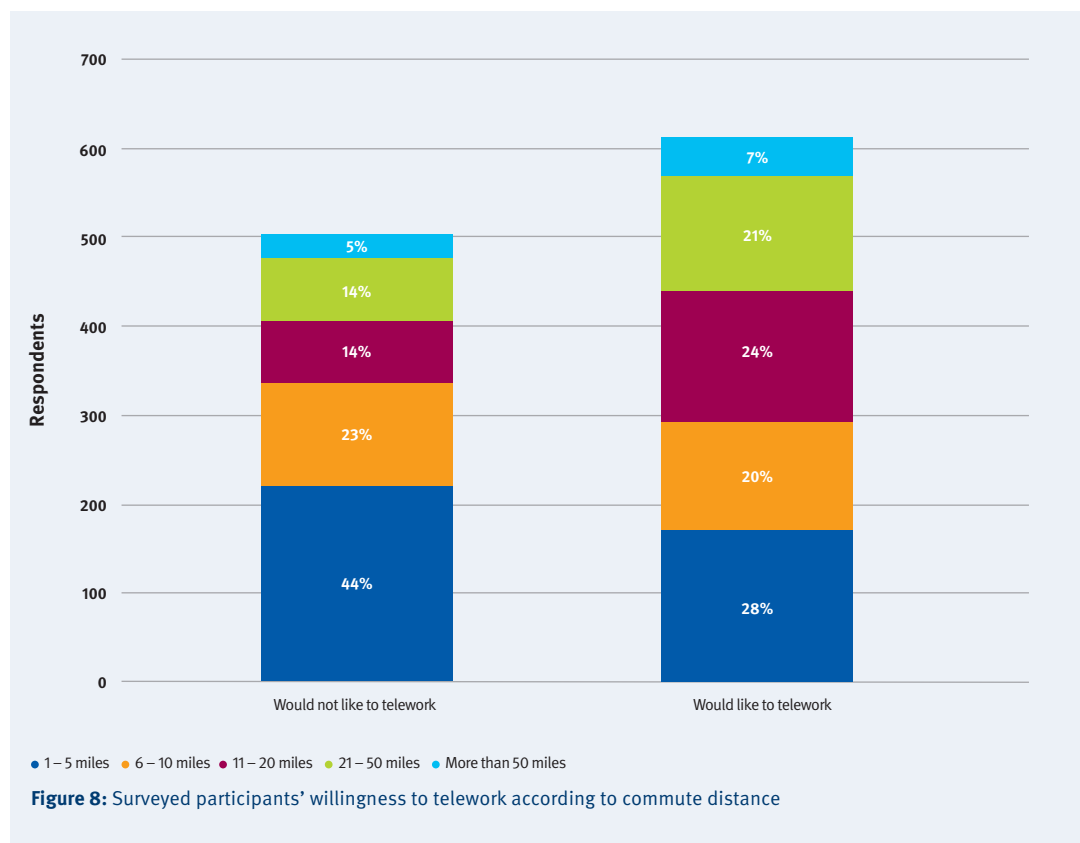
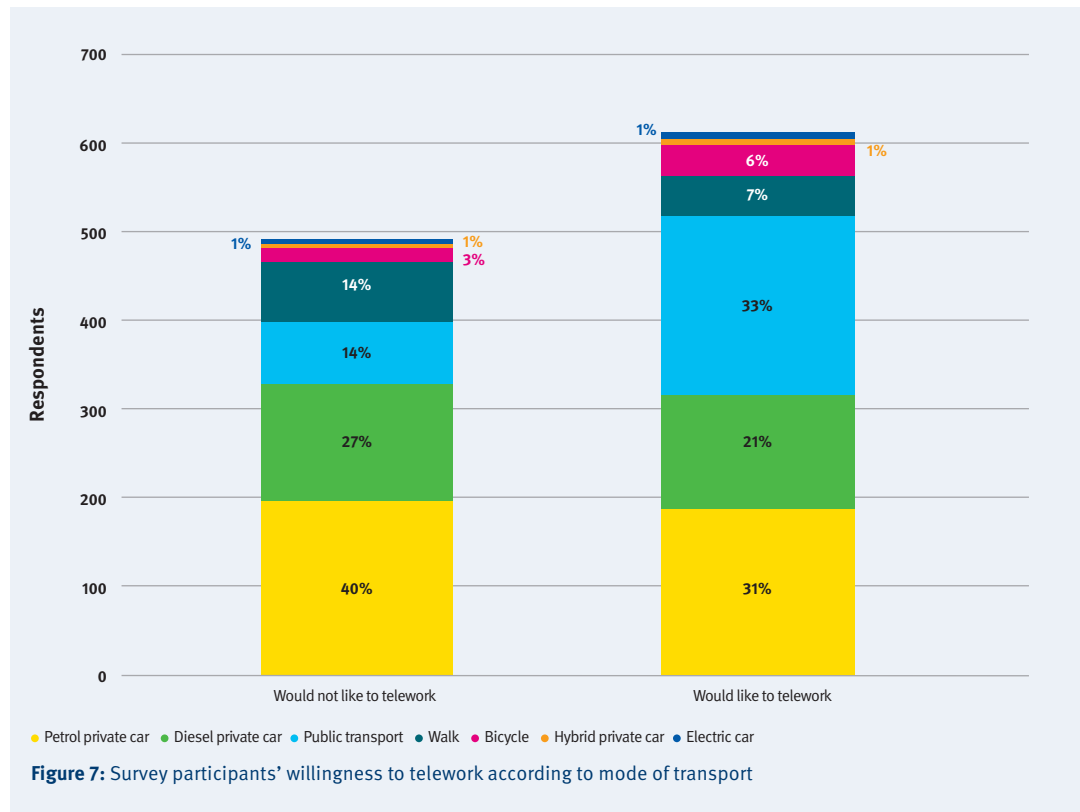
The survey described in the previous subsection evaluated which factors affect people's ability and willingness to telework post-lockdown. Of the total number of respondents approximately 54% wished to telework part- or fulltime after lockdown ended. The main influences identified in this inclination were the type and length of commute and their work environment.

4.4.1 Commute characteristics

Prior to lockdown the preferred mode of transport for respondents who commuted was a private petrol car (35%). Public transport and private diesel cars were favoured by 24% of commuters each. Walking (10%), cycling (4%), and electric or hybrid private cars (3%) were less common. With privately owned cars making up the majority of respondents and as EVs become more popular, there is an intersection between the electricity and transport sectors. The ramifications such a combination would have on household electricity consumption is investigated further in Section 4.5. Post-lockdown, a chi-squared test revealed that a high proportion of public transport users would want to telework, whilst more walkers preferred to continue commuting.

Out of the 502 respondents who did not wish to work from home post-lockdown, 67% lived within 10 miles of their workplace. Conversely, those with longer commutes are more likely to prefer to work from home in the future.

4. Changes in Electricity Use at Household Scale



4.4.2 Work environment

Full-time teleworkers' most common preference was to work from home 3 days per week post-lockdown while the majority of respondents who commuted full-time during the pandemic wished to continue doing so, most likely due to the type of job they have. Office sizes of respondents, organised into square meters, were also reported. Those who worked in smaller offices (less than 99 m²) were less willing to telework than employees working in larger offices, who were more inclined to want to work from home.

4.4.3 Social impact of teleworking

The rise of teleworking under lockdown seems to have opened new doors into a world outside of the office, where employees have the option to work remotely. However, it is also important to discuss the social and economic impact teleworking may have for employees and employers.

Practical benefits to teleworking cited by Mann & Holdsworth (2003) include more flexibility during the working day, better balance between work and home life, as well as reduced commutes, lower overhead costs, and increased productivity. Bloom (2014) noted, in regard to a call centre, a 13.5% increase in productivity and approximately 1,900 USD in savings per employee over a nine-month period when they transitioned to working from home in comparison to office workers in the same company.

However, it is evident that working from home is not practical for everyone and may increase social isolation, lead to unplanned overtime, and encourage teleworkers to persevere through tasks when ill, or not fully recovered, which could worsen their condition and lower the quality of their output

(Papandrea, 2020; Mann & Holdsworth, 2003). There also needs to be due consideration for who is responsible for the expenses incurred through teleworking, as there is dispute over who pays for the cost related to the use of a home office (Collinson, 2020).

This consideration of issues is not exhaustive, and we note that the implementation of teleworking could pose further complications for employers, employees, and the wider economy, with the above only capturing some of its benefits and drawbacks. Different employers will of course address the issue differently, and it is not an option for all businesses. With this in mind, the implementation of teleworking is one which would need to be put in place with thought to maintain both employer and employee satisfaction. An opt-in scheme could be preferable with hot-desks available to accommodate employees who prefer to commute, which may have the additional benefit of reducing office size and costs.

4.5 Activity-based Agent Demand Models

Given the prior investigation into teleworking, it is important to consider how best it could be implemented and what other factors need to be considered. This section uses an activity-based agent simulator to shed light on the complexity of teleworking and the influence it may have on household electricity consumption, in particular in scenarios where EV adoption increases.

Policy analysis of the impacts of working from home on household electricity consumption needs to reflect the role of substantial diversity across households. This relates to both fixed attributes, such as household composition (number of members of certain age, employment status) or residence size and type (number of rooms, flat vs. detached house) as well as more dynamic attributes, such as type of activities (work, sleep, social)

4. Changes in Electricity Use at Household Scale

or use of appliances and devices (hobs, microwaves, laptops). In both instances, further variation in demand will be a result of the interaction between the attributes listed above and contextual variables, such as weather, time of day or season.

In the present setting, we define boundaries of the system to be the household and its members, including activities they take part in when at home. For the purpose of tractability of analysis, we do not incorporate broader considerations related to work-from-home adoption, such as employers' work-from-home policies and attitudes, broader (national and regional) policy and cultural framework, or digital infrastructure and skilfulness. Further discussion of work-from-home impacts in relation to energy can be found in Hook *et al.* (2020). For similar reasons, the EV scenarios are simplified and do not incorporate, for example, EV charging location choice or smart charging, both of which are potentially important in shaping household energy demand profiles and have direct implications for marginal GHG emissions from electricity generation (Tu *et al.*, 2020).

4.5.1 Activity-based agent demand simulator for household electricity consumption

The net change in household electricity consumption as a result of working from home is intuitively positive, due to the increased number of activities, appliance use, or demand for lighting and heating at home. This is also in line with the empirical evidence presented earlier in Section 4.3.2. This level of insight is, however, insufficient for effective management of demand, including implementation of demand side response mechanisms. For such contexts, demand simulation needs to consider the aforementioned sources of fixed and dynamic heterogeneity in households.

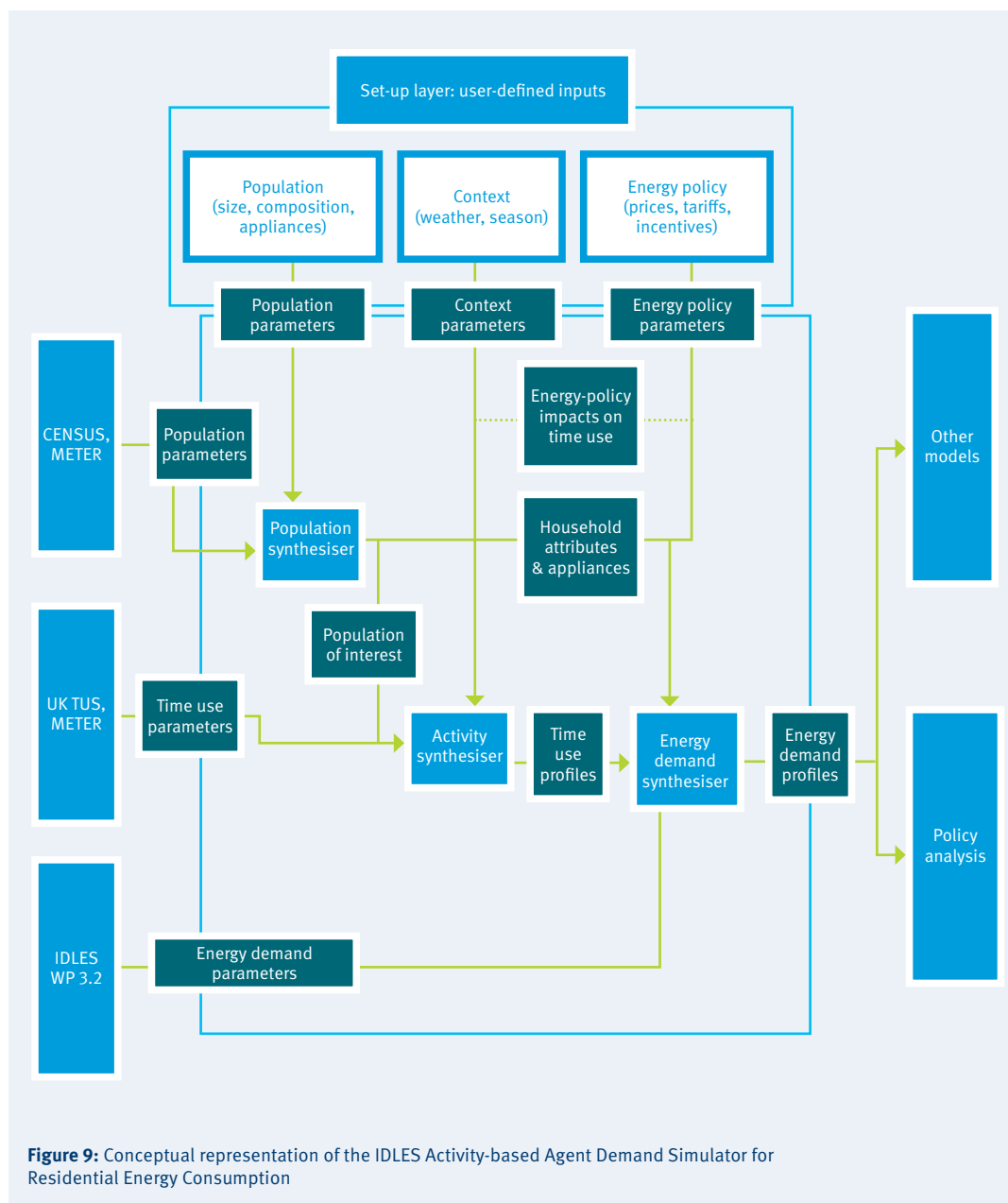
Such a need coincides with the overall agent-based modelling paradigm (Rai & Henry, 2016) whilst the context of teleworking supports the need for activity-oriented modelling. This was the motivation for the development of the activity-based agent demand simulator for household electricity consumption (Figure 9), recently developed as part of the IDLES programme (Pawlak, Imani & Sivakumar, 2020). To demonstrate how this novel approach

» BOX 3: What is Agent-based Modelling?

Agent-based modelling is a simulation technique in which a set of independent, decision-making entities (agents) exist within a system and make decisions based on a set of rules (Bonabeau, 2002). These rules could be based on, for example, probability distributions, econometric models or decision trees.

Agent-based activity models typically operate on a synthetic population (which could be constructed using census data to make it representative of the real population) and is comprised of agents that make decisions on activities such as work, leisure and travel, given budgetary and time constraints. The energy consumed by the agents can then be derived from the activity and travel patterns simulated by the agent-based model.

In the ABM used for this analysis, the agent decisions are simulated using Monte Carlo simulation techniques for the implementation of a sequence of multivariate probabilistic models that capture the stochasticity and heterogeneity of observed behaviours.



allows modelling energy impacts of sophisticated working-from-home scenarios in conjunction with more traditional energy policy considerations (energy pricing, EV adoption), we outline its methodological principles followed by an example analysis using an artificially synthesised population of 4,200 households.

The IDLES demand simulator consists of three primary components: a population synthesiser, an activity synthesiser, and an energy (currently electricity) demand simulator (see Figure 9). The population synthesiser creates a digital representation of the desired agents (often referred to as a synthetic population) that is either purely artificial or consistent with an observed population as reflected in, for example, the census.

4. Changes in Electricity Use at Household Scale

The activity synthesiser in turn simulates the desired representation of time use (activity participation), given parameters set by the user of the simulator, e.g., day of the week or weather, which ensures accurate reflection of in- and out-of-home activities undertaken by the individuals in the synthetic population. The activity synthesis typically follows a Monte Carlo simulation approach on a sequence of multivariate probabilistic choice models describing activity participation (activity type, duration, time) that capture the diversity of observed behaviours⁵. The resulting activity patterns, alongside attributes of the households, are fed into the energy demand simulator that forecasts energy consumption profiles with an arbitrary level of spatial (household, neighbourhood, district, etc.) and temporal (minute, hourly, etc.) resolution. The demand simulator provides a means of comprehensively representing scenarios of interest along three dimensions of set-up (using the Set-up layer – top of Figure 9). Examples of settings that can be tweaked (both independently and jointly) for each of these dimensions include:

- Population: settings to reflect (changes to) population composition, household attributes, employment, affluence, residential conditions, (electric) vehicle ownership, or (smart) appliance possession
- Activity: settings to reflect (shifts in) activity timing, preference for in-, out-of-home or virtual activity participation, flexible working arrangements, co-participation in activities
- Energy policy: settings to reflect (changes in) energy tariffs, pricing as well as per-activity energy consumption under particular circumstances of the household

⁵ Alternatively, the stochasticity can be eliminated for clearer tractability of the changes in the energy consumption due to variation in the input (scenario) assumptions.

4.5.2 Demonstration of the activity-based agent demand simulator with work-from-home and electric vehicle adoption scenarios

The present implementation is calibrated using the 2014-15 UK Time Use Survey (Sullivan & Gershuny, 2017) for the population and activity synthesiser, and METER data (Grunewald & Diakonova, 2019) for the energy (electricity) demand simulator, both collected prior to the COVID-19 pandemic. The population and activity synthesisers incorporate direct draws of the activity-travel and time-use patterns observed in the UK Time Use Survey, whilst the energy (electricity) demand simulator uses a framework described alongside the empirical calibration details in Pawlak, *et al.* (2021). For the current demonstration, we define scenarios that reflect COVID-19 lockdown scenarios by imposing work from home rules. In addition, we explore the role of EVs and how increasing EV adoption rates influence household electricity demand, a pertinent issue given that large-scale adoption of EVs is considered an important pillar in achieving carbon neutrality by 2050 (Reiner *et al.*, 2020).

The scenarios are compared with the baseline, which represents the simulated energy demand in a pre-pandemic world without systematic work-from-home policies or widespread EV adoption. Specifically, the following 12 scenarios are simulated based on a combination of 3 different teleworking arrangements and 4 different EV adoption settings.

Work-from-Home (WFH) arrangements:

- WFH1: All workers work from home
- WFH2: Only non-critical workers work from home. Critical workers are defined based on Standard Occupational Classification and UK Government guidelines on stay-at-home rules for COVID-19 national lockdowns.

- **WFH3:** 50% of non-critical workers work from home. This scenario is considered to reflect the post- pandemic context in which only a fraction of (and not all) non-critical workers continue to work from home. This is motivated by the observed trend towards mixed office- and home-based work arrangements expected to become more prevalent in the post-pandemic reality. In addition, this scenario also highlights the capacity of the model to simulate coordinated and un-coordinated work-from-home policies and their implications for reducing energy demand (discussed later in this section).

Electric Vehicle (EV) adoption settings:

- **EV0:** The rate of EV ownership follows the observed EV market penetration in the METER dataset (6%) which is slightly higher than pre-COVID UK market penetration of below 1% of all vehicles (DfT, 2019b).
- **EV1:** The increased rate of EV ownership is achieved by randomly assigning additional EVs to households so 30% of the population have access to EVs. This is deemed to reflect the gradual uptake of EVs in line with the government's strategy to incentivise EV adoption as a means of reduction in CO₂ emissions from transport (DfT, 2018)
- **EV2:** The increased rate of EV ownership is achieved by positively associating EVs with higher income households. The EV ownership rate varies by income between 1-50%, with half of high-income households switching to EV. This is a more realistic scenario as research shows that EV ownership is positively correlated with household income, e.g. Chen *et al.* (2020), Mersky *et al.* (2016)
- **EV3:** The increased rate of EV ownership is achieved by assigning the additional EVs to critical worker households. Combined with the WFH scenario for the non-critical worker, this creates a presumably favourable situation for net-zero transport as those

who are not working from home and must commute would own an EV. In this scenario, 30% of critical worker households switch their vehicle to an EV. This may not be an entirely realistic scenario given that existing EV owners tend to be upper-income, however, the scenario demonstrates the capability of the model to explore settings that may result in faster reduction of carbon emissions by coordinating WFH policies and EV adoption incentives.

The work-from-home arrangements are simulated by assuming that work activities generated by the activity synthesiser are conducted in-home during pre-defined time periods. In this analysis, we assume working hours between 9 AM and 6 PM with a one-hour lunch break at noon. EV settings are simulated by assuming car trips in households with EVs are made using the EVs. Subsequently, depending on the duration of the trip, the EV battery (consumed at the rate of 0.170kWh/km) needs to be recharged upon returning home (at the rate of 3kW). In all EV scenarios, we are assuming that EV batteries are only charged at home, which presents the most conservative scenario for residential electricity consumption. The simulation is performed for 4,200 artificially synthesised households to present a district-level example of analysis over a period of 24 hours.

4. Changes in Electricity Use at Household Scale

4.5.3 Simulation results

Table 3 summarises the scenarios with average percentage changes in the simulated residential electricity compared to the baseline. What can be observed is that the implementation of teleworking policies leads to about 2–5% higher demand in residential electricity on average, with minor variations attributable mainly to when activities take place (at home) and with how many participants. This is much lower than the impact of EV uptake and the consequent

increase in electricity demand. In order to yield further insight into this net effect across a day, Figure 10 presents aggregate profiles of the electricity demand under different work-from-home scenarios.

What can be clearly observed is that the level of EV ownership (and the consequent charging) places the demand for electricity at substantially different levels, as indicated by the grouping of profiles by EV scenarios. This observation suggests the need for coordinated approaches towards EV ownership and use

Scenario	WFH Definition	EVs Ownership	Simulated change in 24h electricity demand (vs. baseline)
1	All workers work from home (WFH1)	No additional EVs (EV0)	+4%
2	Non-critical workers work from home (WFH2)	No additional EVs (EV0)	+5%
3	50% of non-critical workers work from home (WFH3)	No additional EVs (EV0)	+2%
4	All workers work from home (WFH1)	EVs randomly assigned (EV1)	+42%
5	Non-critical workers work from home (WFH2)	EVs randomly assigned (EV1)	+43%
6	50% of non-critical workers work from home (WFH3)	EVs randomly assigned (EV1)	+40%
7	All workers work from home (WFH1)	EVs assigned more to high income households (EV2)	+26%
8	Non-critical workers work from home (WFH2)	EVs assigned more to high income households (EV2)	+27%
9	50% of non-critical workers work from home (WFH3)	EVs assigned more to high income households (EV2)	+24%
10	All workers work from home (WFH1)	EVs assigned more to critical workers (EV3)	+23%
11	Non-critical workers work from home (WFH2)	EVs assigned more to critical workers (EV3)	+24%
12	50% of non-critical workers work from home (WFH3)	EVs assigned more to critical workers (EV3)	+22%

Table 3 Simulated change in 24h residential electricity demand under the assumed scenarios

4. Changes in Electricity Use at Household Scale

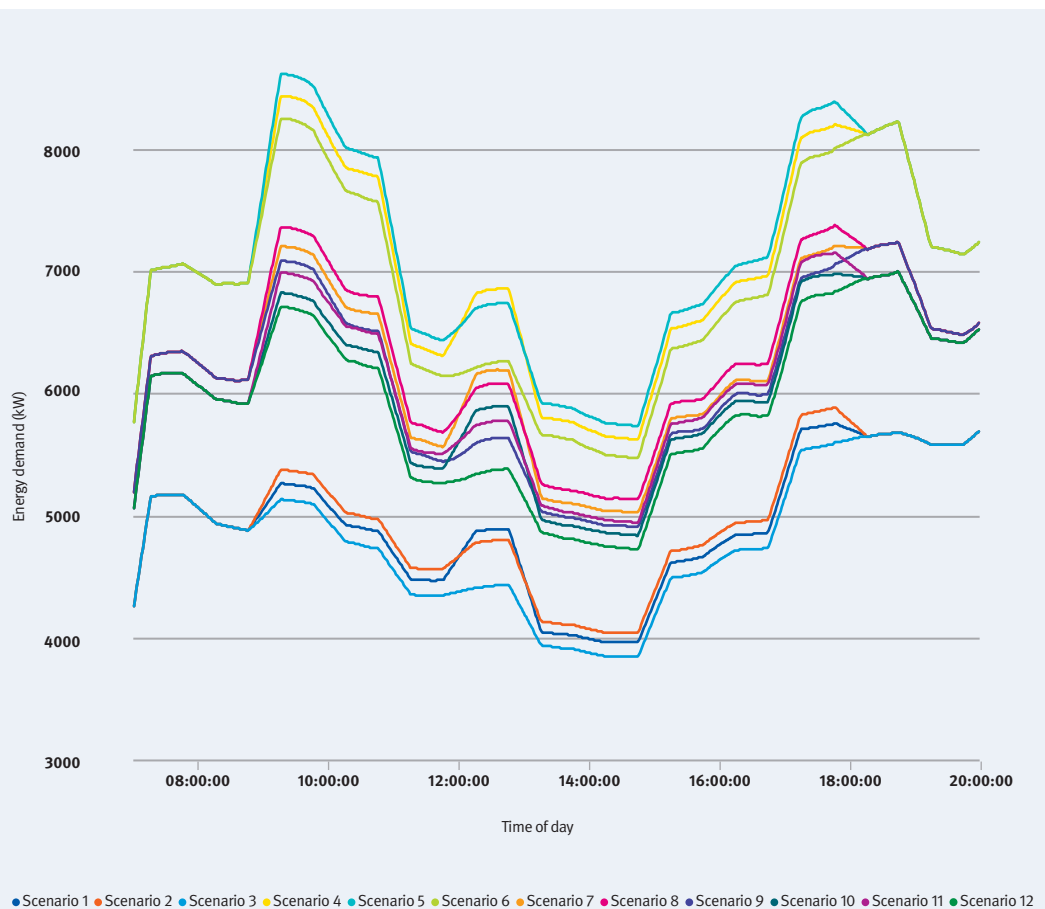


Figure 10: Aggregate electricity demand profile for the assumed scenarios

alongside teleworking policies as the two are inevitably intertwined through activity-travel behaviour patterns of the household members. Future analysis could also include wider transport policies and the displacement towards EV or other commuting modes and their associated energy use and emissions.

Another observation concerns the post-pandemic teleworking practices. In particular, as mentioned earlier, we do not anticipate that everyone will work from home after the pandemic to the extent that they did during the lockdown episodes. Maintenance of teleworking levels may also depend on the industry sector, occupation type, and other organisational considerations. Consequently, the analysis above suggests that the effects of

spatial variation in teleworking on residential energy consumption may be a function of the socioeconomic profile of the area and the propensity of its residents to work from home, alongside their EV ownership level.

Beyond the spatial variation, the adoption of teleworking practices may have a role in driving uncertainty of demand for electricity (energy more broadly, by similar token). In particular, an uncoordinated adoption of work-from-home practices means that any number of households may do so in a particular area on a given day, from all to none. With coordination at a certain level, the demand will not only be lower in that area (as certain employees do not work at home) but also less uncertain. This is clearly visible in Figure 10, where WFH3

demand profiles are the lowest (for each EV scenario). Hence coordinated work-from-home policies in which only particular households in an area work from home may present a viable electricity demand management mechanism, though further research is required to understand pre-requisites and credibility of this notion in real-life contexts.

4.5.4 Conclusions and limitations

The example analysis presented above demonstrates how an increasingly detailed representation of households and their demand for energy provides a mechanism for decomposition of the effects of policy interventions in the energy system. The work-from-home policies implemented due to COVID-19 circumstances present a very clear context for which there is no straightforward precedent and for which simulation of a variety of scenarios can present a meaningful way forward in understanding the post-COVID reality.

It is important to note that outside of the household electricity consumption modelled in these scenarios, public transport will still run and offices will remain open regardless of whether 25% or 75% of workers are based at home. However, the level of work-from-home may inspire hot-desking initiatives or organised teleworking policies leading to smaller workplaces. Resultant emissions and energy consumption will therefore be subject to all these other aspects as well, even if working-from-home policies are adopted.

Naturally, the example above is based on a synthetic population with broad assumptions concerning teleworking adoption and EV use. It should be mentioned that the analysis does not consider other out-of-home activities that became in-home activities during the COVID-19 pandemic such as home-schooling activities of children. However, such changes are less likely to continue post-COVID. It does not

include either any differences in pre-EV and pre-teleworking mode of commute. Ongoing work looks at implementation of the activity and agent-based modelling framework using data that will yield results representative of real-world populations and circumstances. In addition, the modelling capabilities under development are designed to make the underpinning frameworks sensitive to various other parameters, beyond pre-defined work-from-home scenarios and EV adoption levels, to increase the capability and improve the accuracy of the agent-based model in forecasting the response to energy policies.

4.6 Summary

Behavioural shifts influenced household energy consumption under lockdown. With more time spent at home cooking, watching TV, and working throughout the day, demand profiles were altered and weekly electricity consumption increased by 10.4%. For each day spent teleworking, electricity consumption increased by 6%. However, a low-carbon grid sustained through a high capacity of renewables and lack of commute meant the increase in electricity consumption did not translate to higher household emissions, with these in fact declining by 5% per day spent teleworking.

The outcome of the study by Coutellier *et al.* (2021) gives reason to consider policies that support flexible working arrangements to reduce emissions from office-based work. For those surveyed who teleworked in lockdown, their preference post-COVID is a three-day working week from home. Other factors that influence a willingness to telework include mode of transport and commute distance. This suggests that within the same company, employees of the same roles could have different levels of teleworking uptake dependent on their personal geography and commuting habits. Company policies that address teleworking should carefully consider the social implications of doing so and an opt-

in scheme may be more appropriate given how working from home could have varied impacts on individuals.

With the interest surrounding teleworking, an agent-based model revealed that scenarios with part of the workforce working-from-home (such as WFH3) are most optimal in regard to reducing electricity consumption and that coordinated efforts in working from home policies may present a viable electricity demand management mechanism. With the ongoing rise in adoption of EVs and uptake of teleworking, considering these two drivers of future electricity consumption in conjunction with each other could be beneficial for public policy. For example, the patterns of teleworking could be coordinated at employer or even city-level, with suitable incentives in the form of discounted EV charging at employers' premises during certain days for particular employees.

4. Changes in Electricity Use at Household Scale

5. Changes in Electricity System Operations

Low levels of electricity demand coupled with periods of high renewable penetration during lockdown, discussed in Chapter 2, created a grid stability challenge for Great Britain's (GB) Electricity System Operator (ESO), National Grid. Managing and maintaining stability across the network to prevent outages required the use of additional services to cope with the conditions witnessed under lockdown. This chapter will explain why the lockdown period posed a challenge to the UK's electricity grid, describe the actions taken by National Grid ESO to ensure stability, and what a future with high renewable penetration requires to be cost-effective.

5.1 Maintaining grid stability and ancillary services

Renewable generation is inherently intermittent and lacks a quality called inertia (see Box 4), but as there are no fuel costs associated with its generation, it is generally favoured for use ahead of fossil fuelled generators. During lockdown, low demand meant there was little room for more predictable forms of generation on the grid when renewable output was high, so additional ancillary services were required to keep the power system operating in a stable, efficient and safe way. In particular, features of the electricity grid such as frequency and voltage must be carefully managed so that electricity can be transmitted safely.

Ancillary services are a set of processes provided to the system operator that facilitate the continuous flow of electricity to consumers, so that supply will continually meet demand. They are vital for maintaining system stability, addressing any imbalances between supply and demand and aiding recovery after a power system event, discussed below. The ESO works with ancillary service providers to either sign long-term contracts or make short term requests for a service. The challenge of operating a low-inertia grid under lockdown meant that ancillary services had to play a more prominent role, with interim services having to be created and implemented to keep the lights on across the country. The short-term solutions put in place

by the ESO will be discussed in the chapter alongside the consideration of more permanent solutions.

5.1.1 Conditions for grid stability

One of the key features underpinning grid stability is electrical frequency and, in GB, the power system operates at a frequency of 50 Hz. Maintaining a consistent frequency is important because deviating too far from the standard 50 Hz could inflict damage to equipment (Drax, 2017). If supply and demand fall out of balance, then the frequency is affected; an imbalance arises, among other causes, when some power plants suddenly disconnect from the grid due to a failure. If a single generator connected to the grid is suddenly disconnected, it is referred to as an 'N-1' event, where 'N' is the total number of generators. An 'N-1 reliability standard' therefore, refers to the preservation of grid stability when one generator is disconnected. The boundaries relevant for frequency stability for such an occurrence are:

- 1) The Rate-of-Change-of-Frequency (RoCoF): Frequency levels (50 Hz in GB) must not fluctuate by more than 0.125 Hz per second. This limit is currently being relaxed through the Loss of Mains Change Programme.

- 2) Frequency Nadir: Frequency levels must not fall below 49.2 Hz to avoid the activation of Low-Frequency Demand Disconnection. The disconnection of some demand would restore the generation-demand balance and therefore bring frequency back to the desired 50 Hz.

To maintain these conditions and hence ensure grid stability, ancillary services such as inertia and frequency response are required.

» BOX 4: Inertia

Inertia refers to the amount of energy stored in the rotating masses of synchronous generators such as gas turbines. These masses are controlled to rotate at a certain speed to produce an AC current injection of 50 Hz to the grid. Maintaining these at 50 Hz is important to balance supply and demand in the grid, which is achieved by altering fuel injection. On the other hand, most renewables like solar PV and wind turbines use power electronics converters to achieve the required 50 Hz: solar PV has no rotating mass at all, while wind turbines rotate at varying speed to maximise power generation. These converters de-couple the wind turbines from the grid, therefore they do not naturally provide this valuable inertia.

Inertia is essential in maintaining stability, as it provides a valuable energy buffer; in the event of a generation outage, this kinetic energy stored in the rotating masses (i.e. the inertia) is spontaneously released to the grid to contain the imbalance. Synchronous generators, such as gas and nuclear, are the prime source of system inertia, which is why it is challenging to maintain stability whilst experiencing high volumes of non-synchronous renewable generation.

» BOX 5: Frequency Response

Complimentary to inertia, GB relies on ancillary services such as Enhanced Frequency Response (EFR) and Primary Frequency Response (PFR) to provide frequency support (National Grid ESO, 2016). EFR is a dynamic response service that is intended to react within one second of a loss of generation or demand, currently being migrated into a new service with similar characteristics called Dynamic Containment. PFR on the other hand is only required to fully act ten seconds after the event. Batteries have been the main providers of the EFR service, whilst generators act as PFR candidates due to their slower dynamics. Both services are currently needed to maintain grid stability in low-inertia systems. (Badesa *et al.*, 2021)

The main difference between inertia and EFR or PFR is that whilst inertia refers to the instantaneous release of stored kinetic energy in synchronous generators, frequency response requires a control mechanism to inject additional power to the grid, as well as a fuel injection or energy stored in a battery.

5. Changes in Electricity System Operations

5.1.2 Balancing the grid: tools and processes implemented by the ESO during COVID-19

The main factors that posed a challenge to National Grid were suppressed demand and significant generation from renewable and nuclear sources during low-price periods (Badesa *et al.*, 2021). These conditions led to a low-inertia system and meant the ESO had to procure additional services, and rapidly create new offerings, to prevent imbalance. Between May and July 2020, the additional services cost approximately 3 times more than the year prior; £302 million compared to £101 million (National Grid ESO, 2020h).

Why renewable and nuclear generation are favoured during low-price periods

Contracts for Difference (CfD) is a mechanism supporting low-carbon electricity generation in the UK. In essence, they guarantee a fixed rate for electricity generation per MWh and thus shield renewables from volatile wholesale prices (BEIS, 2020). In conjunction with zero fuel costs this gives renewable generators incentive to produce electricity, regardless of market price, as they can profit even in times of negative energy pricing.

Nuclear generation is often in use due to its low marginal cost and inflexible nature (high up and down times). Even with the low prices seen in the energy market, nuclear generators were forecast to maintain high load factors over the course of the lockdown (Magill, 2020).

Scenarios constructed by National Grid in early March anticipated a drop of up to 20% in demand compared to previous years as a consequence of COVID-19 (National Grid ESO, 2020i). In absolute terms, forecasted demand was set to fall down to 12 GW in the summer, with nuclear and renewables favoured in these periods of low demand and with the former comprising of over 5 GW of operational capacity at the time. However, an estimated 8 to 9 GW of synchronous generators were required to be online to provide adequate inertia. Suppressed

demand therefore had the danger of bringing instability to the system and required the ESO to gain downward flexibility – i.e., being able to accommodate more renewable generation - in its operations.

Optional Downward Flexibility Management

The Optional Downward Flexibility Management (ODFM) service was employed to cope with the predicted reduction in demand (Broom & Brennan, 2020). Under this scheme, smaller scale, distributed renewable generators, who did not participate in the balancing market, were compensated for curtailing their output. Similarly, heavy load users were paid for increasing their demand by a set value to meet supply. Having been designed and implemented within 3 weeks, the service was largely successful in attracting 4.5 GW of assets and was used 4 times at a cost of £7 million (Hanson & Weltevreden, 2020).

Bilateral contracts with nuclear generators

To lessen the inertia required on the grid the ESO signed a bilateral contract with EDF to half Sizewell B's output, part-loading the nuclear reactor. Sizewell B outputs up to 1198 MW to the grid in GB and, when at full output, defines the volume of ancillary services required for redundancy in the event of its loss (i.e., the 'N-1 reliability standard'). This fixed term contract cost the ESO between £55 to £73 million between 7 May and 24 September 2020 (National Grid ESO, 2020e).

Balancing Mechanism

The Balancing Mechanism (BM) is an instrument used to stabilise the grid in GB. It operates close to real-time to manage discrepancies between supply and demand, by enabling bids or offers from participants to alter generation or demand accordingly. The BM was developed prior to the pandemic in 2001 (as NETA), but during lockdown it played an important role in committing synchronous generators to provide additional inertia and frequency support, as these generators would not have been chosen in the energy market (which neglects grid stability

requirements), but were needed for stability reasons (Competition & Markets Authority, 2014; Badesa *et al.*, 2021). For example, on Easter Monday bank holiday, 2.3GW of gas plants were brought online for inertia management and additional frequency support (National Grid ESO, 2020f).

Accelerated Loss of Mains Change Programme

Further to this, the Accelerated Loss of Mains Change Programme, first implemented in October 2019 was fast-tracked under lockdown by the ESO. Under this scheme, National Grid provides compensation to distributed generators to alter their protection settings. This allowed for the frequency to vary at a higher rate per second (± 0.5 Hz/s as opposed to ± 0.125 Hz/s) whilst these generators remained connected to the grid, subsequently lowering the required system inertia (Badesa *et al.*, 2021).

These measures enabled the electricity grid to remain stable and operational throughout the lockdown period, responding to changes that were not expected for another decade. Despite the cost of ODFM and the bilateral contracts sounding drastic, to put them into perspective there are approximately 27 million households in GB (Piddington *et al.*, 2017). This means that the additional cost per household for these two combined measures was between £2 - £3, an almost negligible cost at the residential level. So, whilst somewhat affordable and necessary in the short-term, it is important to understand how balancing costs can be minimised proactively with renewable uptake increasing.

5.2 Future Trends

Having analysed the ESO actions and impacts on balancing costs during the first COVID-19 lockdown, these observations were then pulled through into future focussed modelling. The report by Strbac *et al.* (2017) analysed the projected cost of ancillary services by 2030 in Great Britain with the operational challenges decarbonisation presents to the grid in mind. More recently, Badesa *et al.* (2021) analysed

the future trends of ancillary services with new services such as Enhanced Frequency Response. Given the operational challenges associated with deep decarbonisation of the electricity grid, this is an area where lessons can be learned from steps taken during the COVID-19 lockdown. The energy mix detailed in National Grid's 'Leading the Way' scenario (National Grid ESO, 2020g) was simulated in order to better understand how a decarbonised system influences ancillary services costs.

5.2.1 Methodology

To determine the cost of ancillary services in 2030, a generation-dispatch model was run twice, once with the frequency-stability constraints for containing the RoCoF and frequency nadir as detailed in 5.1.1 and the second time without. The difference in costs between these two models equated to the spend on maintaining stability and therefore, ancillary services. Several comparative simulations were run to comprehend the cost implications of a decarbonised system in 2030. First, comparing the percentage cost of ancillary services to 2015 and then examining how 2030's expenditure could vary depending on EFR procurement.

5.2.2 Results & Discussion

Ancillary Costs in 2030

Figure 11 illustrates the expected system costs in 2030. It is anticipated that ancillary services costs will potentially increase by about 10 times relative to the 2015 levels (Strbac *et al.*, 2017). Renewable energy sources (RES) have zero production cost so overall electricity production costs will significantly reduce, however, the low-inertia state of the resulting system with higher RES capacity incurs much larger ancillary services costs.

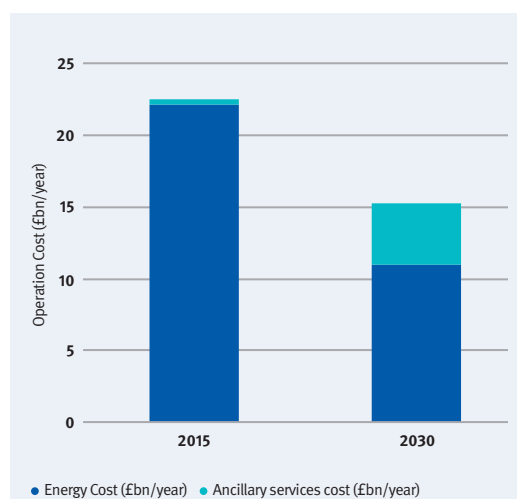


Figure 11: Ancillary services costs in 2015 and expected costs in 2030. (Strbac *et al.* 2017)

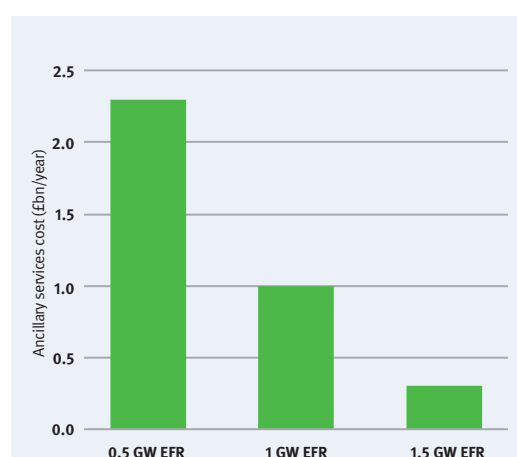


Figure 12: Projected ancillary services costs in 2030 with varying EFR volumes. (Badesa *et al.* 2021)

EFR Procurement

Works such as Badesa *et al.* (2019) illustrate how advancing procurement of fast-frequency response mechanisms such as EFR can be pivotal in handling low-inertia grids. A base case of 1 GW of EFR was considered to understand the value of this service. A sensitivity analysis found that an additional 0.5 GW of EFR (1.5 GW total) could save up to £700 m/year. If instead of 1 GW only 0.5 GW is procured, ancillary service costs could more than double at £2.3 billion/year. See Figure 12 for full analysis.

With a lack of EFR more synchronous generators would have to be kept online to provide inertia, which would increase ancillary service costs. This implies that renewables would be curtailed at times of low net-demand to maintain system stability, increasing both operational costs and carbon emissions.

It is important to note that the investment costs associated with battery energy storage systems that would be the likely providers of EFR have not been considered in the scope of this analysis.

Market Conditions

Currently there is no market for inertia in Great Britain, but the results in these studies show a significant increase in need for and value of these services. Furthermore, ancillary services costs are currently socialised (i.e. shared among all consumers), while it might be appropriate to evolve to a cost-reflective allocation where the actors causing the need for ancillary services bear these costs.

5.3 Applicability to other countries

The analysis in this chapter has so far centred around the response of National Grid ESO in Great Britain, which as an island nation is more exposed to the influence of a low-inertia grid due to reduced interconnection. Other island nations such as Ireland and Australia, as well as the state of Texas, face similar issues in relation to inertia, with little or no synchronous interconnection to other countries or states.

Whilst continental grids within the EU allow for cross-country inertial support, increasing amounts of renewable technologies could prove challenging for these systems as well. It is therefore important to recognise the opportunity Great Britain may have in pioneering mechanisms relating to ancillary services.

5.4 Summary

COVID-19 and the ensuing lockdown gave National Grid a glimpse into net-demand profiles (demand not covered by renewables) only expected in the next decade. Given the short time frame under which the ESO had to act, the ODFM product and Sizewell B contract were effective in preventing any major outages. However, the almost overnight fluctuations in demand caused operational challenges reflected in the large expenditure.

The simulations conducted of system operation in 2030 and discussed in section 5.2 from Strbac *et al.* (2017) and Badesa *et al.* (2021) highlight the importance of cost-effective ancillary services that anticipate low-inertia instability. An emphasis is placed on additional fast-frequency response mechanisms (EFR in GB) to significantly reduce ancillary services costs in the future. Given that these costs are expected to significantly increase, there is a need to reconsider current market conditions that do not remunerate inertia and socialise ancillary services costs.

6. Conclusions and Recommendations for Decarbonisation of the GB Energy System

This Briefing Paper has examined the influence of COVID-19 on the energy system in Great Britain. By assimilating the findings of working groups based at Imperial College, a multidisciplinary view of the mandated lockdown period from 23 March 2020 and the months that followed has been presented from the demand and supply side perspectives. The conditions faced under lockdown allowed a unique glimpse at the future of our energy system and provided lessons on how to prepare for future decarbonisation. With the unique set of circumstances faced by businesses and individuals under lockdown in Great Britain, overall national electricity demand fell by up to 19% whereas at a household level demand was seen to increase as daily routines were transformed. In drawing together these findings on electricity demand changes, the impact of specific COVID-19 containment policies on electricity use and an analysis of system operation actions, the following conclusions have been reached and recommendations made for the transition towards a net-zero energy system.

6.1 The rise of teleworking

Working from home emerged as a key trend throughout 2020 with containment and closure policies forcing workplaces to adjust to a new normal. Whilst not the only consequence felt by employees over the course of the lockdown, teleworking is the only outcome that has merit in long-term applicability. Findings presented within the paper suggest that teleworking had an influence on reducing national electricity consumption over the course of the lockdown, with workplace closures leaving offices absent of employees.

At a household level, a day spent teleworking is thought to have increased weekly electricity demand by 6%, compared to a 2019 baseline. However, with a large proportion of renewables on the grid and reduced commute, this did not translate to an increase in emissions, which instead decreased by 5% per day spent working from home compared to 2019.

The survey of energy consumers in Chapter 4 revealed part-time teleworking as a relatively popular scheme. Therefore, this is recommended as an avenue for businesses to explore which may help lower emissions and

could reduce their office space requirements. However, there are several external factors that should be considered before a long-term strategy is implemented, with respect to the social impacts teleworking brings with it.

6.2 Coordinating policy approaches

Government mandated closures were the most influential on electricity demand in Chapter 3, prompting further investigation into the different demand changes teleworking may bring. This requires forethought in assessing how best to arrange working from home within an organisation, as we find that who and what proportion of workers work from home can result in different electricity consumption levels. This is an intuitive finding, as different types of workers have different activity and travel patterns, which have different implications for the spatial and temporal patterns of electricity demand. However, the activity-based modelling (ABM) tool used for the analysis presented in this paper provides the ability to quantitatively assess the impacts of policies targeted at different population segments.

The use of the ABM tool to analyse how teleworking and electric vehicle (EV) uptake may interact thus enables us to better understand two expected drivers of increased electricity consumption. The interactions between the impacts of these two factors are important to consider in designing appropriate policies to limit emissions. For example, the patterns of teleworking could be coordinated at employer or even city-level, with suitable incentives in the form of discounted EV charging at employers' premises during certain days for particular employees.

6.3 Systems-based change

Analysis from Chapter 4 showed that an increase in consumption does not always equate to an increase in emissions if the grid has high renewable penetration. Whilst behavioural shifts and green grids lend themselves to limiting resultant emissions, isolating for the higher volume of renewables and low carbon intensity of the 2020 grid found that the behavioural shifts in the residential time of use of electricity were not as influential in limiting emissions from electricity consumption. Instead, this revealed that a systems-based approach is necessary to reduce emissions in a net-zero future and to lean solely on demand flexibility is unlikely to be successful in reaching this ambition. This is recommended as a priority, especially given the increase in household electricity demand observed under our simulation scenarios for high EV uptake.

6.4 Enhanced frequency response

Whilst the remedial steps taken by National Grid during the COVID-19 pandemic were successful in maintaining a balanced grid, with no outages in Great Britain over the course of lockdown, it is important to act proactively in a future destined for high renewable penetration. Increasing enhanced frequency response capacity in Chapter 5 was shown to provide more cost-effective outcomes with ancillary services that anticipate low-inertia instability. New technologies such as electric vehicles and synthetic inertia from wind farms could be key for this purpose. As renewable penetration is likely to increase worldwide, low-inertia could prove challenging for even continental grids that allow for cross-country inertial support. It is also important to recognise the opportunity Great Britain may have in pioneering mechanisms relating to ancillary services.

6.5 Market considerations

With no market for inertia, it is notably relevant to understand how to make current energy-based financial support mechanisms for certain generators (e.g., Contracts for Difference) relevant with the provision of inertia, frequency response, and an optimised largest in-feed loss. This has potential to create market conditions more relevant to high renewable penetration and avoid reimbursement for curtailing renewable generation.

References

- Auvermann, O. (2020)** *The Impacts of Government Policy in Response to COVID-19 on Electricity Demand*. MSc Thesis. Imperial College London. Available upon request from: energyfutureslab@imperial.ac.uk
- Badesa, L., Strbac, G., Magill, M. & Stojkovska, B. (2021)** Ancillary services in Great Britain during the COVID-19 lockdown: a glimpse of the carbon-free future. *Applied Energy*. 285 (December 2020), 116500. Available from: doi:10.1016/j.apenergy.2021.116500.
- Badesa, L., Teng, F. & Strbac, G. (2019)** Simultaneous scheduling of multiple frequency services in stochastic unit commitment. *IEEE Transactions on Power Systems*. 34 (5), 3858–3868. Available from: doi:10.1109/TPWRS.2019.2905037.
- Bahmanyar, A., Estebarsari, A. & Ernst, D. (2020)** The impact of different COVID-19 containment measures on electricity consumption in Europe. *Energy Research & Social Science*. 68, 101683. Available from: doi: 10.1016/j.erss.2020.101683.
- Bloom, N. (2014)** *To Raise Productivity, Let More Employees Work from Home*. [Online]. Available from: <https://hbr.org/2014/01/to-raise-productivity-let-more-employees-work-from-home> [Accessed: 24 September 2021].
- Bonabeau, E. (2002)** Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*. 99 (suppl 3), 7280 LP – 7287. Available from: doi:10.1073/pnas.082080899.
- Broom, R. & Brennan, P. (2020)** *National Grid ESO Launches Optional Downward Flexibility Management (ODFM) Scheme*. [Online] <https://www.squirepattonboggs.com/en/insights/publications/2020/05/national-grid-eso-launches-optional-downward-flexibility-management-odfm-scheme>. [Accessed: 24 September 2021]
- Cabinet Office (2020)** *Staying at home and away from others (social distancing)*. [Online]. 2020. Available from: <https://www.gov.uk/government/publications/full-guidance-on-staying-at-home-and-away-from-others/full-guidance-on-staying-at-home-and-away-from-others#staying-at-home> [Accessed: 24 September 2021].
- Chen, C., Zarazua de Rubens, G., Noel, L., Kester, J., et al. (2020)** Assessing the socio-demographic, technical, economic and behavioral factors of Nordic electric vehicle adoption and the influence of vehicle-to-grid preferences. *Renewable and Sustainable Energy Reviews*. 121, 109692. Available from: doi:10.1016/j.rser.2019.109692.
- Cheshmehzangi, A. (2020)** COVID-19 and household energy implications: what are the main impacts on energy use? *Heliyon*. 6 (10), e05202. Available from: doi:10.1016/j.heliyon.2020.e05202.
- Cicala, S. (2020)** Powering Work from Home. *National Bureau of Economic Research Working Paper Series*. No. 27937. Available from: doi:10.3386/w27937.

- Clark, D. (2021)** *Cumulative jobs on furlough UK 2021* / Statista. [Online]. 2021. Available from: <https://www.statista.com/statistics/1116638/uk-number-of-people-on-furlough/> [Accessed: 24 September 2021].
- Collinson, P. (2020)** *Should your employer pay your bills if you work from home?* [Online]. 2020. Available from: <https://www.theguardian.com/money/2020/jan/17/should-employer-pay-broadband-working-home-cqc> [Accessed: 24 September 2021].
- Competition & Markets Authority (2014)** *Energy Markets Investigation: Summary of hearing with National Grid Gas plc trading as National Grid on 14 October 2014*. [Online]. 2014. Available from: https://assets.publishing.service.gov.uk/media/5477006240f0b60244000001/Summary_of_hearing_with_National_Grid.pdf [Accessed: 24 September 2021].
- Coutellier, Q., Hardy, J., Martin, R. & Muûls, M. (2021)** *Homeworking can be Net Positive, Evidence from the UK Lockdown during COVID-19* (September 2021). Available at SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3927719
- Department for Business Energy & Industrial Strategy (2020)** *Contracts for Difference - GOV. UK*. [Online]. 2020. Available from: <https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference> [Accessed: 24 September 2021].
- Department for Transport (2018)** *The Road to Zero: Next steps towards cleaner road transport and delivering our Industrial Strategy*. [Online]. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/739460/road-to-zero.pdf [Accessed: 24 September 2021]
- Department for Transport (2019a)** *Transport statistics Great Britain: 2019*. [Online]. 2019. Available from: <https://www.gov.uk/government/statistics/transport-statistics-great-britain-2019> [Accessed: 24 September 2021].
- Department for Transport (2019b)** *Vehicle Licensing Statistics: Annual 2018*. [Online]. Available From: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/800502/vehicle-licensing-statistics-2018.pdf [Accessed: 24 September 2021]
- Dingel, J.I. & Neiman, B. (2020)** How many jobs can be done at home? *Journal of Public Economics*. 189, 104235. Available from: doi:10.1016/j.jpubeco.2020.104235.
- Drax (2017)** *Why we need the whole country on the same frequency*. [Online]. 2017. Available from: <https://www.drax.com/energy-policy/need-whole-country-frequency/> [Accessed: 24 September 2021].
- Electric Insights (2021)** *Drax Electric Insights: Explore the Data*. [Online]. 2021. Available from: <https://electricinsights.co.uk/#/dashboard> [Accessed: 24 September 2021].
- García, S., Parejo, A., Personal, E., Guerrero, J., Biscarri, F. & León, C.** A retrospective analysis of the impact of the COVID-19 restrictions on energy consumption at a disaggregated level. *Applied energy*. 287, 116547. Available from: doi:10.1016/j.apenergy.2021.116547.
- Gershuny, J.I., Sullivan, O. (2017).** United Kingdom Time Use Survey, 2014-2015. [data collection]. UK Data Service. SN: 8128. Available from: doi:10.5255/UKDA-SN-8128-1
- Graizbord, B. (2015)** Teleworking as a Mobility Strategy for Mexico City. *International Planning Studies*. 20 (1–2), 112–130. Available from: doi:10.1080/13563475.2014.942506.
- Grunewald, P., Diakonova, M. (2019).** *METER: UK Household Electricity and Activity Survey, 2016–2019: Secure Access*. [data collection]. UK Data Service. SN: 8475. Available from: doi:10.5255/UKDA-SN-8475-1

- Hale, T., Webster, S., Petherick, A., Phillips, T., et al. (2020)** *Oxford Covid-19 Government Response Tracker (OxCGRT)*. [Online]. Available from: <https://github.com/OxCGRT/covid-policy-tracker> [Accessed: 24 September 2021].
- Hanson, R. & Weltevreden, A. (2020)** 9. *ODFM and Managing Low Demand*. [Podcast]. 7th July. Available from: <http://powerresponsive.com/summer-insights-2020-industry-podcasts/> [Accessed: 24 September 2021].
- Hook, A., Court, V., Sovacool, B.K. & Sorrell, S. (2020)** A systematic review of the energy and climate impacts of teleworking. *Environmental Research Letters*. 15 (9). Available from: doi:10.1088/1748-9326/ab8a84.
- International Energy Agency (2021)** *Covid-19 impact on electricity*. [Online]. 2021. Available from: <https://www.iea.org/reports/covid-19-impact-on-electricity> [Accessed: 24 September 2021].
- International Energy Agency (2020a)** *Electricity Market Report*. Electricity Market Report. (December). Available from: doi:10.1787/f0aed4e6-en.
- International Energy Agency (2020b)** *Weather-corrected year-on-year comparison of demand in selected European countries to 18 November 2020 – Charts – Data & Statistics - IEA*. [Online]. 2020. Available from: <https://www.iea.org/data-and-statistics/charts/weather-corrected-year-on-year-comparison-of-demand-in-selected-european-countries-to-18-november-2020> [Accessed: 24 September 2021].
- International Energy Agency (2020c)** *Working from home can save energy and reduce emissions. But how much?* [Online]. 2020. Available from: <https://www.iea.org/commentaries/working-from-home-can-save-energy-and-reduce-emissions-but-how-much> [Accessed: 24 September 2021].
- Larson, W. & Zhao, W. (2017)** TELEWORK: URBAN FORM, ENERGY CONSUMPTION, AND GREENHOUSE GAS IMPLICATIONS. *Economic Inquiry*. 55 (2), 714–735. Available from: doi: 10.1111/ecin.12399.
- López Prol, J. & O, S. (2020)** Impact of COVID-19 Measures on Short-Term Electricity Consumption in the Most Affected EU Countries and USA States. *iScience*. 23 (10). Available from: doi:10.1016/j.isci.2020.101639.
- Magill, M. (2020)** 7. *COVID-19 System Operability Challenges*. [Podcast]. 3rd July. Available from: <http://powerresponsive.com/summer-insights-2020-industry-podcasts/>. [Accessed: 24 September 2021].
- Mann, S. & Holdsworth, L. (2003)** The psychological impact of teleworking: Stress, emotions and health. *New Technology, Work and Employment*. 18 (3), 196–211. Available from: doi:10.1111/1468-005X.00121.
- Matson, C. & Gogna, R. (2021)** *What caused January's record high electricity prices and is this the new normal?* [Online]. 2021. Available from: <https://www.lcp.uk.com/our-viewpoint/2021/02/what-caused-january-s-record-high-electricity-prices-and-is-this-the-new-normal/> [Accessed: 24 September 2021].
- Matthews, H. & Williams, E. (2005)** Telework Adoption and Energy Use in Building and Transport Sectors in the United States and Japan. *Journal of Infrastructure Systems*. 11. Available from: doi:10.1061/(ASCE)1076-0342(2005)11:1(21).
- Mehlig, D., ApSimon, H. & Staffell, I. (2021)** The impact of the UK's COVID-19 lockdowns on energy demand and emissions. *Environmental Research Letters*. 16 (5), 054037. Available from: doi:10.1088/1748-9326/abf876.

Mersky, A.C., Sprei, F., Samaras, C. & Qian, Z. (Sean) (2016) Effectiveness of incentives on electric vehicle adoption in Norway. *Transportation Research Part D: Transport and Environment*. 46, 56–68. Available from: doi:10.1016/j.trd.2016.03.011.

Morales Rodriguez, D. (2020) *Could teleworking bring us closer to sustainability in a post-COVID world? A case study of the UK*. MSc Thesis. Imperial College London. Available upon request from: energyfutureslab@imperial.ac.uk

National Grid ESO (2020a) *4 ways lockdown life affected UK electricity use*. [Online]. 2020. Available from: <https://www.nationalgrid.com/uk/stories/grid-at-work-stories/4-ways-lockdown-life-affected-uk-electricity-use> [Accessed: 24 September 2021].

National Grid ESO (2020b) *Britain's Electricity Explained: April 2020*. [Online]. Available from: <https://www.nationalgrideso.com/document/168476/download> [Accessed: 24 September 2021].

National Grid ESO (2020c) *Britain's Electricity Explained: June 2020*. [Online]. Available from: <https://www.nationalgrideso.com/document/172501/download> [Accessed: 24 September 2021].

National Grid ESO (2020d) *Britain's Electricity Explained: May 2020*. [Online]. Available from: <https://www.nationalgrideso.com/document/168706/download> [Accessed: 24 September 2021].

National Grid ESO (2020e) *Decision to extend contract with EDF to turn down output from Sizewell nuclear power station*. [Online]. Available from: <https://www.nationalgrideso.com/document/174271/download> [Accessed: 24 September 2021].

National Grid ESO (2020f) *ESO Coronavirus Preparedness*. [Online]. Available from: <https://data.nationalgrideso.com/backend/dataset/b3c55e31-7819-4dc7-bf01-3950dccbe3c5/resource/efbad1d7-495b-4669-b19c-cd600c0e0048/download/ngeso-covid-19-preparedness-15-04-vfinal.pdf> [Accessed: 24 September 2021].

National Grid ESO (2020g) *Future Energy Scenarios*. [Online]. Available from: <https://www.nationalgrideso.com/document/173821/download> [Accessed: 24 September 2021].

National Grid ESO (2016) *Future Requirements for Balancing Services*.

National Grid ESO (2020h) *Monthly Balancing Services Summary 2020/21: August 2020*. [Online]. August 2020. Available from: <https://data.nationalgrideso.com/backend/dataset/f89a12fc-94ef-4a09-bce2-c094c7212e1f/resource/37a11c22-49c9-4889-9c68-65d6d3ac026d/download/mbss-august-2020-rev-1.pdf> [Accessed: 24 September 2021].

National Grid ESO (2020i) *Summer Outlook Report 2020*.

O'Brien, W. & Yazdani Aliabadi, F. (2020) Does telecommuting save energy? A critical review of quantitative studies and their research methods. *Energy and Buildings*. 225, 110298. Available from: doi:10.1016/j.enbuild.2020.110298.

Office for National Statistics (2020a) *Coronavirus and homeworking in the UK*. [Online]. 2020. Available from: <https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/bulletins/coronavirusandhomeworkingintheuk/april2020> [Accessed: 24 September 2021].

Office for National Statistics (2020b)

Coronavirus and homeworking in the UK labour market: 2019. [Online]. 2020. Available from: <https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/articles/coronavirusandhomeworkingintheuklabourmarket/2019> [Accessed: 24 September 2021].

Office for National Statistics (2020c)

Coronavirus and how people spent their time under lockdown. [Online]. 2020. Available from: <https://www.ons.gov.uk/economy/nationalaccounts/satelliteaccounts/bulletins/coronavirusandhowpeoplespenttheirtimeunderrestrictions/28marchto26april2020> [Accessed: 24 September 2021].

Office for National Statistics (2021a)

Coronavirus and redundancies in the UK labour market. [Online]. 2021. Available from: <https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/articles/labourmarketeconomicanalysisquarterly/december2020> [Accessed: 24 September 2021].

Office for National Statistics (2021b)

Coronavirus and the impact on output in the UK economy. [Online]. 2021. Available from: <https://www.ons.gov.uk/economy/grossdomesticproductgdp/articles/coronavirusandtheimpactonoutputintheuk economy/december2020> [Accessed: 24 September 2021].

Office for National Statistics (2020d) *Great Britain population mid-year estimate*. [Online]. 2020. Available from: <https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/timeseries/gbpop/pop> [Accessed: 24 September 2021].

Office for National Statistics (2021c)

International comparisons of GDP during the coronavirus (COVID-19) pandemic. [Online]. 2021. Available from: <https://www.ons.gov.uk/economy/grossdomesticproductgdp/articles/internationalcomparisonsofgdpduringthecoronaviruscovid19 pandemic/2021-02-01#coronavirus-and-uk-gdp> [Accessed: 24 September 2021].

Ofgem (2020)

9 August 2019 power outage report. [Online]. Available from: https://www.ofgem.gov.uk/system/files/docs/2020/01/9_august_2019_power_outage_report.pdf [Accessed: 24 September 2021].

Papandrea, D. (2020) *Want to work from home? Understand the pros and cons before deciding*. [Online]. Available from: <https://www.monster.com/career-advice/article/pros-cons-of-working-from-home> [Accessed: 24 September 2021].

Pawlak, J., Imani, A.F. & Sivakumar, A. (2020) A microeconomic framework for integrated agent-based modelling of activity-travel patterns and energy consumption. *Procedia Computer Science*. 170, 785–790. Available from: doi: 10.1016/j.procs.2020.03.155

Pawlak, J., A. Faghih-Imani, A. Sivakumar (2021)

How do household activities drive electricity demand? Applying activity-based modelling in the context of the United Kingdom. *Energy Research & Social Science*. Available from: doi:10.1016/j.erss.2021.102318

Peters, G.P., Andre, R.M., Canadell, J.G., Friedlinstein, P., Jackson, R.B., Korsbakken, J.I., Le Quéré, C. & Peregon, A. (2020) Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. *Nature Climate Change*. 10 (1), 3–6. Available from: doi:10.1038/s41558-019-0659-6.

Piddington, J., Nicol, S., Garrett, H. & Custard, M. (2017) *The Housing Stock of The United Kingdom*. [Online]. Available from: https://files.bretrust.com/bretrust/The-Housing-Stock-of-the-United-Kingdom_Report_BRE-Trust.pdf [Accessed: 24 September 2021].

- Rai, V. & Henry, A.D. (2016)** Agent-based modelling of consumer energy choices. *Nature Climate Change*. 6 (6), 556–562. Available from: doi:10.1038/nclimate2967.
- Reiner, C., Beard, G., Park, T. & Kinnear, N. (2020)** *Driving and accelerating the adoption of electric vehicles in the UK*. [Online]. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/914111/driving-and-accelerating-the-adoption-of-electric-vehicles-in-the-uk.pdf [Accessed: 24 September 2021].
- Roth, K.W., Rhodes, T. & Ponoum, R. (2008)** The energy and greenhouse gas emission impacts of telecommuting in the U.S. *In: 2008 IEEE International Symposium on Electronics and the Environment*. 2008 pp. 1–6. Available from: doi:10.1109/ISEE.2008.4562945.
- Sorrell, S. (2015)** Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews*. 47 pp.74–82. Available from: doi:10.1016/j.rser.2015.03.002.
- Staffell, I., Green, R., Gross, R. & Green, T. (2020a)** *Electric Insights Quarterly: April to June 2020*. [Online]. Available from: https://reports.electricinsights.co.uk/wp-content/uploads/2020/10/200828_Drax20_Q2_Report_005.pdf [Accessed: 24 September 2021].
- Staffell, I., Green, R., Gross, R., Green, T. & Clark, L. (2020b)** *Electric Insights Quarterly: January to March 2020*. [Online]. Available from: https://reports.electricinsights.co.uk/wp-content/uploads/2020/10/200515_Drax_20Q1_A2.pdf [Accessed: 24 September 2021].
- Staffell, I., Jansen, M., Green, R., Gross, R., Green, T. & McNally, P. (2020c)** *Electric Insights Quarterly: July to September 2020*. [Online]. Available from: https://reports.electricinsights.co.uk/wp-content/uploads/2020/11/201126_Drax_20Q3_005-1.pdf [Accessed: 24 September 2021].
- Strbac, G., Pudjianto, D., Teng, F., Papadaskalopoulos, D., Aunedi, M., Shakoob, A.A. & Davies, G. (2017)** *ROADMAP FOR FLEXIBILITY SERVICES TO 2030 A report to the Committee on Climate Change*.
- Sullivan, O. & Gershuny, J. (2017)** United Kingdom Time Use Survey, 2014-2015. Available from: doi:10.5255/UKDA-SN-8128-1.
- Sykes, D. (2020)** *Domestic energy usage patterns during social distancing | Octopus Energy*. [Online]. 2020. Available from: <https://octopus.energy/blog/domestic-energy-usage-patterns-during-social-distancing/> [Accessed: 24 September 2021].
- Tera, A., Canal, M. & Hunt, V. (2020)** *COVID-19 in the UK: The impact on people and jobs at risk*. [Online]. 2020. Available from: <https://www.mckinsey.com/industries/public-and-social-sector/our-insights/covid-19-in-the-united-kingdom-assessing-jobs-at-risk-and-the-impact-on-people-and-places#> [Accessed: 24 September 2021].
- Tu, R., Gai, Y., Farooq, B., Posen, D. & Hatzopoulou, M. (2020)** Electric vehicle charging optimization to minimize marginal greenhouse gas emissions from power generation. *Applied Energy*. 277, 115517. Available from: doi:10.1016/j.apenergy.2020.115517.
- Werth, A., Gravino, P. & Prevedello, G. (2021)** Impact analysis of COVID-19 responses on energy grid dynamics in Europe. *Applied Energy*. 281 (August 2020), 116045. Available from: doi:10.1016/j.apenergy.2020.116045.
- Wilson, G., Godfrey, N., Sharma, S. & Bassett, T. (2020)** *We analysed electricity demand and found coronavirus has turned weekdays into weekends*. [Online]. 2020. Available from: <https://theconversation.com/we-analysed-electricity-demand-and-found-coronavirus-has-turned-weekdays-into-weekends-134606> [Accessed: 24 September 2021].



Energy Futures Lab

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