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E-mail: SantosG@Cardiff.ac.uk and rayan.azhari.17@ucl.ac.uk**Keywords:** remote working, homeworking, transport emissions, building emissions, CO₂, greenhouse gases, COVID-19**Abstract**

Using data from official government publications in the UK, we estimate the potential changes in transport and buildings CO₂e emissions in England and Wales if those engaged in jobs compatible with homeworking were to work mainly from home. We find that the net result is likely to be an increase, rather than a decrease in CO₂e emissions. Assuming that 20% to 30% of workers were to work from home, the increase would range from 0.18% to 0.97% relative to emissions from the buildings and transport sectors combined, and from 0.11% to 0.60% relative to emissions from all sources. Under the very unrealistic assumptions that the buildings where the new teleworkers used to work closed permanently rather than remained open or were repurposed, and there were no rebound travel, there would be modest emissions savings, which would range from 0.61% to 1.63% of CO₂e emissions from the transport and building sectors combined, and from 0.38% to 1.01% of CO₂e emissions from all sources when 20% to 30% of workers worked from home.

1. Introduction

A disease, first identified in Wuhan, the capital of China's Hubei province, in December 2019, has expanded throughout the world, which is now experiencing a pandemic, the first in over 100 years. The disease and the virus causing it are so new that they were only named by the World Health Organization (WHO) on 11 February 2020 (WHO 2020a). The disease was named COVID-19 (CORonaVirus Disease 2019), and the virus, SARS-CoV-2 (Severe Acute Respiratory Syndrome CoronaVirus 2). Although the majority of those infected with SARS-CoV-2 experience no or mild symptoms, some escalate to pneumonia, multi-organ failure, and even death (WHO 2020b). At the time of writing this paper, over 5 million deaths have been attributed to COVID-19 worldwide (Johns Hopkins University 2021).

Although in December 2020, a number of vaccines were approved and rolled out in several countries, at the beginning of the pandemic, there were no vaccines and no proven treatment either. The protective measures recommended by the WHO included (and still include) hand-washing and physical distancing (WHO 2020b). In order to facilitate this, many countries, including the UK, implemented emergency protocols, typically in the form of lockdowns. Whilst these were implemented to different degrees, they all entailed asking most of the population to stay at home, except for essential trips and work. Many countries also closed schools, colleges and universities, non-essential shops, hotels, restaurants, cinemas, theatres, and sports facilities around March to July 2020, and later again, over October 2020 to February 2021 and April 2021.

These extreme (but necessary) measures negatively impacted national economies and the global economy. Global GDP experienced negative growth of 3.2% in 2020, and the UK economy contracted by 9.8% (International Monetary Fund, IMF 2021, p. 6, table 1). The question, however, is whether any valuable lessons can be learnt from the 2020 lockdown, which essentially forced a social experiment. In particular, we concentrate on homeworking, and what impact this can have on GHG emissions from commuting trips, and GHG emissions linked to residential and non-residential energy use. Focusing on England and Wales, we estimate the changes in GHG emissions likely to occur if those who can work from home do so instead of commuting. We contribute to the literature on three fronts: (a) we estimate the GHG emissions savings that can be achieved by working from home under a range of scenarios, something that, to the best of our knowledge, has not been done for England and Wales using the lessons learnt from the long 2020 lockdown combined with data pre-pandemic; (b) we present a clear methodology for estimating GHG emissions savings, which can be used for other countries and regions; (c) we propose policy recommendations, based on our findings.

Table 1. Share of teleworkers relative to the total number of people in employment in England and Wales.

Share of teleworkers relative to the total	Comment	Source
14.2% ^a	Worked mainly from home or on the same grounds or buildings as their home in 2019 ^a	ONS (2020a, table 1)
26.7%	Ever worked from home in 2019	ONS (2020a, table 1)
49.2%	Worked from home during the long lockdown in 2020	ONS (2020b)

^a The figure of 14.2% combines two groups of workers: workers that use their home as a base for working (e.g., a hairdresser that works from her living room), and workers that work from the same grounds or buildings as their home. It is hard to distinguish between the two groups and the difference in their energy use; therefore, this study treats both groups the same and assumes their energy use to be similar to the energy use in dwellings with people who do not work.

The paper proceeds as follows. Section 2 reviews the literature. Section 3 concentrates on the share of the workforce that can work from home in England and Wales. Section 4 presents the changes in GHG emissions that would result from an increase in energy consumption from dwellings and a decrease in energy consumption from non-residential buildings. Section 5 focuses on GHG emissions that a reduction in commuting trips can save. Section 6 combines and discusses the results from the previous two sections. Section 7 concludes and proposes policy recommendations.

2. Previous work

2.1. Working from home

Working from home, teleworking, or remote working has been found to have a positive association with job satisfaction and organisational commitment (Felstead and Henseke 2017). Teleworking can also potentially save employers money because if most employees work from home, working premises can be smaller, and therefore cheaper to rent or buy, and have lower associated utility bills.

Before the 2020 lockdown, remote working was mainly implemented in the name of flexible working (Reuschke and Felstead 2020), but it was not a widespread practice, with only 14.2% of the employed workforce in the UK working from home or on the same grounds or buildings as their home in 2019, according to a survey conducted by the Office for National Statistics (ONS 2020a, table 1). Post-pandemic, this may change, partly thanks to the experience gained during lockdown (Etheridge *et al* 2020, OECD 2020). In the long run, working from home may increase productivity (OECD 2020), although the evidence so far is mixed for the UK case and points towards no overall change on average (Etheridge *et al* 2020, Felstead and Reuschke 2020).³

Having said the above, one point to consider is that not all jobs are compatible with working from home (Matthews and Williams 2005, Dingel and Neiman 2020, Reuschke and Felstead 2020). Information technology is crucial for those able to work from home, as this is precisely what often enables remote working (Felstead and Henseke 2017), and this was made evident during the 2020 lockdown, which accelerated the uptake of software and practices previously perceived as optional.

Working remotely from home is also associated with job-related well-being on the one hand and with difficulty switching off on the other (Felstead and Henseke 2017). During the lengthy lockdown, teleworking initially had a negative impact on mental health, but this subsided as workers became more used to working from home or moved back to their usual workplace once restrictions were lifted (Felstead and Reuschke 2020). We need to highlight that during the lockdown period in the UK, many workers not only had to work remotely but they also had to homeschool and/or look after their children. This may have acted as an additional source of stress and anxiety, which will disappear in a post-pandemic world. Furthermore, according to the ‘Understanding Society: Covid-19 Study, 2020’, conducted by the Institute for Social and Economic Research, University of Essex, over 88% of people who worked from home during the lockdown would like to work from home at least part of the week, and over 47% would like to work from home most or all of the time once the pandemic is over (Felstead and Reuschke 2020). However, even jobs that are compatible with working from home may encounter challenges. Some of these challenges may be related to lack of a dedicated workroom or office, or even a dedicated work area, such as a desk in a room used for other purposes too, or to the nature and complexity of the tasks that need to be undertaken (Leesman 2020). In a survey of more than 22,000 workers from around the world, who were able to report on both their home and office experience, 38% had an outstanding experience both at home and in the office, 22% had an outstanding experience at home, but not in

³ For the United States there is some evidence of increased productivity (Emanuel and Harrington, 2020) and for Japan there is some evidence of decreased productivity (Morikawa, 2020).

the office, 24% had a suboptimal experience both at home and in the office, and 16% had an outstanding experience in the office but not at home. These differences were mainly driven by both the complexity and nature of the tasks and the home settings (Leesman 2020).

One last point we would like to highlight regarding working from home is that people working from home means fewer commuters, which inevitably has repercussions on businesses that rely on commuters for their trade. These businesses would no longer be financially viable if the numbers of homeworkers increased substantially in a new normal. The 2020 lockdown in the UK caused this to happen, with many businesses closing temporarily or permanently (BBC News 2020).

2.2. GHG emissions and working from home

Road transport still heavily relies on fossil fuels. In the UK, for example, ultra-low emission vehicles, defined as vehicles that emit less than 75 g of CO₂ per km, only accounted for 2.7% of all new vehicle registrations in 2019 (Department for Transport, DfT 2020a). Until road transport is decarbonised, other policies may go some way towards reducing GHG emissions from road transport. Teleworking has been considered a potential policy to support sustainable transport, at least in the past, as is evident from the ‘Smarter Choices—Changing the Way We Travel’ study (Cairns *et al* 2005), which devoted a whole chapter to teleworking.

In principle, working from home for all or part of the week can reduce congestion (Santos *et al* 2010, Hook *et al* 2020). Reduced commuting can also help reduce GHG emissions from road transport (Hook *et al* 2020, Ohnmacht *et al* 2020a). However, these initial reductions may be lost because of rebound effects, at least to some extent. Rebound effects may be due to homeworkers or other family members making additional car journeys for non-commuting purposes, and homeworkers moving further away from their primary place of work and therefore making longer journeys when they do commute to work (Cairns *et al* 2005, Matthews and Williams 2005, Ravalet and R  rat 2019, Hook *et al* 2020, Ohnmacht *et al* 2020b). For example, Choo *et al* (2005) estimate that working from home reduces vehicle miles travelled by less than 1% because of the rebound effects. To add to the above, money saved on fuel to pay for car travel could be reallocated to other goods and services, and these other goods and services could have associated production and/or consumption emissions (Hook *et al* 2020, Sorrell *et al* 2020).

In addition, the impact of teleworking can be negligible when office employees have dedicated workspaces as opposed to hot-desking, or only a few telework, or those who telework do so only once or twice a week (O’Brien and Aliabadi 2020). This is because energy consumption in the workplace remains virtually unchanged in these cases. Furthermore, workers may leave computers switched on or plugged in at work whilst working on a different computer from home (O’Brien and Aliabadi 2020). To add to this, the impact of working from home can become negative, with more energy consumed overall if the primary commuting mode before switching to homeworking was public transport (Matthews and Williams 2005, Crow and Milliot 2020) or active transport (walking and/or cycling). We need to remark that if the primary commuting mode before switching to homeworking was the car, the impact of working from home could also become negative, with more energy consumed overall, when the additional emissions that result from working from home are higher than the saved emissions from reduced commuting and reduced workplace occupancy.

2.3. What can we learn from the literature?

There are several points to take away from the literature, as follows. Working from home can positively affect job satisfaction, organisational commitment, flexible working, workers’ well-being, and even, potentially, productivity, although it can also make it more difficult for workers to switch off. Working from home can also save employers money in reduced office space rent, and bills. Of course, not all jobs are compatible with working from home. Even those jobs which are compatible with working from home may face challenges related to the lack of a dedicated working area/space at home and the nature of the tasks that need to be performed. Working from home typically results in fewer commuters, a feature that can have a negative impact on the financial viability of businesses that rely on commuters for their trade.

Importantly, a reduction in commuting associated with working from home can reduce congestion and GHG emissions. However, these initial reductions can be lost if there are rebound effects, such as additional car journeys for non-commuting purposes, or homeworkers moving further away from their primary place of work, which can result in longer commuting distances. Money saved on fuel could also lead to a budget reallocation to other goods and services with associated production/consumption emissions. Also, energy savings in non-residential buildings can be negligible when workers have dedicated desks or when only a few work from home or when those who work from home do so only once or twice a week. If public transport and/or active transport are the dominant commuting mode(s), the final result can be an increase rather than a

decrease in GHG emissions, as the emission savings from reduced commuting will be negligible. We note that even if the car is the original dominant commuting mode before the switch to homeworking, emissions savings from reduced commuting and reduced workplace occupancy can be lower than emissions increases due to higher energy use from working from home, resulting in an overall increase in emissions.

To the best of our knowledge, there is no up-to-date estimate of the potential impact that a new normal, entailing large numbers of workers working from home, would have on GHG emissions in England and Wales. In the present paper, we estimate the changes in GHG emissions, expressed in tonnes of CO₂ equivalent (CO₂e), that would result from an increase in teleworking in England and Wales. We do this for a number of scenarios related to the number of workers that would work from home. Our model includes the reduced emissions from reduced commuting and reduced workplace occupancy and the increased emissions from homeworking. We also extend the analysis to include potential rebound effects and no closing down of workplaces.

3. Potential to work from home in England and Wales

The first question we need to tackle is the potential for homeworking in the UK, or in other words, the percentage of jobs that can be carried out from home, i.e., remotely.

Based on information from the US-based O-Net classification and description of just under 1,000 occupations, Boeri *et al* (2020) argue that the share of jobs that can be done remotely, which are mainly service sector jobs, ranges from 32% in the UK, to 28% in France and Germany, to 24% in Italy. On the basis of surveys describing the experience of workers in the US in just under 1,000 occupations, Dingel and Neiman (2020) find that the share of jobs that can be done entirely from home in the US is 37%.

Some jobs can be done entirely from home, and some jobs can be done partly from home, with workers still needing to be physically present in the workplace one or more days a week. In 2019, before the COVID-19 pandemic, an ONS survey found that 5.1% of respondents worked mainly from home, 9.1% worked on the same grounds or buildings as their home, or used their home as a base,⁴ 12.4% had worked from home in the week prior to being interviewed, and 26.7% had ever worked from home (ONS 2020a, table 1). These were mainly knowledge workers in managerial and/or professional occupations, who are also at the highest-earning end, suggesting that higher-paid workers tend to be more likely to work from home (ONS 2020a). This is indeed in line with findings for other countries, like those reported by Boeri *et al* (2020) and Dingel and Neiman (2020).

By late May 2020, two months after the lockdown had been implemented in the UK, almost 25% of employees, or 8 million jobs, had been furloughed under the Coronavirus Job Retention Scheme,⁵ and 2 million self-employed had claimed income support under the Self-Employed Income Support Scheme⁶ (HM Treasury 2020). This confirms that working from home is not compatible with all jobs, and some businesses cannot be run from home (such as those in the hospitality industry). In addition, many key workers, such as, for example, those working in health and social care, key public services, food and essential goods, public safety and national security, continued to physically go to work during the pandemic.

However, one striking fact is that from all adults still in employment in the UK, 49.2% were working from home between 3 and 13 April 2020 (ONS 2020b). There is a sharp contrast between 49.2% of homeworkers in April 2020 and the 26.7% of workers that reported having ever worked from home in 2019 (ONS 2020a, table 1). In 2019 there was no need to work from home, other than convenience or flexibility both for employers and employees. In 2020, under lockdown, the situation was very different.

A careful inspection of employment by occupation (with over 400 different occupations), covering the period January to December 2019, as published by ONS (2020c), allowed us to allocate the type of building workers work in (offices, educational establishments, health care settings, and other). These were matched with the percentages of workers under each main type of occupation (regularly work from home, had worked from home in the week prior to the ONS survey, or had ever worked from home) as reported by ONS (2020a, figure 4).

⁴ From now onwards, we refer to 'worked on the same grounds or buildings as their home, or used their home as base' as 'worked on the same grounds or buildings as their home'.

⁵ The Coronavirus Job Retention Scheme was initially only intended to run between 1 March 2020 and 31 May 2020, but it was extended on a number of occasions, until it ended on 30 September 2021. Under the Scheme, the UK Treasury refunded 80% of employees' wage costs up to a maximum of £2,500 per month, although in July 2021 this was reduced to 70% up to a maximum of £2,187.50 per month, and in August 2021, it was further reduced to 60% up to a maximum of £1,875 per month.

⁶ Under the Coronavirus Employed Income Support Scheme, self-employed workers could claim a taxable grant. There were five grants available between 13 May 2020 and 30 September 2021, when the Scheme ended. These were worth up to £7,500 each in total, except for the second grant, which was capped at £6,570, and was available between July and October 2020. The grants were calculated on the basis of the applicant's average trading profits.

Table 2. People in employment in England and Wales, and the number and shares of employees engaged in jobs compatible with homeworking^a.

Group	Total number	%	Source
Total in employment in England and Wales	28,981,400	100%	ONS (2020c)
Workers who mainly work from home or on the same grounds or buildings as their home	4,057,396	14.2%	ONS (2020a, table 1)
Office workers ^b	7,300,000	25.2%	ONS (2020c)
Education workers	1,884,700	6.5%	ONS (2020c)
Other workers (jobs compatible with homeworking)	4,415,100	15.2%	ONS (2020c)

^a The data correspond to the year 2019.

^b We manually estimated the number of office workers by inspecting the different jobs in ONS (2020c). The figure is very similar to an estimate based on the total office floor space of all offices in England and Wales, using the average space per office worker, 9.6 m², as an indicator, following Harris *et al* (2018).

Table 3. Working from home scenarios.

Scenario	Additional workers working from home		Workers working from home (total)		Workers commuting (total)	
	Share	Number	Share	Number	Share	Number
Baseline	0%	0	14%	4,057,396	86%	24,924,004
Scenario 1	6%	1,738,884	20%	5,796,280	80%	23,185,120
Scenario 2	11%	3,187,954	25%	7,245,350	75%	21,736,050
Scenario 3	16%	4,637,024	30%	8,694,420	70%	20,286,980
Scenario 4	26%	7,535,164	40%	11,592,560	60%	17,388,840
Scenario 5	36%	10,433,304	50%	14,490,700	50%	14,490,700

Source: as explained in the text.

One point that becomes clear from the discussion above is that many workers whose jobs were compatible with homeworking pre-pandemic did not work from home. Table 1 summarises the shares of workers that work or could potentially work from home. Table 2 shows the number of people in employment in England and Wales and the number and shares of employees engaged in jobs compatible with homeworking. We use tables 1 and 2 to assume four different scenarios, which we then use to estimate the changes in CO₂e emissions that would result from an increase in homeworking. Given that 14.2% of workers worked mainly from home or on the same grounds or buildings as their home pre-pandemic, we assume a Baseline of 14% of workers that work from home. We then increase that share to reach 50%, to mirror the share of workers that worked from home during the long 2020 lockdown. Table 3 presents the scenarios, which are then used to estimate the changes in CO₂e emissions in sections 4 and 5.

4. Changes in CO₂e emissions from dwellings and non-residential buildings

There are 27.6 million households in the UK (ONS 2019a), of which 20.9 million have at least one member of working age (16–64 years) (ONS 2019b). Therefore, we assume that 75% of all households have at least one member aged between 16 and 64. Since there is approximately the same number of households as of dwellings, and 75% of households have at least one person of working age, we can assume that 75% of the dwelling stock in the UK (and in each of the four nations, including England and Wales) has one person of working age.

There are 25.8 million dwellings in England and Wales (Welsh Government 2020, Ministry of Housing, Communities and Local Government 2020). There are also 335,000 office premises and 39,000 education premises, plus another 1,055,000 non-residential buildings, excluding factories, but including shops, health centres and hospitals, hospitality venues, arts, community and leisure buildings, amongst others (Department for Business, Energy and Industrial Strategy, BEIS 2021a).

Table 4. Energy consumption and CO₂e emissions from dwellings, offices, education establishments, and ‘other’ non-residential buildings in England and Wales in 2019^a.

Building type	Natural Gas consumption (TWh)	Electricity consumption (TWh)	Gas CO ₂ e emissions (million tonnes of CO ₂ e)	Electricity CO ₂ e emissions (million tonnes of CO ₂ e)	Total gas and electricity CO ₂ e emissions (million tonnes of CO ₂ e)
Dwellings	260.1	91.6	47.8	23.4	71.23
Offices	10.8	20.0	2.0	5.1	7.10
Education	11.9	5.2	2.2	1.3	3.5
Other	70.2	64.8	12.9	16.6	29.5
Total	353.1	181.6	64.9	46.4	111.3

^a Energy consumption was translated into CO₂e emissions using the 2019 conversion factors from BEIS (2019). These were 0.18385 kgCO₂e/kWh for natural gas and 0.2556 kgCO₂e/kWh for electricity.

Source: BEIS (2019, 2021a, 2021b).

Table 5. Energy consumption by end-use in the domestic sector.

End-use	Thousand tonnes of oil equivalent (ktoe)	Share ^a
Space heating	23,386	62%
Water	6,600	18%
Cooking/Catering	1,103	3%
Lighting/Appliances	6,618	18%
Total	37,707	100%

^a The shares do not add exactly to 100% due to rounding.

Source: Table U1, End Uses Data Tables, Energy consumption in the UK (BEIS 2021b).

Table 4 shows the annual energy use and CO₂e emissions for offices and education premises. These act as workplaces for just over 30% of the employed population in England and Wales, as advanced in table 2. Scenarios 4 and 5 necessitate more workers to work from home. Those workers would be from various sectors, which makes it difficult to allocate them to one specific type of non-residential building (i.e., workplace). For this reason, we created an additional non-residential building, which we call ‘Other’, that acts as a ‘representative’ workplace in England and Wales. The annual energy use and CO₂e emissions for this ‘Other’ building category were estimated as the weighted average of the annual energy use and CO₂e emissions from all non-residential buildings⁷ in England and Wales, excluding factories. Factories were excluded because of their energy-intensive processes, which would have skewed the annual energy use and CO₂e emissions of this ‘representative’ non-residential building. In addition, factory jobs are not compatible with homeworking. The numbers in table 4 for annual energy use were taken from BEIS (2021a) and only cover Natural Gas and Electricity.

The energy use data for dwellings was taken from Table U1 of the End Uses Data Tables of ‘Energy consumption in the UK’ (BEIS 2021b), but it is only available for the whole of the UK, so it was scaled down based on the number of dwellings in England and Wales, which is 88% of that in the UK.

4.1. Domestic energy use patterns

Energy consumption by end-use in dwellings is 62% for space heating, 18% for hot water, 3% for cooking, and 18% for lighting and appliances (Table U1, End Uses Data Tables, Energy consumption in the UK, BEIS 2020). We assume that 90% of energy use takes place during active hours when people are awake, and 10% takes place during sleeping hours (from baseload appliances like fridge/freezer and router, and some water and space heating). Table 5 shows energy consumption by end-use in the domestic sector. The Domestic Energy Model (Building Research Establishment, BRE 2015), BREDEM from now onwards, estimates the domestic active occupancy patterns for weekdays and weekends as follows. On weekdays, 8 h are used for sleeping, 9 h, for being active at home, and 7 h, for being away from home. On weekends, 8 h are used for sleeping and 16 h, for being active at home (BRE 2015).

⁷ Non-residential buildings include ‘Arts, Community and Leisure’ (cinemas, community centres, libraries, museums, sports centres, sports grounds), ‘Education’ (nurseries, state schools, private schools, universities), ‘Emergency Services’ (ambulance, fire stations, police stations), ‘Factories’, ‘Health’ (healthcare premises), ‘Hospitality’ (restaurants, hostels, hotels, holiday homes, guest houses, pubs), ‘Offices’, ‘Shops’, ‘Warehouses’, and ‘Other buildings’ (bus stations, moorings, cemeteries, docks, electricity hereditaments, garages, markets, military premises, sewage treatments) (BEIS, 2021, The Non-Domestic National Energy Efficiency Data-Framework document, Annex B, p. 40). It should be noted that ‘Other buildings’ are different from our representative ‘Other’.

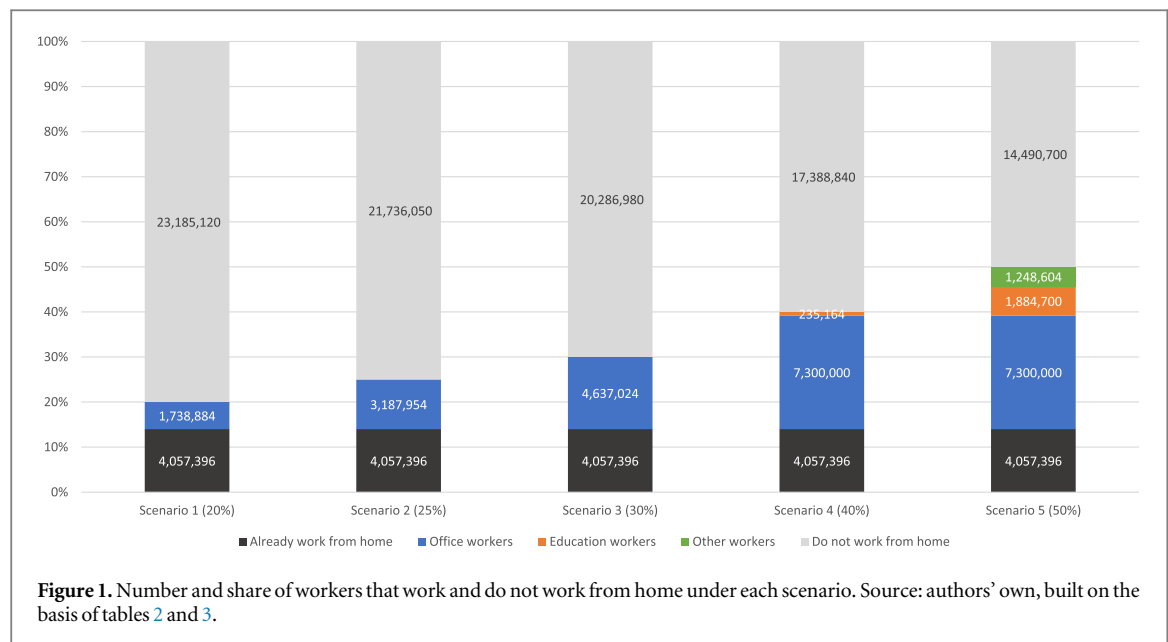


Table 6. Total number of hours in a year grouped by activity based on the BREDEM model.

	Number of hours -working out-side home	% of total hours	Number of hours -working/staying at home	% of total hours
Sleeping	2920	33%	2920	33%
Active	4069	46%	5840	66%
Away	1771	20%	0	0%
Total	8760	100%	8760	100%

Source: BRE (2015).

Over a year, for households with occupants working outside the home, 33.3% of the time is spent sleeping, 20.2% of the time is spent away from home, mainly at work, and 46.4% of the time is spent being active at home, where most of the energy use takes place, as shown in table 6. For households with occupants working or staying at home, the time spent away from home is combined with the time spent active at home.

4.2. Scenarios and homeworking

In order to estimate CO₂e emissions from buildings under the five scenarios introduced in table 3, the total number of workers that work from home was increased from the 14% baseline to a total of 50%. We started with workers engaged in occupations compatible with teleworking (Scenarios 1 to 3) and then added workers engaged in occupations somewhat, although not necessarily fully, compatible with teleworking (Scenarios 4 and 5). Essentially, the first bunch of workers to move to telework will be office workers, as these jobs are the most amenable to working from home. There are enough office workers in England and Wales to increase the share of homeworkers to 30%. Education workers come in Scenario 4, and finally, other workers from various occupations join in Scenario 5. Scenario 5 is an unlikely scenario, but one that became a reality during the 2020 lengthy lockdown in the UK. Figure 1 illustrates the additional number of workers that work from home under each scenario.

4.3. Change in CO₂e emissions from changes in energy consumption in dwellings

Given that, as mentioned above, 25% of households do not have any member of working age, and that 14% of workers already work from home or on the same grounds or buildings as their home, we can assume that 39% of dwellings do not change their energy consumption under any scenario.⁸ However, these households use more energy on average than households with working-age members due to being occupied most of the time. We, therefore, have two types of households:

- households that do not have any member of working age or that have workers already working from home or on the same grounds or buildings as their home, which do not change under any scenario; and
- households with at least one member of working age that is away from home roughly 7 h per day, some of which may be affected under at least one scenario with one family member switching to teleworking.

⁸ This assumes that no dwelling has more than one homeworker.

When *all* households are considered together, we have a national average energy consumption, with associated national average CO₂e emissions, which we normalise at 100. Compared to this national average of 100 based on the average number of active hours in table 6 between the two groups (4,955 h), households in group (a) have a weighted average energy consumption of 116, and households in group (b) have a weighted average energy consumption of 84. These numbers were computed as follows. The energy use during sleeping hours does not change in either group and, as explained above, was assumed to be 10% of the national average energy use. The remaining 90% of the energy use is affected by the number of hours dwellings are occupied. For group (a), the number of active hours per year is higher than the average and is 118% (computed as 5840/4955). For group (b), the number of active hours per year is lower than the average and is 82% (computed as 4069/4955). These figures were used to weigh energy use during active hours for both groups, as follows:

$$\text{Group (a) average energy use} = (10\% \times \text{national average}) + (90\% \times \text{national average}) \times 118\%$$

$$\text{Group (b) average energy use} = (10\% \times \text{national average}) + (90\% \times \text{national average}) \times 82\%$$

The final step was to get the Energy use factor (**Fa**) between the average energy use per group and the national average energy use, as follows:

$$\mathbf{Fa} \text{ Group(a)} = \text{Group(a) average energy use} / \text{national average} = 1.16$$

$$\mathbf{Fb} \text{ Group(b)} = \text{Group(b) average energy use} / \text{national average} = 0.84$$

Thus, the portion of energy consumption ‘affected’ or subject to change was estimated using equation (1):

$$\mathbf{Ea} = \mathbf{Te} \times (1 - (\mathbf{Fo} + \mathbf{Fh})) \times \mathbf{Fa} \quad (1)$$

where:

Ea: Energy consumption affected (Natural Gas and Electricity after excluding the unaffected portions)

Te: Total energy consumption (Natural Gas and Electricity)

Fo: 25% of households do not have any member of working age

Fh: 14% of workers already work from home or on the same grounds or buildings as their home

Fa: Energy use factor for households with at least one member of working age (with **Fa** assumed equal to 0.84)

Increasing the number of workers who work from home will cause the ‘away’ hours to be converted into ‘active’ hours. The ratio of away hours to active hours per year is **AA** = 43.52%.⁹ Also, as explained above, we assume that 90% of energy consumption occurs during active hours and 10% during sleeping hours. This is because when people are sleeping, the use of electricity is minimal (mainly baseload appliances like fridge/freezer and router), and the heating is typically switched off, although heating and hot water may be switched on just before people wake up. With that in mind, it can be assumed that 90% of gas and electricity (**Feg**) consumption occurs during active hours.

To estimate the change in energy consumption, we used equation (2):

$$\mathbf{Ec} = \mathbf{Ea} \times (\mathbf{Feg}) \times \mathbf{AA} \times \mathbf{S} \quad (2)$$

where:

Ec: Estimated energy consumption change (Natural Gas and Electricity)

Ea: Energy consumption affected (Natural Gas and Electricity after excluding the unaffected portions)

Feg: Natural Gas use factor during active hours (0.9)

AA: Percentage of away hours from active hours (0.4352)

S: Scenarios (0.2, 0.25, 0.3, 0.4, 0.5)

4.4. Change in CO₂e emissions from changes in energy consumption in non-residential buildings

The number of workers in non-residential buildings progressively decreases as the number of homeworkers increases through Scenarios 1 to 5, as shown in figure 1. To estimate changes in energy consumption and CO₂e emissions, we make two important assumptions: (a) the workers that become teleworkers do so for the *entire* week, and (b) the ‘space’ previously occupied by the now homeworkers is ‘closed down’. This essentially means that all office space in England and Wales is closed by the time we reach Scenario 4. Although this is an unrealistic assumption, it is a very useful one because it gives the maximum saving that can be achieved with homeworking. If this maximum is relatively low, we can safely conclude that under more realistic assumptions of some workers remaining in the office or working from the office part of the week, the savings will be lower and may not be worth the effort. Table 7 presents how non-residential buildings are progressively closed down under the five scenarios.

⁹ Active hours per year = 4069, Away hours per year = 1771, **AA** = 1771 / 4069 = 43.52%.

Table 7. Reduction in non-residential space under the five scenarios.

Scenario	Additional share of workers working from home	Total share of workers working from home	Reduction in non-residential buildings space
Baseline	0%	14 %	No change
Scenario 1	6%	20%	Office space is reduced by 23.8%
Scenario 2	11%	25%	Office space is reduced by 43.7%
Scenario 3	16%	30%	Office space is reduced by 63.5%
Scenario 4	26%	40%	Office space is reduced by 100% Education space is reduced by 12.5%
Scenario 5	36%	50%	Office space is reduced by 100% Education space is reduced by 100% 'Other' representative non-residential building space is reduced by 28.3% ^a

^a This does not mean that 28.3% of all other residential buildings are closed. Recalling how we created the 'Other' building category, this type of building acts as a 'representative' workplace in England and Wales excluding Factories, originally hosting the additional 10% of workers who eventually switch to teleworking under Scenario 5, which is an unrealistic, non-sustainable scenario, only likely under extreme circumstances, such as a national lockdown.

To estimate the share of employers affected by working from home, we used equation (3):

$$W = Te \times \frac{(S - Fh)}{N} \quad (3)$$

where:

W: Percentage of workers affected by working from home

Te: Total people in employment

S: Scenarios (0.2, 0.25, 0.3, 0.4, 0.5)

Fh: 0.14 workers who already work from home or on the same grounds or buildings as their home

N: Number of workers (office, education, 'other')

The estimated energy change from non-domestic buildings due to working from home was calculated using the percentage of workers affected by working from home in each sector, as shown by equation (4):

$$Ec = Te \times W \quad (4)$$

where:

Ec: Estimated Energy change (Natural Gas and Electricity)

Te: Total actual energy (Natural Gas and Electricity)

W: Percentage of workers affected by working from home

4.5. Results for dwellings and non-residential buildings

Table 8 presents GHG emissions by building type in 2019 in absolute and relative terms. Table 9 and figure 2 present the changes in CO₂e emissions for each scenario and building type. The increase in CO₂e emissions resulting from an increase in energy consumption in dwellings is offset by the reduction in CO₂e emissions resulting from a reduction in energy consumption in non-residential buildings under all five scenarios. However, the key assumption is, as already explained, that the 'space' occupied by workers who previously commuted to work is closed once they switch to homeworking.

4.6. Buildings kept in use and repurposing buildings

The results presented in table 9 and figure 2 rest on two important assumptions: the workers that become teleworkers do so for the *entire* week, and the 'space' previously occupied by the now homeworkers is 'closed down'.

As explained in section 2, the reduction in energy consumption in workplaces can be negligible when employees have dedicated workplaces instead of hot-desking and only telework for part of the week. Also, if all workers in a building become teleworkers, the building becomes an unoccupied building, likely to be repurposed.

If all the space that was previously occupied by now teleworkers is either kept in use or repurposed, there will be no reduction in energy consumption from non-residential buildings, and, depending on what the new purpose of the building is, there could actually be an increase in energy consumption. In such a case, the increase in energy consumption from domestic buildings would not be accompanied by reductions in other buildings. Thus, there would be an overall increase in CO₂e emissions, which at the minimum would be as shown in table 10, with an increase in energy consumption in domestic buildings, as shown in table 9, and no change in energy consumption anywhere else.

Table 8. Data on absolute and relative CO₂e emissions by building type in England and Wales in the Baseline^a.

Building type	Total gas and electricity CO ₂ e emissions (million tonnes of CO ₂ e)	CO ₂ e emissions as % of CO ₂ e emissions from all buildings in England and Wales ^b	CO ₂ e emissions as % of total source CO ₂ e emissions in England and Wales ^c
Dwellings	71.2	54%	19%
Offices	7.1	5%	2%
Education	3.5	3%	1%
Other ^d	29.5	22%	8%
Total	111.3	85%	30%

^a Data for the Baseline are data for 2019.

^b Total CO₂e emissions from all buildings, including factories: 131.43 million tonnes. These were calculated as follows. The total energy use by the domestic sector was obtained from Table C1 of the Consumption Data Tables of 'Energy consumption in the UK' (BEIS 2021b). The total energy use by non-residential buildings was obtained from the Non-domestic National Energy Efficiency Data-Framework 2020: Supporting Data Tables (BEIS 2021a). Energy consumption was translated into CO₂e emissions using the 2019 conversion factors from BEIS (2019). These were 0.18385 kgCO₂e/kWh for natural gas and 0.2556 kgCO₂e/kWh for electricity.

^c Total CO₂e emissions from all sources: 372.55 million tonnes (Thistlethwaite *et al* 2021).

^d 'Other' is a 'representative non-residential building' as defined in the text.

Source: As explained in the table footnotes.

Table 9. Estimated annual CO₂e emissions and annual change in CO₂e emissions for each building type, expressed in million tonnes, and CO₂e emissions change relative to total CO₂e emissions from all buildings and to total CO₂e emissions from all sources in England and Wales.

Scenario	Million tonnes of CO ₂ e from energy consumption					Annual change in million tonnes of CO ₂ e ^b	CO ₂ e emissions change relative to total CO ₂ e emissions from all buildings in England and Wales ^c	CO ₂ e emissions change relative to total CO ₂ e emissions from all sources in England and Wales ^d
	Domestic	Office	Education	Other ^a	Total			
Scenario 1	72.1	5.4	3.5	29.5	110.5	−0.79	−0.61%	−0.21%
Scenario 2	72.9	4.0	3.5	29.5	109.9	−1.46	−1.11%	−0.39%
Scenario 3	73.6	2.6	3.5	29.5	109.2	−2.12	−1.62%	−0.57%
Scenario 4	75.1	0.0	3.1	29.5	107.7	−3.67	−2.79%	−0.98%
Scenario 5	76.6	0.0	0.0	21.1	97.7	−13.6	−10.35%	−3.65%

^a 'Other' is a 'representative non-residential building' as defined in the text.

^b Computed relative to the baseline of 111.34 million tonnes of CO₂e for all buildings (table 8).

^c Total CO₂e emissions from all buildings, including factories: 131.43 million tonnes (computed as explained in table 8 footnotes).

^d Total CO₂e emissions from all sources: 372.55 million tonnes (Thistlethwaite *et al* 2021).

Source: Own calculations as explained in the text.

5. Changes in CO₂e emissions from transport

Commuting trips accounted for 14.71% of all trips made in England in 2019 (DfT 2020b, Table NTS0409a). There are no equivalent data for Wales, so we assume that the share of commuting trips in Wales was the same as in England. Table 11 shows the mode share and the number of commuting trips by mode in England and Wales. The car is the most used mode of transport for commuting trips, with 67.1% of all commuting trips being made by car in England in 2019 and 80.3% in Wales (DfT 2020c, Table TSG0108).¹⁰ The car is also the main contributor to GHG emissions from commuting transport. For that reason, we assumed that all those switching to homeworking under each scenario used to commute by car previously. This assumption means that the estimated CO₂e emissions savings from reduced commuting under each scenario are the maximum that could be achieved and thus represent an upper bound.

¹⁰ London is an exception, because the shares of commuting trips by car and by public transport are 27% and 57%, respectively (DfT, 2020c, Table TSG0108). We reflect on the impact of a large share of commuting trips by public transport in section 5.1.

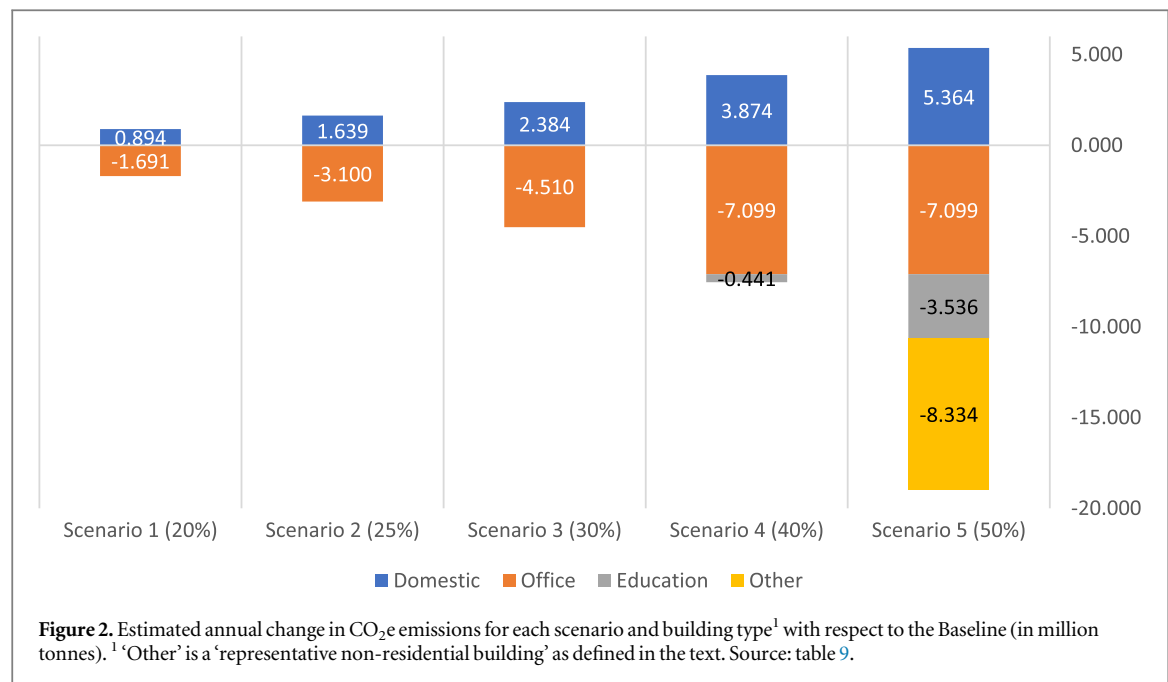


Table 10. Estimated annual CO₂e emissions and annual change in CO₂e emissions for buildings, expressed in million tonnes, and CO₂e emissions change relative to total CO₂e emissions from all buildings and to total CO₂e emissions from all sources in England and Wales, allowing for no building close-down.

Scenario	Million tonnes of CO ₂ e	Annual change in million tonnes of CO ₂ e ^a	CO ₂ e emissions change relative to total CO ₂ e emissions from all buildings in England and Wales ^b	CO ₂ e emissions change relative to total CO ₂ e emissions from all sources in England and Wales ^c
Scenario 1	132.3	0.89	0.68%	0.24%
Scenario 2	133.1	1.64	1.25%	0.44%
Scenario 3	133.8	2.38	1.81%	0.64%
Scenario 4	135.3	3.87	2.95%	1.04%
Scenario 5	136.8	5.36	4.08%	1.44%

^a Computed relative to the baseline of 111.34 million tonnes of CO₂e for all buildings (table 8).

^b Total CO₂e emissions from all buildings, including factories: 131.43 million tonnes (computed as explained in table 8 footnotes).

^c Total CO₂e emissions from all sources: 372.55 million tonnes (Thistlethwaite *et al* 2021).

Source: Own calculations as explained in the text.

Table 11. Mode share and number of commuting trips by mode in England and Wales in the Baseline.

	Car	Motorcycle	Bus	Rail ^a	Bicycle	Walk
England mode share	67.1%	3.9%	6.5%	12.4%	9.3%	0.8%
Wales mode share	80.3%	1.6%	4.9%	2.3%	9.5%	1.0%
Weighted average England and Wales mode share ^b	67.8%	3.8%	6.5%	11.9%	9.3%	0.8%
Weighted average England and Wales number of trips by mode ^c	16,893,988	936,330	1,608,010	2,960,202	2,310,661	210,926
	As a driver: 14,938,200					
	As a passenger: 1,955,789					

^a Includes national rail, underground, light railway and trams.

^b The weights used were the shares of people employed in England (95%) and Wales (5%) with respect to the total number of employed people in England and Wales.

^c In 2019, from every 85 commuting trips by car in England, 75 were made as the driver, and 10, as a passenger (DfT 2020b, Table NTS0409a). Therefore, the actual number of car trips for commuting purposes is lower than the number of people commuting by car. Since there are no data on car occupancy for Wales, we assume the same numbers apply to Wales too.

Source: (a) for mode share: DfT (2020c, Table TSGB0108); (b) for number of trips by mode: these were computed as the share by mode multiplied by the number of employed people who commute (table 3).

Table 12. Number of commuting trips by mode under each scenario^a.

	Car as the driver	Car as a passenger	Motorcycle	Bus	Rail	Bicycle	Walk	Total
Baseline	14,938,200	1,955,789	937,641	1,608,097	2,961,470	2,310,954	210,926	24,920,682
Scenario 1	13,400,623	1,754,481	937,641	1,608,097	2,961,470	2,310,954	210,926	23,181,798
Scenario 2	12,119,310	1,586,725	937,641	1,608,097	2,961,470	2,310,954	210,926	21,732,728
Scenario 3	10,837,996	1,418,968	937,641	1,608,097	2,961,470	2,310,954	210,926	20,283,658
Scenario 4	8,275,369	1,083,455	937,641	1,608,097	2,961,470	2,310,954	210,926	17,385,518
Scenario 5	5,712,742	747,943	937,641	1,608,097	2,961,470	2,310,954	210,926	14,487,378

^a As already explained, the number of car trips for commuting purposes is lower than the number of people commuting by car. The actual numbers of car trips needed to satisfy the demand for commuting trips by car under each scenario are those in the column entitled 'Car as a driver'. Bus and train occupancy assumptions are not needed, as the reduction in commuting trips is fully allocated to cars.

Source: estimated on the basis of tables 3 and 11.

Table 13. Share and number of commuting and other trips under each scenario.

Scenario	Share of commuting trips	Number of commuting trips	Share of other trips	Number of other trips ^a
Baseline	14.7%	24,924,004	85.3%	144,555,218
Scenario 1	13.8%	23,185,120	86.2%	144,555,218
Scenario 2	13.1%	21,736,050	86.9%	144,555,218
Scenario 3	12.3%	20,286,980	87.7%	144,555,218
Scenario 4	10.7%	17,388,840	89.3%	144,555,218
Scenario 5	9.1%	14,490,700	90.9%	144,555,218

^a The assumption of no rebound trips is relaxed in section 5.1.

Source: table 3 and DfT (2020b, Table NTS0409a).

Table 14. Data on absolute and relative CO₂e emissions from selected modes of transport in England and Wales in the Baseline.

	Car	Motorcycle	Bus	Rail	Bicycle	Walk
Million tonnes of CO ₂ e	59.7	0.5	2.7	1.5	0.0	0.0
CO ₂ e emissions as % of CO ₂ e domestic transport emissions in England and Wales ^a	60.1%	0.5%	2.7%	1.5%	0.0%	0.0%
CO ₂ e emissions as % of total source CO ₂ e emissions in England and Wales ^b	16.0%	0.1%	0.7%	0.4%	0.0%	0.0%

^a Total CO₂e emissions from domestic transport: 99.26 million tonnes (Thistlethwaite *et al* 2021). Domestic transport includes cars, motorcycles, buses, rail¹¹, heavy goods vehicles, light vans, other road transport, domestic aviation, domestic shipping, military aircraft and shipping, and aircraft support vehicles (DfT 2020c, Table ENV0201/TSGB0306).

^b Total CO₂e emissions from all sources: 372.55 million tonnes (Thistlethwaite *et al* 2021).

Source: Thistlethwaite *et al* (2021).

Table 12 presents the number of commuting trips made under each scenario (using table 3 as the starting point). Since the reduction in commuting trips is allocated to cars in each scenario, the number of commuting trips by all other modes remains constant, and the shares of commuting trips by car and other modes progressively decrease and increase, respectively. The share of commuting trips, which is 14.71% in the Baseline, also goes down, as we assume that all non-commuting trips remain unchanged, as shown in table 13. This assumption is later relaxed to allow for rebound effects in section 5.1.

In order to estimate the changes in CO₂e emissions, both in absolute and relative terms, data on absolute and relative CO₂e emissions from selected modes of transport in England and Wales for 2019 was needed. This data was sourced from the National Atmospheric Emissions Inventory report, hosted by BEIS and prepared by Thistlethwaite *et al* (2021). Table 14 shows the data of interest for the present study.

Table 15 mirrors table 14 but focuses on commuting trips only. The CO₂e emissions from commuting trips in England and Wales in the Baseline were estimated for each mode of transport using equation (5):

$$Hct_j = M_j \times C \times Hat_j \quad (5)$$

where:

Hct_j: CO₂e emissions from commuting trips for each mode, with j = Car, Motorcycle, Bus, Rail, Bicycle and Walk

M_j: share of commuting trips by each mode, with j as above (table 11)

C: share of commuting trips relative to all trips (which is 14.7% in the Baseline, as shown in table 13)

Hat_j: CO₂e emissions from all trips for each mode in England and Wales, with j as above (table 14)

¹¹ There are no direct emissions from electric trains but the end user emissions from electric trains include the emissions resulting from the production of the electricity used by electric trains (DfT 2020c, Table ENV0201/TSGB0306).

Table 15. Estimates of absolute and relative CO₂e emissions from commuting trips in England and Wales in the Baseline.

	Car	Motorcycle	Bus	Rail	Bicycle	Walk	Total
Million tonnes of CO ₂ e	5.95	0.00	0.03	0.03	0.0	0.0	6.00
CO ₂ e emissions as % of CO ₂ e domestic transport emissions in England and Wales ^a	5.99%	0.00%	0.03%	0.03%	0.00%	0.00%	6.05%
CO ₂ e emissions as % of total source CO ₂ e emissions in England and Wales ^b	1.60%	0.00%	0.01%	0.01%	0.00%	0.00%	1.61%

^a Total CO₂e emissions from domestic transport: 99.26 million tonnes (Thistlethwaite *et al* 2021).

^b Total CO₂e emissions from all sources: 372.55 million tonnes (Thistlethwaite *et al* 2021).

Source: authors' own calculations, using equations (5)–(7).

The share of CO₂e emissions from commuting trips for each mode relative to total CO₂e emissions from domestic transport in England and Wales in the Baseline was computed using equation (6):

$$Pct_j = M_j \times C \times Pat_j \quad (6)$$

where:

Pct_j: share of CO₂e emissions from commuting trips for each mode relative to total CO₂e emissions from domestic transport in England and Wales, with j = Car, Motorcycle, Bus, Rail, Bicycle and Walk

M_j: as defined for equation (5)

C: as defined for equation (5)

Pat_j: share of CO₂e emissions from all trips for each mode relative to total CO₂e emissions from domestic transport in England and Wales, with j as above (table 14)

The share of CO₂e emissions from commuting trips for each mode relative to total CO₂e emissions from all sources in England and Wales in the Baseline was computed using equation (7):

$$Gct_j = M_j \times C \times Gat_j \quad (7)$$

where:

Gct_j: share of CO₂e emissions from commuting trips for each mode relative to total CO₂e emissions in England and Wales, with j = Car, Motorcycle, Bus, Rail, Bicycle and Walk

M_j: as defined for equation (5)

C: as defined for equation (5)

Gat_j: share of CO₂e emissions from all trips for each mode relative to total CO₂e emissions from all sources in England and Wales, with j as above (table 14)

As stated above, we assume that all emissions savings from commuting trips result from a reduction in the number of commuting trips by car, with the number of commuting trips by all other modes staying constant. One important point for emissions savings calculations for each scenario is car occupancy. The actual number of car trips for commuting purposes is lower than the number of people commuting by car, as shown in table 11. It can therefore be reasonably assumed that under each scenario, car occupancy for commuting trips remains constant at 1.13. It can also be assumed that when the number of car trips is reduced, emissions are reduced in the same proportion. Thus, combining the number of car trips for commuting purposes (assumed equal to the number of commuting trips by car as the driver) from table 12, and the CO₂e emissions from commuting trips by car in the Baseline from table 15, the direct rule of three can be applied to estimate CO₂e emissions from commuting trips by car under each scenario. These are shown in table 16.

5.1. Rebound effects and high share of commuting trips by public transport

The results presented in table 16 rest on two important assumptions: there are no rebound effects, and the dominant mode for commuting trips is the car. This section relaxes both assumptions and explores the potential impact of doing so on final emissions savings.

As explained in section 2, rebound effects include telecommuters or other family members making trips that they did not make before telecommuting and telecommuters relocating to areas further away from their main place of work, so that they end up travelling longer distances when they do commute to work. These additional trips can erode part of the emissions savings shown in table 16. By way of example, table 17 shows the emissions savings that would be achieved if there were rebound effects, assuming these were equivalent to increasing the number of trips by car by (a) 30% and (b) 60% of the initially suppressed car trips under each scenario. These are simply illustrations for comparison purposes: the emissions savings achieved are obviously lower than those estimated in table 16, and they are lower the larger the rebound effects are.

Table 16. Estimated annual CO₂e emissions and annual change in CO₂e emissions from commuting trips by car, expressed in million tonnes, and CO₂e emissions change relative to total CO₂e emissions from domestic transport and to total CO₂e emissions from all sources in England and Wales.

Scenario	Million tonnes of CO ₂ e	Annual change in million tonnes of CO ₂ e ^a	CO ₂ e emissions change relative to total CO ₂ e emissions from domestic transport in England and Wales ^b	CO ₂ e emissions change relative to total CO ₂ e emissions from all sources in England and Wales ^c
Scenario 1	5.33	−0.61	0.62%	0.16%
Scenario 2	4.82	−1.12	1.13%	0.30%
Scenario 3	4.31	−1.63	1.64%	0.44%
Scenario 4	3.29	−2.65	2.67%	0.71%
Scenario 5	2.27	−3.67	3.70%	0.99%

^a Computed relative to the baseline of 6 million tonnes of CO₂e for all commuting transport (table 15).

^b Total CO₂e emissions from domestic transport: 99.26 million tonnes (Thistlethwaite *et al* 2021).

^c Total CO₂e emissions from all sources: 372.55 million tonnes (Thistlethwaite *et al* 2021).

Source: Own calculations as explained in the text.

Table 17. Estimated annual CO₂e emissions and annual change in CO₂e emissions from commuting trips by car, expressed in million tonnes, and CO₂e emissions change relative to total CO₂e emissions from domestic transport and to total CO₂e emissions from all sources in England and Wales allowing for rebound effects.

Rebound effects	Scenario	Million tonnes of CO ₂ e	Annual change in million tonnes of CO ₂ e ^a	CO ₂ e emissions change relative to total CO ₂ e emissions from domestic transport in England and Wales ^b	CO ₂ e emissions change relative to total CO ₂ e emissions from all sources in England and Wales ^c
30% ^d	Scenario 1	5.52	−0.48	−0.49%	−0.13%
	Scenario 2	4.98	−1.02	−1.03%	−0.27%
	Scenario 3	4.47	−1.53	−1.55%	−0.41%
	Scenario 4	3.60	−2.40	−2.42%	−0.64%
	Scenario 5	2.58	−3.42	−3.45%	−0.92%
60% ^e	Scenario 1	5.70	−0.30	−0.30%	−0.08%
	Scenario 2	5.13	−0.87	−0.88%	−0.23%
	Scenario 3	4.62	−1.38	−1.39%	−0.37%
	Scenario 4	3.91	−2.09	−2.11%	−0.56%
	Scenario 5	2.89	−3.11	−3.14%	−0.84%

^a Computed relative to the baseline of 6 million tonnes of CO₂e for all commuting transport (table 15).

^b Total CO₂e emissions from domestic transport: 99.26 million tonnes (Thistlethwaite *et al* 2021).

^c Total CO₂e emissions from all sources: 372.55 million tonnes (Thistlethwaite *et al* 2021).

^d The equivalent of 30% of initially suppressed trips go back to the roads.

^e The equivalent of 60% of initially suppressed trips go back to the roads.

Source: Own calculations as explained in the text.

Finally, an important point raised in section 2 is that if public transport and/or active transport are the dominant commuting mode(s), then the reduction in CO₂e emissions from a reduction in commuting trips will be negligible. In an extreme, unrealistic scenario, where all commuting trips were made by walking or cycling, reducing commuting trips would yield zero-emissions savings.

In another unrealistic scenario, if all commuting trips were made by public transport, reducing commuting trips would have a very small impact on CO₂e emissions because CO₂e emissions from buses and, especially, rail, are relatively low, as can be seen by recalling table 14.

6. Net changes in CO₂e emissions from dwellings, non-residential buildings and transport

Table 18 combines the results presented in tables 9 and 16. There are emissions savings under all scenarios. However, these are small relative to total CO₂e emissions from all sources in England and Wales. The most plausible scenarios (Scenarios 1 to 3), which assume a share of homeworkers of 20% to 30%, yield emissions savings of only 0.38% to 1.01% relative to total annual CO₂e emissions. The extreme, unlikely scenario of 50% of homeworkers yields a more sizeable reduction of 4.64% relative to total annual CO₂e emissions.

Relative to total CO₂e emissions from the transport and building sectors combined, the savings in Scenarios 1 to 3 range from 0.61% to 1.63%. In Scenarios 4 and 5, the savings are 2.74% and 7.49%, respectively.

Table 18. Change in CO₂e emissions from transport and buildings under each scenario.

Scenario	Change in CO ₂ e emissions from transport (million tonnes of CO ₂ e)	Change in CO ₂ e emissions from buildings (million tonnes of CO ₂ e)	Total change in CO ₂ e emissions (million tonnes of CO ₂ e)	CO ₂ e emissions change relative to total CO ₂ e emissions from domestic transport and buildings in England and Wales ^a	CO ₂ e emissions change relative to total CO ₂ e emissions from all sources in England and Wales ^b
Scenario 1	−0.61	−0.79	−1.40	−0.61%	−0.38%
Scenario 2	−1.12	−1.46	−2.58	−1.12%	−0.69%
Scenario 3	−1.63	−2.12	−3.75	−1.63%	−1.01%
Scenario 4	−2.65	−3.67	−632	−2.74%	−1.70%
Scenario 5	−3.67	−13.60	−17.27	−7.49%	−4.64%

^a Total CO₂e emissions from domestic transport: 99.26 million tonnes (Thistlethwaite *et al* 2021) and total CO₂e emissions from all buildings, including factories: 131.43 million tonnes (computed as explained in table 8).

^b Total CO₂e emissions from all sources: 372.55 million tonnes (Thistlethwaite *et al* 2021).

Source: tables 9 and 16.

The problem with these results is that they rest on two unrealistic assumptions: (a) buildings not occupied by workers any longer close down, and (b) there are no rebound trips. The assumption of non-residential buildings closing down is unlikely to materialise in the real world, as most employers may choose to downsize rather than close down their premises. Even if all non-residential buildings were closed down, they would be probably repurposed. Once converted to another use, they would continue to contribute to CO₂e emissions, as discussed in section 4.6 and entertained in table 10. The assumption of no rebound trips is also unlikely to be verified in practice. As explained in sections 2 and 5.1, teleworkers may move further away from their workplace and end up travelling longer distances when they do commute. Also, these teleworkers or other family members may make new non-commuting car journeys previously not made. Examples of the potential impact of these rebound effects are presented in table 17.

Table 19 combines the results from tables 10 and 17 and shows the results when the assumptions of buildings closing down and no rebound trips are relaxed. As it can be seen, the net result is an increase rather than a decrease in CO₂e emissions. This increase, however, is always under 1% of total emissions from domestic transport and buildings, and never above 0.6% of all emissions from all sources.

Another caveat that should be borne in mind is that we assumed all suppressed commuting trips were trips made by car. If those switching to homeworking used a mode of transport other than the car before switching to homeworking, the reductions in CO₂e emissions from reduced commuting would be very small, as explored in section 5.1.

In addition, as the car fleet is progressively electrified in the UK, the emissions savings from any reduced commuting are likely to be eroded.

7. Conclusions and policy recommendations

Using data from official government publications in the UK, we estimate the change in CO₂e emissions that would result from an increase in the number of homeworkers in England and Wales. Around 14% of those currently employed already work from home or on the same grounds or buildings as their home, and they did so pre-pandemic. We assume five different scenarios under which 20%, 25%, 30%, 40% and 50% of those employed work from home.

Emissions associated with commuting trips and energy consumption in workplaces would decrease, and emissions associated with energy consumption in dwellings would increase. Assuming former workplaces close down and there are no rebound trips, the net change would be a reduction in CO₂e emissions in England and Wales. This reduction would range from 0.61% to 7.49% relative to CO₂e emissions from the transport and building sectors and from 0.38% to 4.64% relative to CO₂e emissions from all sources. The upper end of the estimates corresponds to the extreme assumption of 50% of the workforce working from home.

The assumptions of former workplaces closing down permanently and no rebound trips are unrealistic. Allowing for repurposing of buildings and rebound trips yields an increase rather than a decrease in CO₂e emissions. The increase, however, is very small and ranges from 0.18% to 0.97% relative to emissions from the buildings and transport sectors combined and from 0.11% to 0.60% relative to emissions from all sources.

Table 19. Change in CO₂e emissions from transport and buildings under each scenario, allowing for no building close-down and for rebound effects.

Rebound effects	Scenario	Change in CO ₂ e emissions from buildings (million tonnes of CO ₂ e) ^a	Change in CO ₂ e emissions from transport (million tonnes of CO ₂ e) ^b	Total change in CO ₂ e emissions (million tonnes of CO ₂ e)	CO ₂ e emissions change relative to total CO ₂ e emissions from domestic transport and buildings in England and Wales ^c	CO ₂ e emissions change relative to total CO ₂ e emissions from all sources in England and Wales ^d
30% ^d	Scenario 1	0.89	−0.48	0.41	0.18%	0.11%
	Scenario 2	1.64	−1.02	0.62	0.27%	0.17%
	Scenario 3	2.38	−1.53	0.85	0.37%	0.23%
	Scenario 4	3.87	−2.40	1.47	0.64%	0.39%
	Scenario 5	5.36	−3.42	1.94	0.84%	0.52%
60% ^e	Scenario 1	0.89	−0.30	0.59	0.26%	0.16%
	Scenario 2	1.64	−0.87	0.77	0.33%	0.21%
	Scenario 3	2.38	−1.38	1.00	0.43%	0.27%
	Scenario 4	3.87	−2.09	1.78	0.77%	0.48%
	Scenario 5	5.36	−3.11	2.25	0.97%	0.60%

^a Computed relative to the baseline of 111.34 million tonnes of CO₂e for all buildings (table 8).

^b Computed relative to the baseline of 6 million tonnes of CO₂e for all commuting transport (table 15).

^c Total CO₂e emissions from domestic transport: 99.26 million tonnes (Thistlethwaite *et al* 2021) and total CO₂e emissions from all buildings, including factories: 131.43 million tonnes (computed as explained in table 8).

^d Total CO₂e emissions from all sources: 372.55 million tonnes (Thistlethwaite *et al* 2021).

Source: tables 10 and 17.

The findings of this study provide valuable benchmarks as policymakers attempt to learn lessons from the COVID-19 lockdown. As discussed in section 2, working from home increases job satisfaction, workers' well-being and organisational commitment and may also increase productivity. Downsizing can potentially save employers rent and bills. All these are good reasons to move towards homeworking for those engaged in jobs compatible with working from home. The answer to the question of whether we can save CO₂e emissions by working from home (in a new normal) is probably no. The net result is actually likely to be a small increase in CO₂e emissions. However, this increase in CO₂e emissions is likely to disappear as dwellings switch from gas to electricity for heating, in line with the Energy White Paper (BEIS 2020).

Policies such as road transport electrification, building insulation, and switching to electricity for heating are much more likely to reduce GHG emissions than working from home. Another policy that has traditionally been perceived as the cornerstone of sustainable transport has been the increase in the mode share of public transport, as explored in section 5.1. Public transport use, however, became controversial during the COVID-19 pandemic, with public transport users stating that they were not intending to return to public transport post-pandemic (Autotrader 2020), which would inevitably increase the number of journeys made by car, along with fuel consumption and GHG emissions (Crow and Milliot 2020). This poses a new challenge for public transport agencies and local government, but the problem falls outside the remit of the present study.

The findings reported here apply to England and Wales and may not be transferable to other countries, for the following reasons: (a) The share of jobs compatible with homeworking may be different, especially in developing countries; (b) The energy generation mix, which in turn determines conversion factors to translate energy consumption into GHG emissions, may be different; (c) The share of gas and electricity in energy consumption may be different; and (d) The mode share of commuting trips may be different.

What needs to be noted, however, and this applies to any country, is that (a) Working from home is mainly compatible with managerial and/or professional occupations, and so, unless a sizeable share of the labour force falls under that description, working from home may not be viable; (b) The energy mix plays an essential role in GHG emissions, and so if electricity is produced using carbon-intensive technologies, then a change in the energy mix is likely to be more effective than any shift to homeworking; (c) The higher the reliance of residential and non-residential buildings on electricity and the higher the share of clean electricity, the lower the Baseline GHG emissions from the buildings sector are likely to be; and (d) The lower the share of the car as a commuting mode, the less likely that reduced commuting will result in any significant reduction in GHG emissions.

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Data availability statement

All data that support the findings of this study are secondary data available from the sources we cite within the article.

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References

- Autotrader 2020 Coronavirus: Half of Public Transport Users Consider Switch To Cars (<https://autoserveclub.co.uk/blog/coronavirus-half-of-public-transport-users-consider-switch-to-cars/>)
- BBC News 2020 Warnings of 'ghost towns' if staff do not return to the office, 27 August (<https://bbc.co.uk/news/business-53925917>)
- Boeri T, Caiumi A and Paccagnella M 2020 Mitigating the work-safety trade-off *Covid Economics: Vetted and Real-Time Papers* 1/2 60–6 (<https://cepr.org/content/covid-economics-vetted-and-real-time-papers-0>)
- Building Research Establishment 2015 BREDEM 2012 - A technical description of the BRE Domestic Energy Model (<https://bre.co.uk/filelibrary/bredem/BREDEM-2012-specification.pdf>)
- Cairns S, Sloman L, Newson C, Anable J, Kirkbride A and Goodwin P 2005 'Smarter Choices—Changing the Way We Travel' (Chapter 10: Teleworking), Final report to the Department for Transport, The Robert Gordon University and Eco-Logica London, UK (<https://webarchive.nationalarchives.gov.uk/20100304004945/http://www.dft.gov.uk/pgr/sustainable/smarterchoices/ctwwt/>)
- Choo S, Mokhtarian P and Salomon I 2005 Does telecommuting reduce vehicle-miles travelled? An aggregate time series analysis for the US *Transportation* 32 37–64
- Crow D and Milliot A 2020 Working from home can save energy and reduce emissions. But how much? *Commentary* (Paris: International Energy Agency) (<https://iea.org/commentaries/working-from-home-can-save-energy-and-reduce-emissions-but-how-much>)
- Department for Business, Energy and Industrial Strategy, BEIS 2019 Greenhouse gas reporting: conversion factors 2019 (<https://gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019>)
- Department for Business Energy and Industrial Strategy, BEIS 2020 Energy White Paper: Powering our Net Zero Future (<https://gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future/energy-white-paper-powering-our-net-zero-future-accessible-html-version#chapter-4-buildings>)
- Department for Business Energy and Industrial Strategy, BEIS 2021a Non-Domestic National Energy Efficiency Data-Framework 2020 (ND-NEED) (England and Wales): Supporting Data Tables (<https://gov.uk/government/statistics/non-domestic-national-energy-efficiency-data-framework-nd-need-2020>)
- Department for Business Energy and Industrial Strategy, BEIS 2021b Energy consumption in the UK (<https://gov.uk/government/statistics/energy-consumption-in-the-uk-2021>)
- Department for Transport, DfT 2020a Vehicle Licensing Statistics: Annual 2019. Statistical release 30 April (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/882196/vehicle-licensing-statistics-2019.pdf)
- Department for Transport, DfT 2020b Table NTS0409a: Average number of trips (trip rates) by purpose and main mode: England (<https://gov.uk/government/statistical-data-sets/nts03-modal-comparisons>)
- Department for Transport, DfT 2020c Transport Statistics Great Britain (<https://gov.uk/government/statistics/transport-statistics-great-britain-2020>)
- Dingel J and Neiman B 2020 How many jobs can be done at home? *NBER Working Paper Series, Working Paper 26948* (<https://nber.org/papers/w26948>)
- Emanuel N and Harrington E 2020 'Working' remotely? Selection, treatment, and the market provision of remote work, Job Market Paper (https://scholar.harvard.edu/files/eharrington/files/harrington_jmp_working_remotely.pdf)
- Etheridge B, Wang Y and Lang T 2020 Worker Productivity during Lockdown and Working from Home: Evidence from Self-Reports, Institute for Social & Economic Research, Working Paper No. 2020-12 (<https://iser.essex.ac.uk/research/publications/working-papers/iser/2020-12.pdf>)
- Felstead A and Henseke G 2017 Assessing the growth of remote working and its consequences for effort, well-being and work-life balance *New Technol. Work Employ.* 32 195–212
- Felstead A and Reuschke D 2020 *Homeworking in the UK: before and during the 2020 lockdown*, WISERD Report (Cardiff: Wales Institute of Social and Economic Research) (<https://wiserd.ac.uk/publications/homeworking-uk-and-during-2020-lockdown>)
- Harris R, Bedford M, Gillen N, Jack F, Rees S and Whitehead C 2018 Office Occupancy: Density and utilisation, British Council for Offices: London (http://research.bco.org.uk/resources/clients/3/user/resource_854.pdf)

- HM Treasury 2020 Latest figures show millions benefitting from Treasury coronavirus support schemes (<https://gov.uk/government/publications/latest-figures-show-millions-benefitting-from-treasury-coronavirus-support-schemes>)
- Hook A, Court V, Sovacool B and Sorrell S 2020 A systematic review of the energy and climate impacts of teleworking *Environ. Res. Lett.* **15** 093003
- International Monetary Fund 2021 World Economic Outlook Update, July 2021 (<https://imf.org/en/Publications/WEO/Issues/2021/07/27/world-economic-outlook-update-july-2021>)
- Johns Hopkins University 2021 Coronavirus Resource Centre (<https://coronavirus.jhu.edu>)
- Leesman 2020 Your Workplace of the Future (https://j4kul1vgvngzak62jhqile4-wpengine.netdna-ssl.com/wp-content/uploads/2020/12/Leesman-Your_Workplace_of_the_Future-SP-1.pdf)
- Matthews H and Williams E 2005 Telework adoption and energy use in building and transport sectors in the United States and Japan *J. Infrastruct. Syst.* **11** 21–30
- Ministry of Housing, Communities and Local Government 2020 Live tables on dwelling stock (including vacants) (<https://gov.uk/government/statistical-data-sets/live-tables-on-dwelling-stock-including-vacants>)
- Morikawa M 2020 Productivity of working from home during the COVID-19 pandemic: Evidence from an employee survey, COVID Economics: Vetted and Real Time Papers, Issue 49, 18 September (<https://cepr.org/content/covid-economics-vetted-and-real-time-papers-0>)
- O'Brien W and Aliabadi F 2020 Does telecommuting save energy ? A critical review of quantitative studies and their research methods *Energy & Buildings* **225** 110298
- OECD 2020 Productivity gains from teleworking in the post COVID-19 era: How can public policies make it happen? (https://read.oecd-ilibrary.org/view/?ref=135_135250-u15liwp4jd&title=Productivity-gains-from-teleworking-in-the-post-COVID-19-era)
- Office for National Statistics, ONS 2019a Families and households in the UK: 2018 (<https://ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2018#:~:text=In%202018%2C%20there%20were%2027.6%20million%20households%20in%20the%20UK,10%2Dyear%20period%20from%202008>)
- Office for National Statistics, ONS 2019b Working and workless households in the UK: April to June 2019 (<https://ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/bulletins/workingandworklesshouseholds/apriltojune2019>)
- Office for National Statistics, ONS 2020a Homeworking in the UK Labour Market, Jan–Dec 2019 (<https://ons.gov.uk/releases/coronavirusandhomeworkingintheuklabourmarket2019>)
- Office for National Statistics, ONS 2020b Wave 3, Opinions and Lifestyle Survey (<https://ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/bulletins/coronavirusstheukconomyandsocietyfasterindicators/23april2020>)
- Office for National Statistics, ONS 2020c Employment by Occupation: England and Wales (SOC2010) by sex (<https://nomisweb.co.uk/datasets/aps168/reports/employment-by-occupation?compare=W92000004>)
- Ohnmacht T, Thao V and von Arx W 2020a Job mobility biographies in coworking spaces: a theoretical contribution to new social and spatial structurings *Mobility Over the Life Course* ed J Scheiner and R Henrike (Cheltenham: Edward Elgar) pp 100–16 Chapter 7
- Ohnmacht T, Z'Rotz J and Dang L 2020b Relationships between Coworking Spaces and CO₂ emissions in work-related commuting: first empirical insights for the case of Switzerland with regard to urban-rural differences *Environ. Res. Commun.* **2** 125004
- Ravalet E and R  rat P 2019 Teleworking: decreasing mobility or increasing tolerance of commuting distances? *Built Environment* **45** 582–602
- Reuschke D and Felstead A 2020 Changing workplace geographies in the COVID-19 crisis *Dialogues in Human Geography* **10** 208212
- Santos G, Behrendt H and Teytelboym A 2010 Policy instruments for sustainable road transport *Research in Transportation Economics* **28** 46–91
- Sorrell S, Gatersleben B and Druckman A 2020 The limits of energy sufficiency: a review of the evidence for rebound effects and negative spillovers from behavioural change *Energy Research & Social Science* **64** 101439
- Thistlethwaite G et al 2021 Report: Greenhouse Gas Inventories for England, Scotland, Wales & Northern Ireland: 1990–2019 (https://naei.beis.gov.uk/reports/reports?report_id=1019)
- Welsh Government 2020 Dwelling stock estimates by local authority and tenure (<https://statswales.gov.wales/Catalogue/Housing/Dwelling-Stock-Estimates/dwellingstockestimates-by-localauthority-tenure>)
- World Health Organisation, WHO 2020a Naming the coronavirus disease (COVID-19) and the virus that causes it ([https://who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance/naming-the-coronavirus-disease-\(covid-2019\)-and-the-virus-that-causes-it](https://who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance/naming-the-coronavirus-disease-(covid-2019)-and-the-virus-that-causes-it))
- World Health Organisation, WHO 2020b Q&A on coronaviruses (COVID-19) (<https://who.int/news-room/q-a-detail/q-a-coronaviruses>)