What impact have COVID-19 induced changes in working practice had on greenhouse gas emissions? A rapid review

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Systematic Review

Keywords: working from home (WFH), environmental impact, greenhouse gas emissions

Posted Date: May 20th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1677535/v1

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Abstract:
The changes in working practice over the pandemic went through several distinct phases: the initial 'lockdown' period, a period of relaxation in some restrictions, and a longer-term period where working from home (WFH) was preferred if possible but many other aspects of life returned to near-normal.
This Rapid Review was accompanied by high level life cycle assessment (LCA), to quantify the environmental profile of products, processes and behaviours based on energy use and commuting activity of office workers over a 7 day period. We aimed to describe trends in environmental effects, specifically regarding greenhouse gas emissions relating to energy usage and commuting behaviour, during the pandemic.
For the rapid literature review, 32 studies were identified.

- Rapid Review findings corroborated the life cycle assessment findings that energy for space heating (both at home and in the office) and transport dominated the greenhouse gas emissions profile.
- Domestic energy consumption remained elevated after easing restrictions with a displacement of energy normally consumed in business premises.
- Overall, there was a net reduction in consumption and greenhouse gas emissions with greater working from home.
- There has been a shift away from public transport with a negative effect on greenhouse gas emissions.
- Travel distance and mode of transport are significant factors in determining the magnitude of benefits seen when working from home.
- Air quality is reported to have been affected by the lockdown period, but no studies have directly evaluated the working from home component of this.

For the Life cycle assessment, analysis was based on 10 workers at home or in an office in typical UK housing and a typical office with two transport options for commuting (car and train), over 7 days. A clear benefit was seen in reducing greenhouse gas emissions for working from home compared to office work with travel by car, and a smaller benefit for working from home compared to office work by train. The working from home scenario had significantly lower impact than both the car and train commute scenarios on marine ecotoxicity and freshwater ecotoxicity indicators.

Funding statement: The BioComposites Centre, Bangor University was funded for this work by the Wales Covid-19 Evidence Centre, itself funded by Health & Care Research Wales on behalf of Welsh Government.

Wales COVID-19 Evidence Centre (WCEC)
Rapid Review

What impact have COVID-19 induced changes in working practice had on greenhouse gas emissions?

Report number RR_00031 March 2022

Rapid Review Details
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TOPLINE SUMMARY

What is a Rapid Review?
Our rapid reviews use a variation of the systematic review approach, abbreviating or omitting some components to generate the evidence to inform stakeholders promptly whilst maintaining attention to bias. They follow the methodological recommendations and minimum standards for conducting and reporting rapid reviews, including a structured protocol, systematic search, screening, data extraction, critical appraisal, and evidence synthesis to answer a specific question and identify key research gaps. They take 1- 2 months, depending on the breadth and complexity of the research topic/question(s), extent of the evidence base, and type of analysis required for synthesis.

This Rapid Review was accompanied by high level **life cycle assessment (LCA),** to quantify the environmental profile of products, processes and behaviours based on energy use and commuting activity of office workers over a 7 day period.

Background / Aim of Rapid Review

The changes in working practice over the pandemic went through several distinct phases: the initial 'lockdown' period, a period of relaxation in some restrictions, and a longer-term period where working from home (WFH) was preferred if possible but many other aspects of life returned to near-normal. We used two parallel workstreams to contribute data to this report: a **high level life cycle assessment** based on UK national data, and a **rapid literature review**. We aimed to describe trends in environmental effects, specifically regarding **greenhouse gas emissions** (GHGE) relating to energy usage and commuting behaviour, during the pandemic. This work was conducted for the Welsh Government TAG Environment (TAG-E) Subgroup.

Key Findings

***Life cycle* assessment**

- Analysis was based on 10 workers at home or in an office in typical UK housing and a typical office with two transport options for commuting (car and train), over 7 days.
- A **clear benefit was seen in reducing greenhouse gas emissions for working from home** compared to office work with travel by car, and a smaller benefit for working from home compared to office work by train.
- The **working from home scenario had significantly lower impact** than both the car and train commute scenarios **on marine ecotoxicity and freshwater ecotoxicity** indicators.

Rapid literature review

Extent of the evidence base

- **32 studies** were identified, of which 11 related to the UK and Republic of Ireland, and 21 related to other EU-27 countries.

Recency of the evidence base

- The search was limited to studies published after 1st January 2020.

- Some papers also referred to a further body of work in telecommuting and remote working pre-dating the pandemic.

Findings

- **Rapid Review findings corroborated the life cycle assessment findings** that energy for **space heating** (both at home and in the office) and **transport** dominated the greenhouse gas emissions profile.
- **Domestic energy consumption remained elevated after easing restrictions** with a displacement of energy normally consumed in business premises.
- **Overall there was a net reduction in consumption and greenhouse gas emissions** with greater working from home.
- There has been a **shift away from public transport** with a negative effect on greenhouse gas emissions.
- **Travel distance and mode of transport** are significant factors in determining the magnitude of benefits seen when working from home.
- **Air quality** is reported to have been affected by the lockdown period, but no studies have directly evaluated the working from home component of this.

Evidence gaps

- The **magnitude of greenhouse gas emissions savings** for a switch to flexible or hybrid working where offices remain open is **unclear** as there may be doubling up of heating and lighting for two premises
- **Building energy performance** (domestic and offices) and **multiple scenarios** representing typical commuting behaviour should be considered in further work.
- There was a **lack of indoor air quality data** for working from home.
- **No water quality data** were found in this review.

Policy Implications

- Policy to **encourage working from home** could form **part of a larger platform** to reduce greenhouse gas emissions but would need to include **equity considerations**.
- Improvements in **building energy efficiency** and the **emissions reduction associated with travel** would also be beneficial.
- Encouraging commuters back onto **public transport** could help reduce greenhouse gas emissions.
- Commissioners should seek to **fund research** focussing on the effects of changes to working practices on indoor air quality and water quality.

Strength of Evidence

Life cycle assessment was conducted using secondary UK data sources. The rapid review did not include quality appraisal of studies owing to volume of literature.

TABLE OF CONTENTS

Abbreviations:

Acronym	Full Description
CO_2e	Carbon dioxide equivalents
EO	Employer's office
FLD	Full lockdown
GHG	Greenhouse gas
GWP	Global warming potential
HO	Home office
ICT	Information and communications technology
LCA	Life cycle assessment
LCI	Life cycle inventory
LPG	Liquefied petroleum gas
NEED	National Energy Efficiency Data
PM	Particulate matter
RES	Renewable energy share
ROI	Republic of Ireland
SLD	Soft lockdown
Scope 1 emissions	Emissions arising from the company's direct operations, e.g. burning fuel to run a vehicle
Scope 2 emissions	Emissions arising indirectly from the company's activities, e.g. purchasing electricity or other services to support direct operations
Scope 3 emissions	Emissions associated with the company's activities for which is it indirectly responsible up or down the value chain including investments; franchises; leased assets; buying, using or disposing of products from suppliers etc.
TC	Telecommuting
VOCs	Volatile organic compounds
WFH	working from home
WOS	Web of Science

Terminology:

The term *working from home* (WFH) has been used in this review to reflect the action of working at home during the COVID pandemic.

Working from home can be considered to be broadly equivalent to other terms such as *telecommuting*, *e-commuting* and *remote working*. However, some of these other terms also include other activities such as the use of a third-party location (e.g. library, coffee shop or teleworking facility) which may also reduce distance travelled compared to the employer's office, but be outside the home (and less likely to be used during the COVID period). With the advent of cloud computing and internet access from a wide range of locations, the distinction between these terms has softened.

Working from home is also considered to be a component of other working systems such as *flexible working*, *mobile working* and *hybrid working*, in which there may be a greater adaptability of timing of work as well as location. The hybrid working model uses a combination of days working at home or in third party locations with days spent in the office.

Where these alternative meanings are intended by the chosen term used in the scientific papers reviewed by the team, we have retained the original term used by the paper authors to indicate this.

1. BACKGROUND

This Rapid Review is being conducted as part of the Wales COVID-19 Evidence Centre Work Programme. The above question was suggested by Welsh Government TAG Environment Subgroup (TAG-E).

1.1 Purpose of this review

The measures introduced during the COVID-19 pandemic in the UK and Wales led to dramatic shifts in numbers of people working from home or on furlough at different stages in the pandemic. Some of these stages were accompanied by altered traffic levels, altered energy consumption and altered resource use, with an associated impact on the environment. Capturing the environmental effects will support future policy, for example towards reducing carbon emissions on the road to net zero, or considering flexible working patterns and commuting behaviours within well-being of future generations commitments.

The refined research question posed by the stakeholders is:
What impact have COVID-19 induced changes in working practice had on greenhouse gas emissions?

2. RESULTS

2.1 Overview of the Evidence Base

This rapid review comprised two parallel streams of work. Firstly, a simple **life cycle assessment (LCA) exercise** was undertaken using publicly available data or published datasets, to cover the environmental factors relating to a shift from working in an office to working from home. This is reported in Section 2.2, and the full report is attached as an Appendix. This LCA took into account changes in gas and electricity usage at home and in the office, as well as changes in travel. It considered the global warming potential (GWP, relating to greenhouse gas emissions) as well as the ecotoxicity (the measure of the impact of chemical or other stressors on ecosystem health), air quality and water quality factors.

Secondly, a **rapid review of scientific literature** was conducted to identify all papers within the period 1st January 2020 to 17th February 2022 relating to working from home, flexible working, and related concepts such as telecommuting. Within this set, all papers which addressed the following themes were retained for review: **energy usage**, **transport for commuting**, **air quality outdoors and within the home-office context and water quality**. This review is reported in Sections 2.3 to 2.5.

Within the review, to exclude the period during which full lockdown was imposed on the UK (which included closure of industry, manufacturing and many sectors of the economy), the search sought sets of papers relating to working from home and flexible working, deliberately not using the keyword 'lockdown'. A control set used search terms relating to pre-COVID and pre-pandemic to gain a perspective on environmental profile of 'normal' working before the pandemic occurred.

Within the time period studied, a total of **2846 scientific papers** were found using Web of Science, segregated as shown in Table 1. A small number of records occurred in two out of the three sets, as shown in the final column.

Table 1: Web of Science Search terms

Group	Search terms	No of records	Duplicates
Flexible working	"hybrid working" or "at home working" or hybrid near/2 work* or "remote working" or flexi-work* or "mobile work" or "flexible working" or "dynamic working"	821 hits	7 x pre-COVID 76 x WFH
Pre-COVID	work or working and pre-COVID or pre-pandemic	802 hits	7 x flexible 27 x WFH
Working from home (WFH)	"working from home" or WFH or working near/2 home or telecommute* or tele-commute*	1224 hits	76 x WFH 27 x pre-COVID

From this large set of papers, a Python script was used to search for populations of keywords on the five themes, as outlined in the Appendix.

- air quality,
- energy,
- global warming potential (GWP),
- travel and
- water quality

The papers containing keywords from the five themes were then interrogated using a second Python routine to filter by country(ies) in the title, with a manual verification to confirm correct allocation and to check for countries named within the abstract.

The review team then verified the relevance of the set of papers naming the **UK, Great Britain, or nations within the UK, as well as the Republic of Ireland**. The ecology and behaviour in these two nations was considered sufficiently similar to address them together. This step retained a total of **13 records of interest**. These were predominantly relating to energy and travel phenomena, but several covered multiple themes.

As the number of records for UK and ROI was relatively low, the search was **expanded to include all 27 countries of the European Union**. This generated **a further 30 records** of interest. This set included a greater number of records relating to the GWP and air quality theme in addition to further information on energy and travel behaviour. No records relating to water quality were found.

Within the five categories, some papers occurred in more than one thematic group, as shown in Table 2. This is due to the closely related nature of these topics, where energy and transport were considered to be substituents of the global warming potential (GWP) set, but as the data reveals, **a higher number of papers were found on the energy or transport themes than directly calculating or reporting GHG emissions and GWP values**. Similarly, air quality is considered to be closely related to and partially overlapping with the transport and the energy sets. There is clearly a **gap in the evidence relating to water consumption or waste water generation during the pandemic period**. A fuller breakdown of these papers is provided in Section 6.2.

Table 2: Number of papers in each thematic group

	Air	Energy	GWP	Travel	Water
UK and ROI	4	10	2	2	0
EU27	8	23	5	6	0
Total	12	22	7	8	0

After full text screening by the reviewers, **11 studies relating to the UK and ROI, and 21 relating to EU 27 countries were retained**. Several records from the energy and air themes were ultimately reported in the travel section.

Table 3: Key literature articles relating to the five themes studied, or providing background demographic information.

	Air quality	**Energy**	**GWP**	**Travel**	**Water quality**	**Demographic information**
Reviews						
Literature review	Salamone et al. (2021b)		Fabiani et al. (2021)	Campisi et al. (2020) Ellder (2020)		Doling and Arundel (2022)
Primary studies						
Quantitative	Polednick (2021) Falzone et al. (2021) Vajs et al. (2021)	Russo et al. (2021) Manjunath et al (2021) Bielecki et al. (2021)	Fabiani et al. (2021) Kylili et al. (2020) El Geneidy et al. (2021)	Gonzalez et al. (2021) Qin et al. (2021)		
Survey	Salamone et al. (2021a) Salamone et al. (2021b) Torresin et al. (2021a) Torresin et al. (2021b) Torresin et al. (2022)		Fabiani et al. (2021)	Budnitz et al. (2020) Clark et al. (2020) Bieser et al. (2021) Schaefer et al. (2021) Campisi et al. (2021) Ellder 2020 Beno (2021)		
Modelling	Giallouros et al. (2020) Weber et al. (2021) Mohammadi et al. (2021)	Bazzana et al. (2022)	Cerqueira et al. (2020)	Cerqueira et al. (2020) Giallouros et al. (2020) Crowley et al. (2021) Bazzana et al. (2022) Noussan and Jarre (2021)		
LCA			El Geneidy et al. (2021)			
Case study		Kirli et al. (2021)				

The two parts of this study cover similar topics relating to the environmental impacts of working from home, but providing different perspectives. They will be reported in the sections which follow.

In the absence of full coverage of the topics by the published literature studies about the UK, the life cycle assessment provides a clearer picture of key trends for the Wales and UK context, whereas the literature review component provides the overarching picture, using data from the EU-27 countries to supplement the UK and ROI papers. Findings from the two activities are in broad agreement, as will be seen and discussed below.

2.2 Life Cycle Assessment: Effectiveness of WFH for GHG emissions and other environmental indicators

The goal of this Lifecycle Assessment (LCA) is to assess the environmental impacts of working from home (WFH) compared to working in an office.

Life cycle assessment is a well-established technique for quantifying the environmental profile of products, processes and behaviours. When making comparisons it is important to clearly define the system boundaries, and to ensure that all scenarios represent an equivalent functional unit.

The system boundary has been scoped to **focus on the energy use and commuting activity of office workers over a 7-day period** (Table 4). This LCA excludes any production / manufacturing of office equipment such as laptops, desktops and monitors etc. and any inputs that may relate to leisure or personal trips. The full report with all methodology information is presented in the Appendix.

Three scenarios have been considered in this study:

(1) working from home (WFH),
(2) commuting to an office via car, and
(3) commuting to an office via train.

The functional unit for this study has been determined as a 7-day period of ten individuals working in the UK from either their home or in an office.

2.2.1 Data sources and assumptions

As this work has been undertaken within the Rapid Review it not been possible to use primary data, so **all inputs and quantities have been assumed or taken from secondary data available from published reports, predominantly by the UK government.** The mass and energy data that has been collected have been paired with the most relevant environmental Life Cycle Inventory (LCI) datasets from Ecoinvent v3.6 (Wernet et al. 2016) using a cut-off approach. The LCI data was then analysed using the ReCiPe 2016 Midpoint (H) impact assessment method.

Electricity consumption

Individual electrical appliances included in this study, and their wattages, are shown in Table 4. The figures are based on the average specification and performance that would be used in a standard office role during an **8-hour day over 5 working days**.
In the WFH scenario, full operation of the laptop and monitor has assumed to be 7 hours, and 1 hour allocated for these devices to be put on 'standby' mode for a lunch break.
In the office scenario, full operation of the computer desktop has assumed to be 6 hours, and 2 hours allocated for this device to be left on 'standby' mode representing a lunch break, and periods away from the desk for meetings and other office duties.

Table 4: Inputs considered in the LCA and their quantities of 10 individuals over one week.

Profile of employee	*Aspects considered in the modelling*	Energy consumption	Unit
WFH	Use of laptop	17.5	kWh
	Use of computer monitor	3.75	kWh
	Use of lights	24	kWh

	Heating of home	3212.12	kWh
	Other items	9.4	kWh

Profile of employee	***Aspects considered in the modelling***	**Energy consumption**	**Unit**
Office	Round trip in a car	1609.34	km
	Round trip on a public train	3283.06	person km
	Use of computer desktop	30	kWh
	Use of lights	24	kWh
	Heating of the room (including keeping home warm when not occupied)	2683.08	kWh
	Other items	9.4	kWh

Gas consumption

The gas consumption figures used in this analysis has been collected from published reports by the Department for Business, Energy & Industrial Strategy (BEIS, 2019, 2020) which provide annual gas usage figures per m^2 for Domestic and Non-domestic building types within the National Energy Efficiency Data (NEED) work stream. As this analysis does not use site-specific gas consumption, there may be some margin of error to account for. However, **data represents the full range of ages of premises, sizes and occupancy levels, so represents the average of the population as a whole**. Within the National Energy Efficiency Data (NEED) data for non-domestic premises there is a subset for offices, which was used within this study. The Life Cycle Inventory (LCI) dataset to represent heat from a gas boiler is assumed to be a central or small-scale (<100kW) modulating condensing boiler using natural gas.

It is understood that different consumers might have different set temperatures within the home or use different numbers of hours of heating etc. However, as the BEIS data already contains a gross average of UK heating behaviours the use of a simple percentage value for change in gas usage was deemed most appropriate for this study. Future work could address the same question using primary data for actual user behaviour and actual dwelling types, ages etc. Further studies around the topic of domestic and non-domestic gas consumption would aid this study.

Gas consumption in houses and flats

Using the annual domestic gas consumption of the average house in England and Wales (130 kWh per m^2), and the average flat (165 kWh per m^2) in 2017 (BEIS, 2019), a weekly value was determined.

To acknowledge an increase in gas use as more people WFH **a typical household day was considered**. For the office work household it was assumed gas would be used to heat the house for 3 hours in the morning, then leave for work and heat the house for 4 hours in the evening in a typical working day (total 7 hours), with higher usage reflecting three intervals of gas heating on weekend days (total 10 hours). This gives a weekly usage of 55 hours. For the WFH household, the weekday consumption was increased with a lunchtime interval of 3h gas heating, giving a total of 10 hours, while weekends remained unchanged, giving a weekly total of 70 hours for WFH. This represents an increase of 27% on the office work scenario. As a result, a factor of 27% was added to the total gas consumption to obtain the WFH values (Table 5).

Table 5: Calculations to heat the home / flat of 10 individuals when working from home.

	Gas consumption (2017) average house (Office scenario)	Estimated gas consumption post COVID (WFH scenario)	Unit
1 year per 1m² (house)	*130.0*	*165.1*	kWh
1 week per 1m²	*2.5*	*3.2*	kWh
1 week per 96m² - 10 people	*2400.0*	*3048.0*	kWh
	Gas consumption (2017) average flat	**Estimated gas consumption post COVID**	
1 year per 1m² (flat)	*165.0*	*209.6*	kWh
1 week per 1m²	*3.2*	*4.0*	kWh
1 week per 960m² - 10 people	*3046.2*	*3868.6*	kWh
Total gas consumption of 1 week per 10 people (house and flat)	**2529**	**3212**	kWh

Gas consumption in offices

For the office scenario, the mean gas intensity of offices in England and Wales in 2018 was used 160 kWh per m^2 (BEIS, 2020). This figure is the average gas intensity per m^2 of all offices varying in floor area and business size but has been used in this study as a representative of the average gas usage in an office.

Once more, the annual gas consumption per m^2 is broken down to represent a 7 day period which was then multiplied by the amount of floor space used for 10 individuals' working space within an office (Table 6). This was 50m² for 10 individuals at average workstations (4-6m² per person, Commercial Real Estate, 2019).

In addition, the pre-COVID domestic gas consumption value (Table 5) has been added to the office workers scenario to ensure comparability of the two populations.

Table 6: Calculations to heat the office of 10 employees.

Office		
	Gas intensity	**Unit**
1 year per 1m²	160.0	kWh
1 week per 1m²	3.1	kWh
1 week per 50m² - 10 people	**153.8**	kWh

Transport

Two scenarios regarding transport were considered: **commuting to work via car and via train.** In each group it was assumed that all ten consumers used the same mode of transport, for all five working days.

Life Cycle Inventory (LCI) datasets for the transport were assigned. The typical car commuting to work was considered to be a European passenger car (petrol, diesel and electric) in the classes EURO 3,4 and 5 regarding petrol and diesel vehicles, which is well established in Ecoinvent (Wernet et al. 2016). The average commuting distance of a round trip in a car was set as 32.19 km, which was taken from the Department for Transport report regarding commuting trends in England (DoT, 2017).

The same DoT report was used to gather the average commuting journey of a passenger train which was stated as 65.66 km. LCI datasets for passenger trains in the UK are limited in Ecoinvent, thus an average has been taken from passenger trains in Austria, Belgium, Germany, France, and Italy to represent an average European passenger train.

2.2.2 Results – Greenhouse gas emissions

Figure 1 displays the total GHG emissions associated with a 7 day period of working in an office via car and train, and a WFH scenario. These are expressed as kilograms of carbon dioxide equivalents (kg CO_2e). It is notable that no GHG emissions relating to materials were recorded for the three scenarios, as no change in consumption of stationery or other resources was included in the scenarios.

It is evident that **commuting to an office via car is the most environmentally impactful scenario** emitting 1256.7 kg CO_2e. This is followed by commuting to an office via train at 892.7 kg CO_2e, and the WFH scenario performing the best, emitting 854.7 kg CO_2e. Thus, the WFH and office via train scenario emit 32% and 29% less CO_2 respectively, compared to the office via car scenario. Although **the gas boiler in both locations is the largest contributor overall**, the emissions from travelling to work via car is the definitive factor in these results, emitting 535.9 kg CO_2e alone. While these transport emissions are based on average commuting distances respective to the mode of transport, it is clear that **commuting via train is much less damaging in terms of GHG emissions than via car, even when travelling greater distances.**

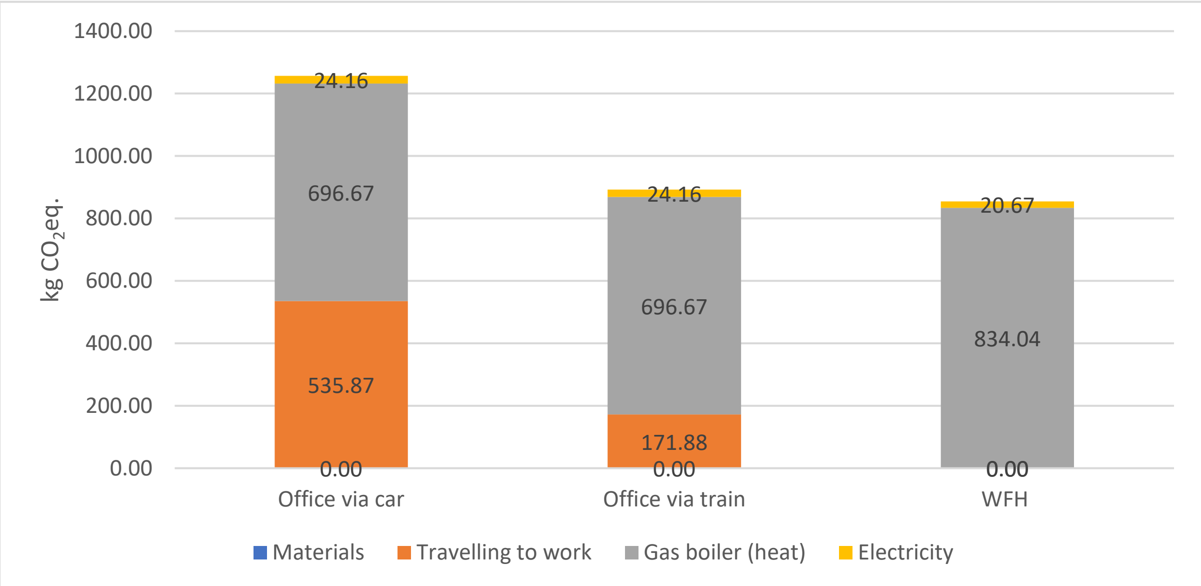

Figure 1: GHG emissions associated with the energy use and commuting activity of office workers over a 7 day period comparing three scenarios.

Figure 2 shows the relative contribution of each input to the overall carbon footprint (GHG emissions) associated with each scenario showing more clearly the environmental hotspots. **The gas boiler is the largest contributor in all scenarios**, which is especially true in the WFH scenario as it contributes to 98% (834 kg CO_2e) of total emissions with the remaining 2% (20.1 kg CO_2e) coming from electricity. However this includes all heating and gas usage for a typical dwelling, and reflects currently accepted awareness of the impact of space heating on national greenhouse gas emissions. Although the WFH scenario emits less GHG emissions overall, it does perform noticeably worse when comparing emissions directly from space heating, as in both the office scenarios (via car and train) the gas boiler emits 696.7 kg CO_2e, reflecting the economies of scale of heating a single office space for multiple employees.

Despite the **electricity emissions having a very small impact overall, it is worth noting that emissions are lower in the WFH scenario**. It has been assumed that when working from home a laptop and monitor are used instead of a computer desktop which are often used in an office, and as a computer desktop typically uses more electricity than a laptop, the GHG emissions from electricity in office working reflect this.

Figure 2: Percentage breakdown of GHG emissions (kg CO_2 eq) associated with the energy use and commuting activity of office

Unexpectedly, **the working in an office via train scenario and the WFH scenario perform at a similar level.** This is due to the added gas consumption in the WFH scenario which is almost cancelled out by the emissions from the train. Due to the system boundary focused to an 8 hour workday over a 7 day period, this LCA does not include the materials needed for the buildings of the workplace nor the equipment used. It only includes materials that may be used during the day such as water, as a result there is an insignificant amount GHG emissions from the materials input.

2.2.3 Normalisation to investigate other environmental indicators

According to the ISO 14044 Standard on LCA, normalisation is defined as "calculating the magnitude of category indicator results relative to reference information", which produces a single numerical score to identify "important" impact categories, interpret and communicate the impact results (International Organization for Standardization, 2006). Using normalisation in LCA is optional but it aids a better understanding of the relative magnitude of each indicator result of the product(s) under study (Pizzol et al., 2017). Through the normalisation treatment, Figure 3 displays the normalised scores of each environmental impact category for the three scenarios in this study.

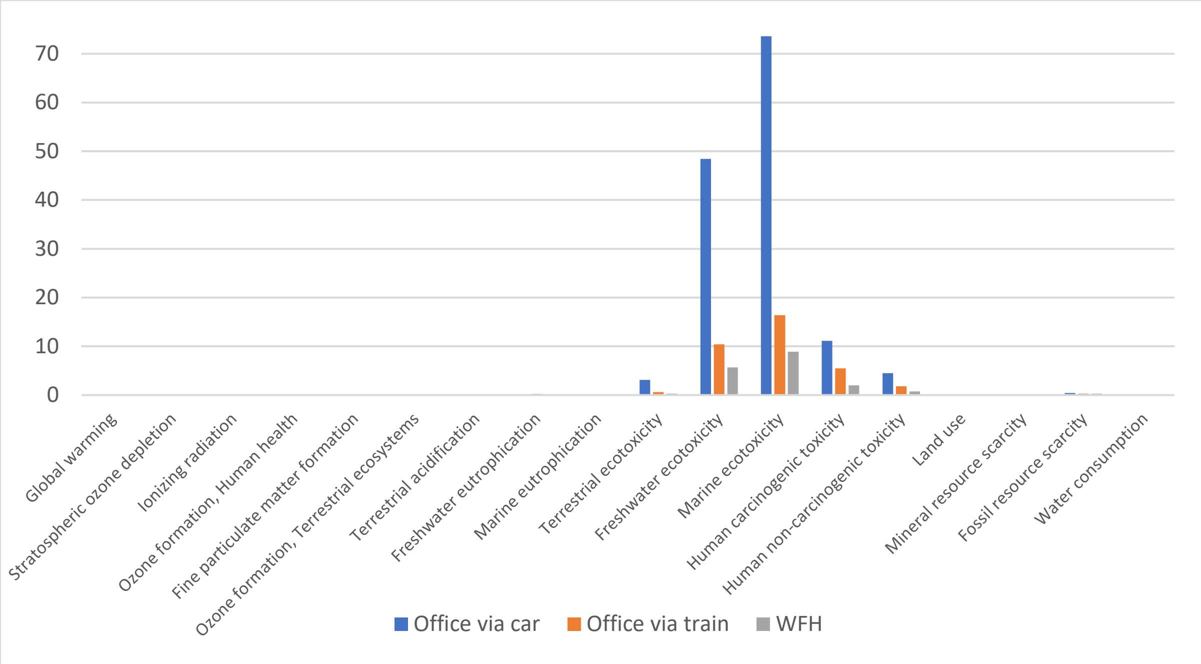

Figure 3: Normalisation results associated with the energy use and commuting activity of office workers over a 7 day period comparing three scenarios.

While the data in Figures 1 and 2 relate to GHG emissions, the normalised data reveals that other environmental indicators may be more significant. The impact categories that are noticeable in Figure 3 are the same across all scenarios, having most of the impact in the toxicity and eco-toxicity categories. However, **the office via car scenario scores extremely high in the freshwater and marine ecotoxicity categories which are directly correlated to the environmental impact of the car** (Figure 4). This is a similar theme across the remaining visible bars in Figure 3, as Human carcinogenic and non-carcinogenic toxicity, and terrestrial ecotoxicity are still heavily influenced from the car. These normalised results demonstrate that environmental impact categories such as Global Warming Potential (GWP), fine particulate matter formation and eutrophication etc. may not be as relevant to the impacts of office / home working when compared to ecotoxicity and toxicity.

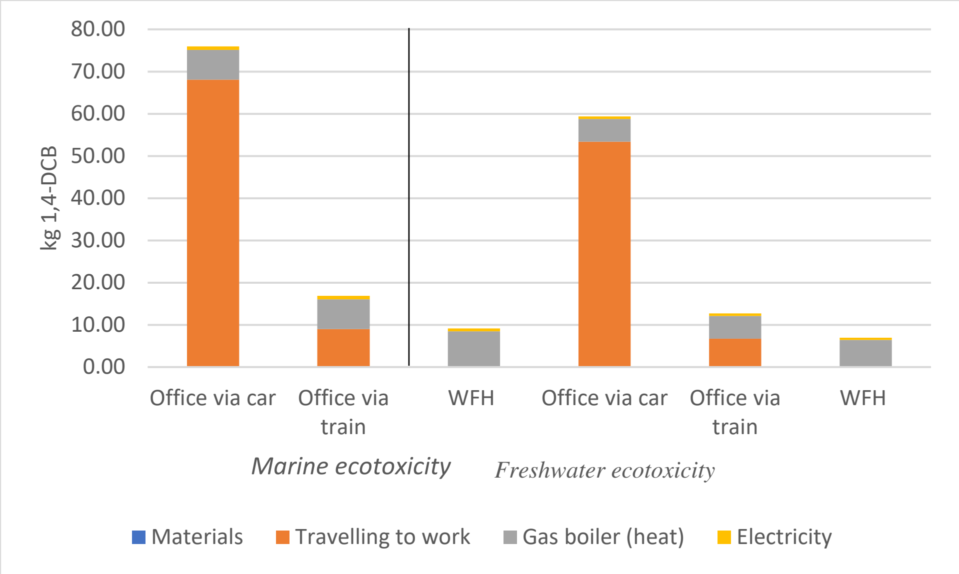

Figure 4: Marine ecotoxicity and freshwater ecotoxicity associated with the energy use and commuting activity of office workers over a 7 day period comparing three scenarios.

The **WFH and office via train scenarios performed relatively similarly in terms of GHG emissions (Figure 1) and are far less impactful than the office via car scenario**. However, much of the other indicator scores in the WFH scenario are associated with the gas boiler with minimal inputs from electricity, while the impact of the train roughly doubles these scores in the relevant impact categories (Figure 4), and ultimately the results favour a shift towards WFH.

2.2.4 Conclusions from life cycle assessment (LCA)

The main aim of this LCA was to assess and compare the environmental impacts of 10 individuals WFH, and 10 individuals working in an office over a 7 day period. As a result, three scenarios have been depicted: WFH, commuting to an office via car, and commuting to an office via train. As there was no primary data available, this study has used data collected from UK government reports, along with informed assumptions.

In terms of GHG emissions, **the least impactful scenario was identified as WFH, which was closely followed by the office via train scenario**. **By far the most impactful scenario was commuting to an office via car**, emitting 32 and 29% more GHG emissions than WFH and commuting via train respectively. **The major environmental hotspot in all scenarios was recognised as the space heating by gas boiler**, which was most damaging in the WFH scenario, compared to the office scenarios where economies of scale applied. This related to the larger floor area needed to heat up a typical house or flat rather than a shared office space over the 8 hour period. However, this dynamic could change if the functional unit considered office workers having separate office spaces and thus more floor space per individual, consequently requiring more gas.

Evidently this study has shown **that WFH is the least environmentally impactful scenario which is not just apparent from GHG emissions but also, the remaining environmental impact categories shown in the normalisation results.** Although the gas boiler is a high emitter in terms of GHG emissions, transport is the crucial issue across many of the other environmental impact categories. This raises the relative impact of transport and more specifically, commuting via car.

The derived conclusion would be for office workers to WFH where possible, but if commuting to an office is necessary, then commuting via train is the least impactful. Yet, rail travel in the UK is imperfect with non-direct routes, limited number of journeys and often delays and / or cancellations. If these are issues and make commuting via train impracticable, then a hybrid work model could be implemented. Effectively splitting the number of days to WFH and commuting via car would lower the overall environmental impact if WFH full-time was not possible. This was not considered in the current study, but is supported by promising results from published studies in Europe (Noussan and Jarre 2021, Crowley et al. 2021). The impact of distance on the transport emissions benefits of remote working is considered by Fabiani et al. (2021).

2.2.5 Bottom line results for GHG emissions from LCA

A clear reduction in GHG emissions was demonstrated for the WFH scenario when compared to the office workers travelling by car scenario.

The GHG emissions for office workers travelling by train were closer to the value seen for WFH, reflecting the lower carbon footprint of this mode of travel.

However, when the other environmental indicators were considered, the **WFH scenario had significantly lower impact than both the car commute and the train commute scenarios**.

Dominance of domestic and business energy for space heating was seen for all scenarios, indicating that there is considerable scope to further reduce emissions through energy efficiency measures in homes and offices.

2.3 Review: Effectiveness of WFH for energy

2.3.1 Impact of lockdown – energy and water

Manjunath et al. (2021) reported that European Network of Transmission System Operators for Electricity (ENTSO-E) data shows total daily electricity demand dropped by between 15 and 30% during the pandemic.

Data from the UK grid, analysed by Kirli et al. (2021) clearly showed that overall energy demand decreased at the start of lockdown, compared to earlier in March 2020. This was as a result of commercial users (e.g. factories, businesses etc) shutting down. The consumption pattern also changed, as seen in the altered shape for typical times of day. Base demand dropped by 10%, whereas peak demand dropped by 20% and mean demand by 24%. Prime time peaks were less pronounced, as shown in Figure 5, e.g. morning pick-up and evening surge. In addition, the morning peak shifted to a later time (9am, compared to 8am for pre-lockdown). While the evening surge total energy decreased, the steepness of the curve increased, as a ramp of 9,500 MW occurred over 5 hours post lockdown, whereas previously the surge was smaller as it started from a higher initial value in late afternoon.

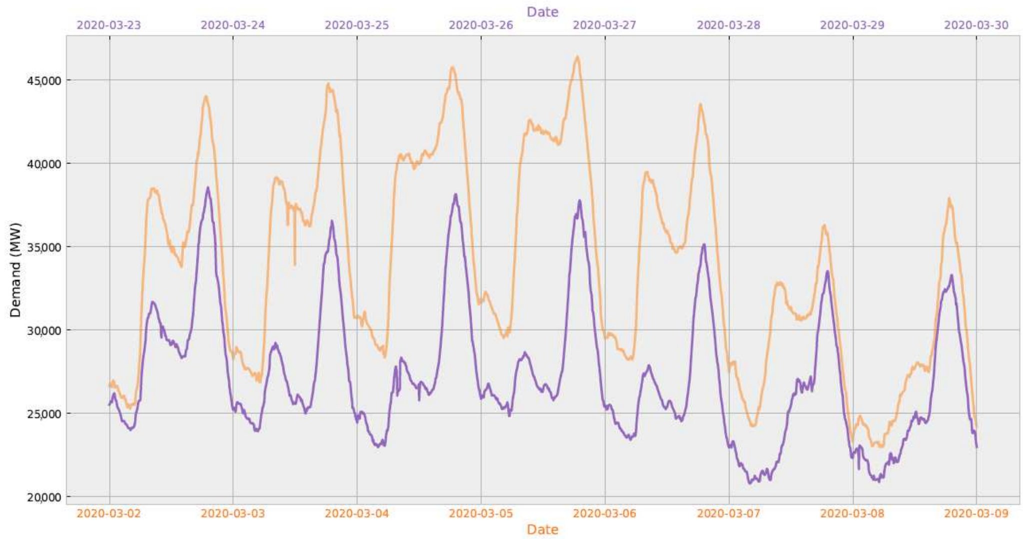

Figure 2. Aggregated system demand before (w/c 02/03/20) and after (w/c 23/03/20) the coronavirus 2019 (COVID-19) actions. Changes are observed in demand magnitude and profile with decreased demand after the lockdown.

Figure 5. Source: Kirli et al. (2021) where energy usage in early March is shown in orange, and during lockdown period in purple.

In addition, **Kirli et al. (2021) investigated the renewable energy share (RES) and found that it increased after lockdown for the UK**. Pre-lockdown RES was 25%, and after lockdown it rose to 33%, mainly as a result of decrease in reliance on generation by other energy types when total demand fell from 34GW pre-COVID to 27GW at the start of lockdown. It was commented that flexibility in the generator mix is required to be able to accommodate high generation by renewables when the conditions favour this, but to permit rapid response if renewable supply drops with change in weather or other conditions. Thus responsive systems such as biomass and natural gas are favoured compared to coal. The ranking of renewables in the merit order, and the decreased output by some non-renewable operators led to a decrease in wholesale market price. An alternative pricing system was discussed to address some of the unusual pricing effects seen within the data.

Data shared by **Dŵr Cymru revealed a net increase in water consumption during lockdown,** with the decrease in water use by non-domestic customers being outweighed by increases in water use by householders. While this is different to the picture for electricity – where industrial shutdowns in lockdown led to a reduction in total demand – interesting parallels can be drawn for the domestic components of these two utilities. One component of the presence of people in their homes is that the profile of water usage across the day became flatter, and more similar to weekends, as water using tasks could be fitted into all parts of the day not the pre-work and post-work parts of the day. This is similar to the pattern for household electricity demand.

A report by Artesia (2021) using data from all water companies across the UK reported similar phenomena UK-wide. A total demand increase of 2.6% was observed for the February-October 2020 period, during which household water consumption increased by between 9% and 13%, and non-household consumption decreased by about 25%. **Water consumption increase was strongest for the lockdown period, and returned slowly towards more normal weekday profiles as easing occurred.** Weather plays a very strong influencing role in water consumption, especially at weekends. The changes seen during lockdown weekdays were possibly partly influenced by good weather and weekend type behaviours by consumers.

2.3.2 Looking beyond lockdown – energy data

A study of energy use, by sector, in Portugal shows very clearly the overall effect of the shift from normal working to lockdown, and subsequent derestriction of various activities during 2020. Russo et al. (2021) provided data for electricity, natural gas and various liquid fuels (as used in road transport, shipping and aviation). The consumption in the first two months of 2020 was similar to 2019, but on the introduction of a stay at home order (broadly equivalent to UK lockdown) industry and many services shut down, and the population remained in their homes until end of May 2020. **This period saw a decrease in energy used by industry (12.6% less electricity and 20.3% less gas), by services (31.6% less electricity, 32.4% less gas) and transport (16.7% decrease for electricity, 8.6% less LPG, 38.2% less diesel and 31.5% less petrol). Whereas domestic electricity consumption rose by 23.2%, and gas consumption rose by 26.7%, during the lockdown period**.

However, in the lockdown period the decrease of energy use in industry and services dominates any effect of shifting the office-based workforce to their homes. It is during the later stages of 2020 where the restrictions are lifted, and during the re-tightening of restrictions at the end of the year to prevent a second wave of COVID that the working from home effect is better visible, as industrial processes remained active in these later stages (Russo et al. 2021). In the deconfinement period (June to October 2020) domestic electricity and gas use remained higher than 2019 levels, +12.5% and +14.5%, and during the new state of emergency (Nov-Dec 2020) the domestic usage was elevated as people worked from home (+8.8 electricity and +8.9% gas). **The corresponding decrease in industrial energy was minor, but services reductions were of similar magnitude to the increase seen in domestic consumption.**

2.3.3 Effect on carbon footprint or GHG emissions

Global carbon dioxide (CO_2) emissions are believed to have decreased during the period when COVID-19 control measures were imposed by governments worldwide, Jones et al. (2021) report studies estimating a decrease of 4-7% or even 8.8% from different research teams. However, this results from reductions in all sectors and a wide range of lockdown measures, not simply a shift to working from home. To assess the impact of WFH it is necessary to look to bottom-up studies calculating changes in emissions resulting from specific populations adjusting work location from office to home, or to specific phases within the pandemic.

A study of the carbon footprint of a knowledge organisation, based in three European countries with a small footprint elsewhere in Europe and Asia, was conducted by El Geneidy et al. (2021). The data gathering occurred prior to the COVID-19 pandemic, providing a useful baseline for pre-pandemic conditions. However, based on selected additional data from 2020, the authors also considered three post-COVID scenarios in which a proportion of days were still working from home, and international travel remained lower than pre-pandemic levels.

The studied organisation had three main European offices (Finland, Germany, and Spain), and Scope 2 and Scope 3 emissions were considered for all activities. Scope 2 emissions are indirect emissions relating to the activities of the organisation, while Scope 3 emissions are associated with the organisation’s activities, up or down the supply chain (for example the manufacturing emissions of a product purchased and used by staff). As it was a knowledge organisation, no direct emissions (Scope 1 emissions) were detected. In 2018 the estimated total carbon footprint of the organisation was 644 t CO_2e, equivalent to 5.135 t CO_2e per person. The dominant categories within this carbon footprint were flights (62%), heating (12%) and hotel and restaurant services (7%). Many other categories were included – even the paper, office supplies and tea or coffee consumption was accounted. Within the total emissions, 87% were Scope 3, and the remainder Scope 2.

At a country level, differences were seen between the offices of the organisation, for example the Spanish office had no CO_2 emissions relating to heating as geothermal heat was used, whereas the German and Finnish offices used district heating and oil powered heating respectively, both generating CO_2 emissions (El Geneidy et al. 2021). It is therefore important to consider the heating method and fuel mix when drawing conclusions about shifts towards WFH.

Emissions savings for post pandemic scenarios were dominated by the effect of flights and long distance trips, which had also dominated the pre-pandemic carbon footprint. In the post pandemic scenarios El Geneidy et al. (2021) considered three different quantities of reduction in travel – a 19%, 36% and 93% reduction in flights and corresponding reduction in use of hotels and restaurants, and train travel in scenario 1, 2 and 3 respectively. This was offset by a corresponding increase in use of telecommuting and internet services. Heating for the offices was reduced by 40% across all scenarios – relating to staff working from home 2 days per week. This resulted in an overall 22% reduction in emissions for scenario 1, a 34% reduction for Scenario 2, and 75% reduction for scenario 3. Within these scenarios, the proportion of emissions relating to travel remained high for scenario 1 (80%, compared to 79% in the pre-pandemic case), but decreased a small amount for scenario 2 (to 76%) and a showed significant decrease for scenario 3 (to 34%).

As a result of the study, several policy recommendations were proposed, including to reduce all unnecessary travel, reduce the number of flights and avoid premium class flights, reduce trips by car, and use train or bus for long distance travel (El Geneidy et al. 2021). Other proposals made by the authors related to carbon-offsetting.

2.3.4. Considering the WFH element within the pandemic

Manjunath et al. (2021) used electricity data to generate representative demand profiles for different phases of the introduction of lockdown measures at the start of the pandemic for four European countries (see Figure 6). This approach better captures the transition to working from home without the influence of full shut down of industry, as is seen for studies which use the lockdown itself, or the unlocking stage. However, the short duration of each transition (some periods were only a few days or a week in length) means that anomalies may exist, or that the population had not fully adopted working from home measures within that time window.

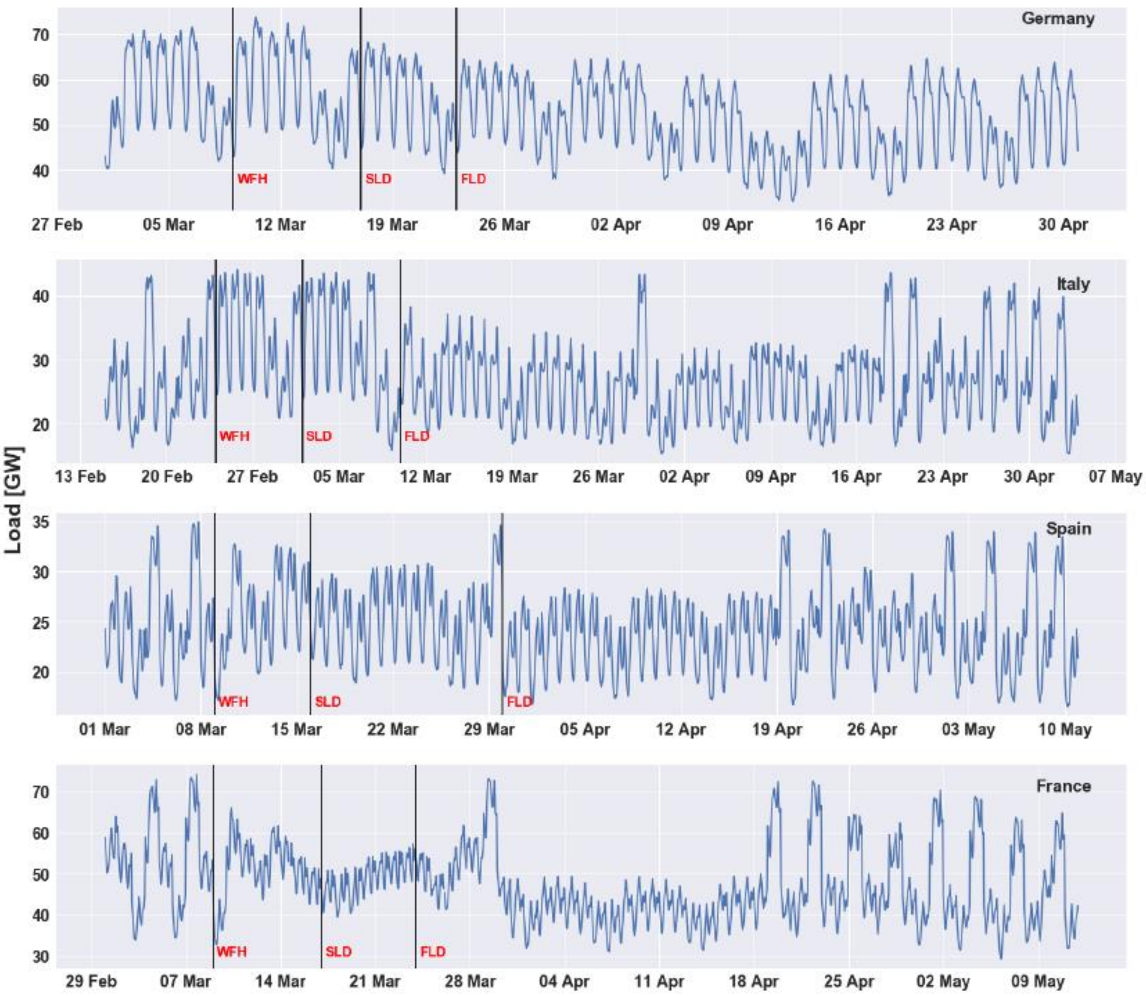

Figure 2. Timeline of the WFH, SLD, and FLD phases for Germany, Italy, Spain, and France (as denoted by the legends) with their corresponding energy demands in MW. The vertical black lines indicate the starting date of a given phase (labelled in red, adjacent to the line). For reference, see Table A1 for the starting date of each phase for each country.

Figure 6. Source: Manjunath et al. 2021, where WFH = working from home, SLD = soft lockdown and FLD = full lockdown.

The nations studied were German, France, Italy and Spain, and in Italy there is regional variation between Lombardy where the pandemic escalated earlier and the rest of the country. The periods considered were working from home (WFH), soft lock down (SLD) and full lock down (FLD). Timings of these measures vary for each country, and this was accounted for in comparing with equivalent days within the reference five years of data for that nation. Weekdays and weekends were handled separately. The outcome is a useful set of reference demand curves, showing differences in how the energy demand curve is shifted in different nations. The shape of the demand curves is altered, notably the classical working-hour peak is flattened. Time shifts in the SLD and FLD curves for weekdays are more significant for Spain and France, and least significant for Germany. The WFH curve shows a shift in France but relatively small difference in the other nations.

A study in Poland by Bielecki et al. (2021) showed a similar flattening of the electrical energy demand during the day in lockdown (16th March to 18th April 2020) for approx. 7000 dwellings in Warsaw. The study also showed that at weekends energy demand peaked near the middle of the day (2pm), as occupants were not allowed to go outside, so all entertainment or recreation had to be done inside the flats. For the weekdays, while peak demand was slightly smaller, the period of elevated demand was broader, from 8am throughout the day, before a small increase for the peak load in the evening at approx. 8pm.

Bielecki et al. (2021) went on to consider the post-pandemic scenario in which some of the increased remote working may remain. They discussed energy requirements and opportunities, for example the potential of Demand Side Response) for residential consumers to alter the timing of electricity usage to reflect pricing, and the potential for an increase in photovoltaic or other renewables within the residential sector, increasing household self-sufficiency for energy.

Manjunath et al. (2021) commented that other researchers have reviewed the capacity of European nations to shift to working digitally, and pointed out that Germany and Italy are the least suited to this transition – in the case of Germany due to the high level of manufacturing industry, and in Italy due to the lack of access to ultra-fast fibre broadband.

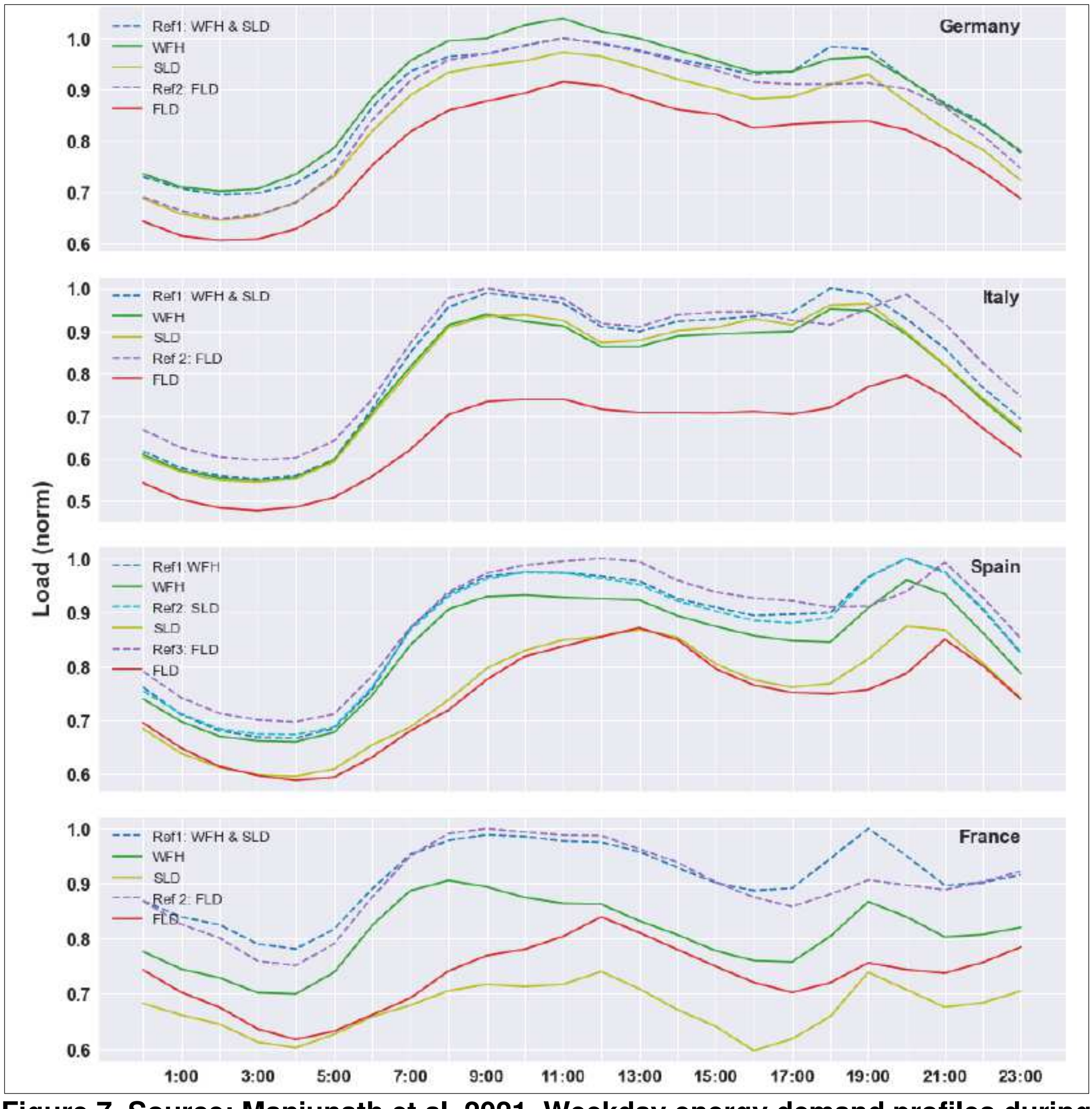

Figure 7. Source: Manjunath et al. 2021. Weekday energy demand profiles during WFH, SLD and FLD periods, along with corresponding reference profiles, for Germany, Italy, Spain and France.

2.3.3 Bottom line results for energy

While overall energy usage decreased during lockdown, it is important to recognise that this energy usage data includes additional factors such as closure of industry and manufacturing, as well as the changes in domestic consumption. However, studies have indicated that the period prior to lockdown or during easing of restrictions provides a useful dataset for investigating WFH effects.

Distinct shifts in consumption of electricity by domestic customers were seen during lockdown, for example delaying the morning peak and evening peak, while flattening the profile of usage throughout the day, to reflect the greater flexibility of times at which domestic tasks or work tasks could be done while working at home. **As restrictions eased some remnants of this flexibility of timing and flattening of the load curve remain visible while many in the population remain in WFH mode.**

Interestingly, studies in different European nations reveal a strong character relating to the typical behaviours of each population, meaning that **gathering data specific to Wales or UK could be informative for future policy or planning.**

2.4 Review: Effectiveness of WFH for travel behaviour

2.4.1 Lockdown and easing influence on travel

Bazzana et al. (2022) predominantly reported the impact of lockdown, not remote working. However, they did indicate that at the height of the ‘stay-at-home’, or ‘social distancing’ regulations in May 2020, GHG emissions in Italy decreased by 26%, on average. About half of this was a direct result of change in transport, which was in part caused by working from home.

Beno (2021) reported a study in which Austrian employees were surveyed at four points in 2020 – prior to COVID in February, during the first lockdown in March, during easing of restrictions in May and during the second lockdown in November. The proportion of employees working in cubicle offices was compared to the e-commuter population, and showed a distinct shift during first lockdown, which was not fully recovered on easing (see Table 7).

Table 7: Proportion of workers e-commuting at different stages of 2020 (source: Beno 2021).

%	Before COVID	Lockdown	Easing	Second lockdown
Cubicle workers	77.92	7.79	42.86	32.47
E-commuters	22.08	92.21	57.14	67.53

Beno (2021) also commented on transport type for commuting. Prior to the pandemic 60% of commuters studied used cars, and 22.5% used public transport, while walking or cycling was only 17.5%. The average Austrian commute takes 25 minutes. During lockdown and after the easing of restrictions, a relatively high proportion of employees were still e-commuting. The survey revealed that all commuters preferred cars over other types of transport, because of inefficiency of public transport and the fear of risk of infection with COVID-19. There was also a small shift to bicycle transport. One suggestion by Beno (2021) was that e-commuting for two days a week could offer the balance of collaborative and quiet work, while still benefiting from reduced travel time and reduced stress of commuting.

Considering the period immediately prior to lockdown, where governments began to suggest working from home where possible, without fully limiting mobility for other activities is a useful benchmark. In the study by Gonzalez et al. (2021) for Fuenlabrada (on the outskirts of Madrid in Spain), the decrease in public transport usage in the week prior to declaration of a state of alarm was 36%, and decrease in private vehicle usage was 27%. This compared to a decrease of 86% and 72% respectively for the first week of the state of alarm (equivalent to lockdown), and dropped further in the week which followed (95% and 86% respectively), which was the minimum recorded in the datasets studied. The greater decrease seen in public transport reflects the fear of infection in shared public vehicles, and would not occur in a working from home scenario outside of the pandemic, however the decrease in trips by between one quarter and one third may be a useful indicator for widespread shift to working from home.

During the de-escalation of the pandemic restrictions (equivalent to lockdown easing), partial recovery in numbers of public transport trips made and numbers of vehicles on the roads occurred, however this settled at approx. 50% reduction compared to pre-pandemic for public transport and approx. 15% reduction for private vehicles by September 2020 (Gonzalez et al. 2021).

Travel modes during lockdown were reported by Schaefer et al. (2021) who found a significant reduction in public transport use and an increase in car use and biking. Women were more likely to report that they reduced their public transport use due to the fear of catching the virus in transport facilities. The reduction behaviour was hence gendered. Additionally, income had a significant effect on substitution choices, as higher income correlated significantly with an increase of car use. Environmental concern was a strong predictor as well, showing that people who are eco-conscious switched to cycling rather than car use.

Within the private transport trips data, a comparison of time of day on weekdays, Fridays and weekends was made, and this revealed several factors. The peak hour in the morning shifted to an earlier time during the state of alarm period, possibly reflecting the type of employee for whom travel whom travel remained essential (Gonzalez et al. 2021). The peak afternoon period moved from an evening rush hour to a 2.30pm peak, with a smaller evening peak after 6pm. In the lockdown easing phase the profile of weekdays remained dominated by these three peaks, rather than returning to the pre-pandemic state. Friday trip numbers showed similar shifts, and the curves became more similar to the Monday to Friday curves for lockdown and easing stages. Trends in the public transport trip data showed a similar shift to an earlier morning peak for weekdays, however the peak between 2-3pm occurred as two maxima. Commuter train journeys remained the strongest among the different public transport modes for the morning peak during lockdown and after easing, possibly indicating the lack of alternative options for this distance of journey. However, later in the day use of commuter trains was lower than the other transport options, even during the afternoon peak and the evening minor peak.

2.4.2 Remote working and flexible working patterns

Benefits of remote working were summarised by Kylili et al. (2020) based on a textbook (Nickson and Siddons 2012) from before the pandemic. The non-environmental benefits included improved work life balance, eliminating time wasted in commuting, flexible work hours, reduction in expensive office equipment and improved geographical coverage for the organisation. Environmental benefits include reduced consumption in transport fuel and reduced CO_2 emissions. Associated with this reduction in fuel use is a **reduction in atmospheric pollutants including nitrous oxides (NO_x), particulate matter (PM) and**

volatile organic compounds (VOCs). Additional indirect benefits relate to reduced noise pollution, reduced need for land in road networks and infrastructure, reduced road congestion and savings in energy and material resources associated with the office activities.

Nickson and Siddons (2012) categorise two types of remote working – home office working (in which the employee works in their home for at least 2 days a week) and coworking (in which the employee works in a different working environment alongside other unaffiliated professionals paying a fee to use of this open plan office environment. These were used as scenarios by Kylili et al (2020) and compared with working in the office.

Prior to the pandemic, it has been estimated that if 20% of the working population in Ireland worked from home one day a week, it could result in a 3.17 ktCO_2 reduction (O'keefe et al., 2016). A study by Crowley et al. (2021) followed up on this, indicating that if all those that could work from home did so for one day a week it would result in a 1% decrease in annual emissions in the Irish transport sector, rising to 3% if all those who could work from home did so on a full-time basis.

Data from Eurostat (2019) was used by Doling et al. (2022) to present the shift towards WFH prior to the pandemic. This shows a clear shift across all EU nations, including the UK (as data related to 2005 and 2015). High growth in WFH was seen in Sweden, Finland, Denmark, Netherlands, Norway, France, the UK and Ireland. For the UK, the growth was from 8% to 22% in the ten year period to 2015. The shift was slightly stronger for men than women in the UK, and included a dramatic increase in managerial and professional roles (as was seen across all EU countries).

Similarly, Noussan and Jarre (2021) considered the impact of hybrid working (i.e. working remotely 3 days per week) in Lombardy, Italy, as many workers don't want total isolation from the workplace. If 10% of the workforce worked in this hybrid pattern, then emissions from commuting would be expected to drop by 4-17%, with higher reductions in emission if the people with the longest car-based commutes preferentially elect to work remotely.

Transport fuel usage data provided for Portugal in the lockdown and deconfinement periods of the pandemic (Russo et al. 2021) shows the decrease in international air travel very clearly, relating to restrictions on entering various countries over the period of the pandemic. Aviation fuel was significantly reduced for the lockdown period (75.9%), the deconfinement period (71.5%) and the new state of emergency period (60.6%). However, road fuel showed a larger magnitude of reduction, despite being smaller on a percentage basis. A reduced electricity usage for transport was also observed, which related to trains and subway services; these partially returned to normal during the deconfinement period.

In a study of various hypothetical commuting scenarios, Russo et al. (2021) considered the effect of a local worker using bus transport daily with a remote worker attending the office one, two or four times per month from a more distant home location. This clearly demonstrated the potential for working from home with occasional visits to the central office to reduce total transport emissions, however it did not consider other factors connected with working from home such as electricity use and heating in the different locations.

2.4.3 Travel and carbon footprint or GHG emissions

A survey of almost 500 Italians with desk-based jobs in a wide range of business types investigated a broad range of factors on the acceptability of remote working, and the travel behaviour and other environmental footprint elements (Fabiani et al. 2021). The survey results were used in several statistical analyses to determine the factors contributing to a greater acceptability for remote working – dominant among these was the distance from the workplace and the availability of additional space for working within the house. Additional factors related to comfort factors, including the total floor area of the house, the age of the structure, internet availability.

Using the survey data, cluster analysis revealed four distinct populations, classified based on distance to the workplace, and these were used in a lifecycle assessment study based on survey responses. The group who lived up to 10 km from the workplace were most likely to be not working during lockdown, or to have to continue to work in the workplace, whereas the groups at 10-40km distance, 40-80km distance and over 80 km distance were increasingly likely to be able to work from home (Fabiani et al. 2021). The carbon footprint or global warming potential for these four clusters were calculated before the pandemic, and for the lockdown period (Figure 8). The study included energy for space heating the home, energy for laptop computers, and transport emissions for commuting, transport for buying food, and transport for leisure or sports activities. The difference between pre-pandemic and lockdown showed a marked increase in proportion of emissions relating to energy for heating for all clusters. The total emissions decreased most for the cluster at the greatest distance (cluster 3 in Figure 8), and this decrease reduced for the mid- range distances, however the cluster living closest to work (cluster 0) saw an increase in emissions, as space heating effects outweighed the minor change in transport emissions.

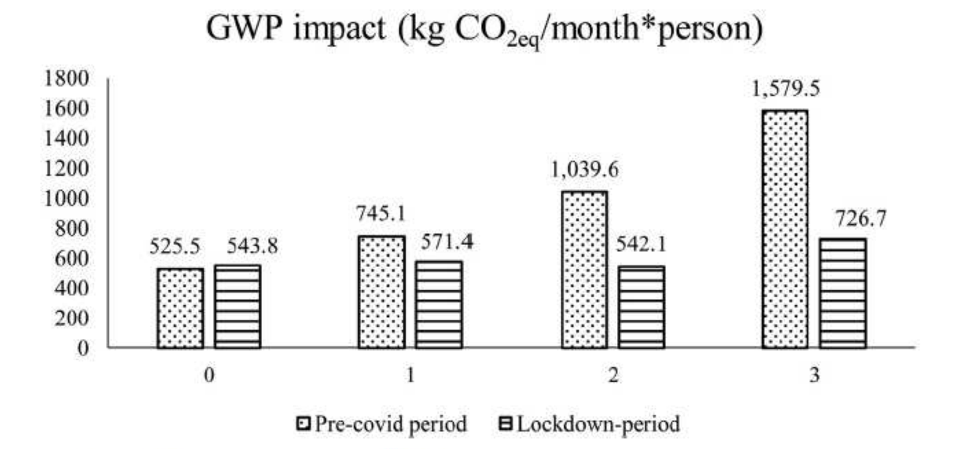

Fig. 3. GHGs emissions in "pre-COVID" and "lockdown" period for the fours examined clusters.

Figure 8. Source: Fabiani et al. 2021. Cluster 0 up to 10km from the office, cluster 1 between 10-40 km, cluster 2 between 40-80km and cluster 3 over 80km from the office.

On a percentage basis, the pre-pandemic travel dominated the cluster with the greatest commuting distance (Figure 9) but was also high for the cluster with 40-80 km distance from work (cluster 2). Both were substantially reduced by the lockdown period. Within all clusters a number of individuals still travelled to the workplace, so energy for office heating is still present in the lockdown data, but greatly reduced. The emissions relating to sports and leisure diminished, by a small amount, as such activities were restricted during lockdown or permitted only close to home. The use of these different categories permits some of the effects and factors for a more general working from home case to be visible, despite the study being conducted on a lockdown scenario. It is clear that space heating and transport remain the two largest factors to consider if seeking to understand the effect of greater telecommuting on carbon footprint.

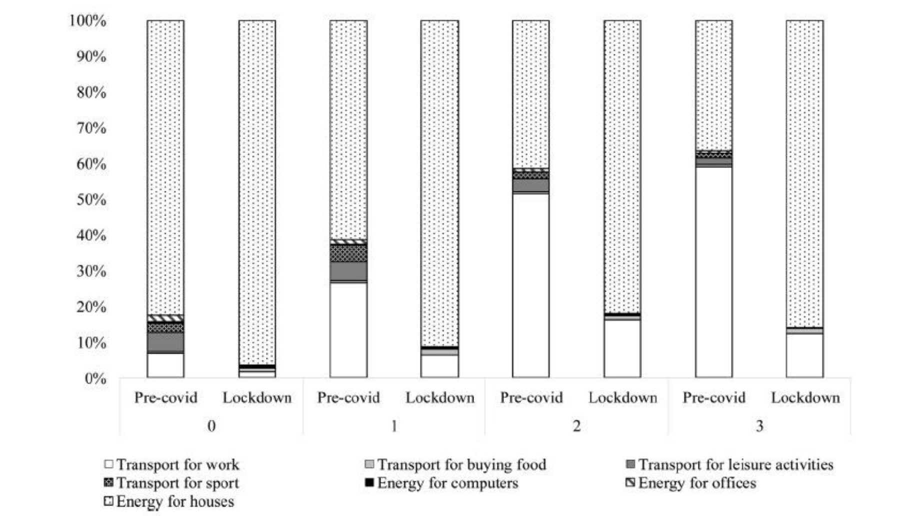

Fig. 4. Incidence of each activity on the total GWP impact in "pre-COVID" and "lockdown" period for the fours examined clusters.

Figure 9. Source: Fabiani et al. 2021. Cluster 0 up to 10km from the office, cluster 1 between 10-40 km, cluster 2 between 40-80km and cluster 3 over 80km from the office.

For a theoretical study based on university workers, Kylili et al. (2020) calculated the benefit of decreased travel in home working to be a 51% decrease in carbon emissions, whereas the same workers, if opting for co-working in remote offices the reduction in travel distance led to a 43% reduction in carbon emissions. For both scenarios the related pollutant emissions (e.g. VOCs, PM and NO_x) were all reduced by an equivalent amount, the exception was ozone depletion category of the LCA, where an increase was seen.

In Cyprus, where air cooling is a large user of electrical energy, the closure of office spaces during the pandemic led to a decreased demand for energy, during the actual lockdown period this was a 25% reduction compared to the equivalent period in 2019 (Kylili et al. 2020). At the start of the pandemic, prior to full lockdown the electricity consumption actually increased rather than decreased – this period may be more indicative of the working from home activity, but reflect the fact that offices and industry were still opening their premises despite fewer employees attending sites.

Cerqueira et al. (2020) commented that current urban travel demand forecasting practice and environmental policies rarely consider work location (in-home or out-of-home) or employment type as explanatory variables. They found that there are some complexities and limitations in the analysis of teleworking and travel. For instance, although CO_2 emissions for teleworkers and workers with multiple workplaces are mainly related to kilometres travelled for work, the findings show non-work trips also have a significant environmental impact for teleworkers. Similarly, home-based workers account for slightly higher levels of CO_2 emissions than workers with a single workplace because their non-work-related travel offsets the absence of regular commuting trips in the UK. Therefore, the comprehensive approach and findings introduced by the structural equation modelling approach calls for an in-depth discussion of GHG reduction policies.

Ellder (2020) found that in Sweden (where teleworking has been increasing steadily since 2005) those who telework all day make fewer trips than those who do not telework. Par-day teleworkers make significantly more trips than do non-teleworkers. However, the marginal effects are considerably larger for full day teleworkers compared to the part-day teleworkers.

Ellder (2020) distinguished between total travel distance (PKT) and total travel distance by car, which is a useful distinction for considering road congestion and emissions or air quality.

When it comes to total travel distance (PKT), it is clear that those who telework full days travel shorter distances than do those who do not telework. However, those who telework part of the working day travel significantly farther. But again, the marginal effects are much larger for the full day teleworkers. There were no significant differences in total travel distance by car (VKT) between those who telework and those who do not telework. The control variables have similar results as in the PKT model. Workers are also more likely to use active travel modes when teleworking full days.

They also found important differences between part- and full-day teleworking. The model confirmed that those who telework throughout the day are significantly less likely to travel during rush hour (Ellder 2020). Those who telework part of the day make trips during rush hour more often than do those who do not telework. The marginal effects are however again more than twice as large for those who telework throughout the day. Women, the elderly, low-income earners, workers without car access, and those lacking higher education are less likely to travel during rush hour

It is evident that those who telework throughout the day reduce their travel (Ellder 2020). The models show that full-day teleworkers make significantly fewer and shorter trips than do those who do not telework. We find no significant differences in VKT, but the likelihood of a non-teleworker making a car trip is higher than for a full-day teleworker. These results stand in stark contrast to those of most other studies of the last decade using similar representative data. However, we believe that this is partly because no studies concluding that telework has a complementary effect capture travel activities during the period when telework was actually performed. The analysis also showed that full-day teleworkers are more likely to only walk or cycle. This speaks in favour of the real reprioritization of travel modes and of full-day teleworking making room for more active travel.

An analysis of commute transport modes by Bieser et al. (2021) showed that some diarists in Stockholm used the same commute transport modes or switched to less energy intensive ones (e.g. from car to biking or walking) on telecommuting (TC) centre days. They did not find any indication that working from the TC centre led to a shift to more energy-intensive commute transport modes. This shows that offering workplace facilities in a local neighbourhood can facilitate use of energy-efficient transport, as telecommuters will walk and bike to work. However, if travel for private purposes was conducted when working from home, diarists mainly used the car, altering the carbon footprint of that workday. One approach to counteract such an effect would be to actively offer sustainable transport options (e.g. ride sharing, bike sharing) or delivery services to telecommuters.

Whether TC brings about net direct energy and GHG savings depends largely on TC-induced changes to (1) time spent in transport, (2) use of transport modes, (3) the substitute non-travel activities and their marginal direct energy requirements, and (4) the direct energy requirements for heating, cooling and lighting at all work locations (employers office, TC centre, and home office space). In order to increase energy-savings, corporate TC strategies should aim at reducing telecommuters time spent in transport, in particular motorized transport, and the office space required.

2.4.4 Travel types and acceptability

Although regular telecommuting reduces the number of commuting trips that workers make, the willingness of frequent telecommuters to live further from their place of work and to make more journeys for non-work purposes has led researchers from the USA to the Netherlands to question whether telecommuting practices result in fewer trips or mileage, or more than a marginal reduction in car travel at the household or even national scale (Zhu, 2013, cited by Budniz et al. 2020). Yet even a UK-based study sceptical of the sustainability of telecommuting noted that two-worker households with one regular telecommuter appear to make more efficient journeys and redistribute travel to minimise mileage (De Abreu e Silva and Melo 2018, cited by Budniz et al. 2020)

Budnitz et al. (2020) found that in England frequent telecommuters are slightly more likely to commute by train when they do go to work, take slightly greater numbers of short walks and 'other' walks per person, and a slightly higher proportion live in households with fewer cars per adult. The numbers are small, but significant.

Clark et al (2020) found that longer commute times were found to be associated with lower mental health for commuters in the UK. While females had substantially lower mental health than men, they were no different in sensitivity to longer commute times. The results also indicated that when commute time increased, job satisfaction reduced. The coefficient representing within-individual variation is significant at the 99% confidence level, indicating a robust relationship and the magnitude of effect is also quite large, at least when compared against the effect of income on job satisfaction — a 10-min increase in commute time (one-way) is equivalent to a 19% reduction in monthly income in terms of the effect on job satisfaction (on average). Working from home is shown to be associated with increased job satisfaction and leisure time satisfaction, indicating benefits of working in this way for those for whom this is possible.

Bieser et al. (2021) commented that telecommuting can change time spent on non-travel activities, which are also associated with energy requirements and energy-related emissions. Their diarists, based in Stockholm, were more frequently replaced working from the telecommuting (TC) centre for working from the more distant employer's office (EO) than for working from home. Time spent traveling on TC centre days was significantly shorter than on EO days and shortest on home office (HO) days. When diarists worked from home, they spent more time on everyday chores. Time spent on work was less affected by the work location.

Qin et al. (2021) also commented that the shift to remote working led to a conflict between travel substitution effects and travel generating effects. Their study considered the locations of dwellings (from highly urbanised to rural areas) and the housing type (detached, semi-detached, flats etc) as related to time spent on telecommuting use of the internet or other ICT-enabled activities such as teleservices and leisure. The mean usage hours of ICT for work was somewhat higher in rural and slightly urban areas, reflecting a trend to use ICT to allow work from more remote locations. This effect has been commented on by other studies, many out of scope, for example relating to the potential to counter rural-urban migration through improved internet access in remote locations. One example is Bürgin et al. (2021) who studied multi-location working in mountainous regions of Switzerland.

Fabiani et al. (2021) reviewed various papers relating to the acceptability of telecommuting or working from home at the start of their report on survey data and carbon footprint calculations. This included the contrasting viewpoints in the established literature from before the pandemic, split between a concept in which working from home is viewed positively as offering work - life balance and greater flexibility and job satisfaction, and a viewpoint in which remote working is seen as a high stress method of working with greater managerial demands and a risk of spill-over of work stress into home life. The papers from the lockdown period also showed a split between academics experiencing intense work overload, and those finding the new way of working boosted concentration and benefitting from the increased flexibility. A large number of papers which were rejected as being out of scope from this study reported these contrasting views, and in particular considered gender effects both on type of work and level of contribution to the household activities or child minding as co-factors in the reported satisfaction rating or stress score for working from home during lockdown.

2.4.5 Bottom line results for travel

In a similar manner to the electricity usage data, the lockdown period includes several separate but co-occurring effects. Lockdown meant that many people worked from home, but that many more were furloughed and unable to work, thus not travelling. Additionally, the whole population observed restrictions on mobility, reducing travel to essential trips only, or to highly limited quantities of leisure activities as easing began.

While restrictions were eased, a long period of working from home continued, with a variable proportion of the population also furloughed, but greater mobility for shopping and leisure activities. Traffic data is therefore difficult to use to directly assess the WFH component.

A further factor is that the occurrence of the pandemic led to a **marked shift away from public transport**, at times supported by statements by governments. As restrictions were eased, the evidence clearly indicates that travellers have been reluctant to return to public transport, with this mode of travel lagging significantly behind private vehicle usage.

The **shift away from public transport is contrary to the environmental benefits revealed by papers where the carbon footprint of public transport compared to car use for commuting is clearly demonstrated for all journeys above a very short distance**.

It is clear that short distance travel can also benefit from cycling or walking, and many telecommuters are willing to embrace this option. This is compatible with the potential of coworking at district telecommuting facilities, rather than WFH or traveling to the office.

2.5 Review: Air quality effects from lockdown and WFH

Air quality partially correlates with road traffic, so has been included in the review to capture evidence relating to this aspect of environmental footprint. However, it must be noted that other factors such as weather, agricultural activity and time of year play a substantial role in the observed data, and findings from these papers were the least conclusive of the papers reviewed, despite various news headlines published during the lockdown period.

2.5.1 Air quality measurements

Air Quality (AQ) is complex, and many factors affect the quality of the air. Anthropogenic factors include transport, economic and household activities that lead to emissions including carbon dioxide (CO_2) and short-lived climatic factors including, sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO) and organic and black carbon (also known as particulate matter (PM_x) (Weber et al. 2020). A Cochrane Review, considering interventions to reduce air particulate matter provides a comprehensive overview of the interaction of these different pollutants with health (Burns et al. 2019).

PM_{10} and $PM_{2.5}$ are considered to be generated by household wood burning and road traffic – arising from vehicle exhausts, tyre and brake wear (Falzone et al. 2021). However, the anthropogenic factors relating to these emissions are compounded by environmental factors including temperature, air movement and urban design, which all have an overarching effect on the quality of the air (Mohammadi and Calautit, 2021).

The introduction of stay-at-home restrictions, to slow the spread of COVID-19, has greatly reduced transport-related emissions. NASA (2020) and ESA (2020), for example, have shown that lockdown measures have resulted in significant reductions in nitrogen dioxide (NO_2), while the European Environment Agency (2020) found that NO_2 levels have almost halved in many major European cities. A report by the Policy Department for Economic, Scientific and Quality of Life Policies (2021) for the European Union reviewed data from available studies and summarised the domain trends as a decrease of between 30-50% for NO_2 levels during lockdown, a smaller decrease for $PM_{2.5}$ (5 to 20%) and only a marginal effect on PM_{10} levels. Ozone increased slightly. These changes were considered to be most closely linked to a change in the traffic pollutants – and it was commented that in major European cities traffic decreased by approximately 60% during lockdown.

Within Wales, Ricardo (2020) published a report for Welsh Government to consider the impacts of COVID-19 on air quality. Headline findings were that from the 16th of March 2020 (the start of recommended social distancing) NO_x and NO_2 levels decreased by an estimated 49% and 36% respectively. These decreases occurred during daytime, and were consistent with a reduction in road traffic. Ozone increased, by an average of 18%. This was due to the reduced concentrations of NO_x, which typically scavenges ozone.

$PM_{2.5}$ and PM_{10} concentrations were more challenging to interpret, due to the large variability in background contributions. Averaged values for $PM_{2.5}$ after restrictions started were higher than levels before the restrictions. However, more detailed analysis across urban monitoring stations showed a very small decrease was possible. When diurnal changes were analysed, the $PM_{2.5}$ at busy road junctions did reflect a reduction in daytime values, corresponding with reduced traffic (Ricardo 2020). A rapid evidence review by DEFRA Air Quality Expert Group (2020) reported an increase in $PM_{2.5}$ for the UK as a result of meteorological conditions during lockdown, however once combined with models to account for this, a small decrease was observed for the lockdown period.

There was a very limited number of papers directly reporting the effects of working from home on air quality, most papers referred to the effects of full lockdown on air quality, which includes the closure of industrial manufacturing and other sectors and widespread travel bans. Many of the lockdown papers focus on the reduction in road traffic and the associated pollutants (Ropkins and Tate, 2021 Wyche et al. 2021, Higham et al, 2021), however these are out of scope for this study. Fabiani et al (2021) also observed that many papers had considered the lockdown period and its effects on environmental factors such as air quality resulting from changes in industrial emissions, and changes in commuting distances or reduction of other travel activities.

The implementation of lockdown measures by governments to slow down the spread of COVID-19 has resulted in a notable improvement of air quality in many urban areas worldwide (Polednik, 2021; Hudda et al., 2020, Nigam et al. 2021) and decreases in PM_x, CO, SO_2 and NO_2 (Wang et al., 2020; Polednik, 2021; Mohammadi and Calautit, 2021; Seress et al. 2021b), however it is noted that not all pollutants were found to be reduced, notably a number of papers have shown a rise in tropospheric ozone (O_3) as an indirect consequence of the reduced emissions from vehicle traffic (Sicard et al. 2020).

Contrary to other studies, Falzone et al. (2021) found no correlation between $PM_{2.5}$ values and traffic levels as commuting and other travel activities increased during lockdown easing from 17 March to 25 June 2020 in Belgium. $PM_{2.5}$ concentrations were measured at three locations near schools, and one location for background concentration. In Belgium the first three weeks of lockdown had a 98.5% reduction in road traffic, and distances reduced by 80%, yet PM_{10} and $PM_{2.5}$ levels in Brussels and Wallonia remained at levels close to pre-lockdown (Brussels Environment data and ISSeP data cited by Falzone et al. 2021). When air quality sensors were deployed near schools in Arlon, a small increase in $PM_{2.5}$ was observed, despite a strong reduction in traffic early in lockdown, this is likely to relate to other factors not covered by the study. Small increases in $PM_{2.5}$ were seen with each stage of unlocking, however there was no correlation overall between traffic levels and $PM_{2.5}$

concentrations. This study highlights the fact that traffic is only one component within the $PM_{2.5}$ for European cities, pollen, agricultural activities and heating also contribute to this category of fine particles. Additionally, readings of $PM_{2.5}$ are highly dependent on where the monitors are installed and how close they are to sources, such as heavy urban traffic. The researchers recommended further studies at other times of the year to eliminate the effects of agricultural influences.

Vajs et al. (2021) considered neural networks for improving the quality of data from low cost air quality sensors by adjusting for temperature and relative humidity effects. When deployed during lockdown in Belgrade (Serbia) they observed a remarkable decrease in NO_2 but that carbon monoxide and PM_{10} were constant or slightly higher. They commented that similar effects on these three variables had also been reported for Novi Sad (Serbia) and Florence, Pisa and Lucca (Italy). The CO and PM_{10} values can be influenced by household heating and industrial heating plants as well as traffic.

2.5.2 Air pollution and commuter health

Giallouros et al. (2020) considered whether walking and cycling should be avoided for respiratory health reasons on days with elevated levels of fine particles ($PM_{2.5}$). They considered that in all of the cities studied (Helsinki, London, Warsaw, Sao Paolo, Beijing and New Delhi) everyday walking and cycling was beneficial for health, and that avoiding walking and cycling on high air pollution days did not lead to better combined health in any cities. In contrary, in Beijing and New Delhi avoiding walking and cycling on high air pollution days could decrease physical activity benefits more than it would decrease air pollution risks, leading to net health loss.

Additionally, in survey about Sicilian attitudes to travel after the pandemic, Campisi et al (2020) found that respondents who supported remote working were 4.2 times more likely to raise their cycling frequency than respondents who were neutral to the idea of remote working. Negative effects were also observed, for example in people who were reluctant to use public transport before the pandemic were likely to reduce cycling frequency after the pandemic.

2.5.3 Air pollution and the interface between outdoor and indoor environment

In the rapid evidence review by DEFRA Air Quality Expert Group (2020) it was commented that little is known about the indoor air quality during lockdown. They raised the question of $PM_{2.5}$ and volatile organic compounds within the home, resulting from domestic tasks including cooking and cleaning. The restrictions on leaving the house may have led to prolonged exposure to these factors. However, this is a phenomenon relating to lockdown, rather than inherent to working from home.

The possible improvement in outdoor air due to the reduction in anthropogenic factors has also influenced indoor air quality in the urban environment. Mohammadi and Calautit (2021) investigated the impact of ventilation, urban canyoning and thermal stack effect on the movement of pollution (specifically PM_x) from the outdoor environment to the indoor environment. The paper models the effects of urban canyoning between two buildings on either side of the movement of road derived pollutants. The paper highlights that non-pollutant factors have a negative effect on the indoor air quality of both upstream and downstream buildings. If this paper is considered within the work of Polednik (2021) and the conclusion that the concentration of traffic-related particles were over 5-times lower than pre-lockdown value it can be derived that the internal air quality of urban-buildings would have increased through the lockdown, however as previously mentioned the work of Weber et al.

(2020) these changes returned to pre-COVID levels 'very rapidly' after the lockdown had been lifted.

The indoor environment became increasingly important during the lockdown, and studies considering the home working space were numerous, but out of scope for this study. One set of work addressed a combination of ventilation, window opening behaviour and indoor soundscapes for dwellings in the UK and Italy (Torresin et al. 2021a). The primary difference between dwellings was the availability of air cooling systems in Italy, compared to window opening in the UK. A perceived importance of dominance of building services in the indoor soundscape, as compared with natural ventilation, which was found to be preferable in a second study by the same team (Torresin et al. 2022). The use of natural ventilation was seen as preferable for reducing GHG emissions (compared to air conditioning), however levels of outdoor noise or air pollution could limit uptake of this option (Torresin et al. 2021a). It was observed that the shift towards working from home in the post-pandemic era is likely to make building occupants differently vulnerable to acoustic conditions at home and more demanding of high-quality acoustic environments (Torresin et al. 2021b).

Indoor air quality, thermal comfort and available space were also investigated by Salamone et al. (2021a) in a survey of Italian civil servants adjusting to WFH in April-May 2020. More than half were satisfied or very satisfied with the home working space, and indoor air quality satisfaction was high. Salamone et al. (2021b) used a web-based survey of 330 Italian employees to see how they perceived the indoor environmental quality of residential spaces when WHF. Indoor air quality assessed by a question with responses of "not smelly, slightly smelly, smelly or very smelly". Most respondents were 'satisfied' with their indoor environment 74% for visual comfort 68% for acoustic quality and 81% for indoor air quality. Layout of furniture negatively influenced the WFH experience. Visual comfort was the most relevant variable that affected productivity.

2.5.4 Bottom line results for air quality

Air pollution papers relating to the pandemic predominantly referred to the lockdown period, meaning that it is difficult to infer precise trends for the WFH component. This is exacerbated by the complexities of air quality monitoring and the interaction with weather, wind speed and location of monitoring equipment.

However some useful considerations arise from the studies presented, including the influence of outdoor pollutant levels on indoor air quality when WFH, and the highly subjective question of perception of acceptability of indoor air – relating to stuffiness or level of ventilation. Another factor of interest if promoting WFH measures is the conflict between both natural ventilation (window opening) or air conditioning and noise factors, depending on location.

One study considered the range of levels of PM pollutants in six major cities and concluded that even on high pollutant level days, the health benefits of cycling or walking outweighed the disbenefits of the PM inhalation.

2.6 Effectiveness of working from home for reducing GHG emissions

It is clear from the LCA analysis, and from comparable studies within the reviewed papers, that a small or medium reduction in carbon emissions can be achieved through increased working from home.

The magnitude of the change seen depends on several factors, and further studies are advised to address these.

Greater reductions in GHG emissions were seen for car travel than train travel, and it could be assumed that bus, subway, tram etc would have benefits more similar to the train example than the car example.

The benefit in terms of space heating switch off will only be observed if the office is fully closed, as was the case during the lockdown period. This may also be the case where an organisation moves fully to remote working, or greatly reduces the area of office space at the central location.

Studies which used a mix of home working with some days in the office tended to report lower GHG reductions. This is because the office is still heated, even for a lower number of employees on site per day. If a benefit is to be observed in this flexible working mode, the office arrangements such as number of available hot desks or change in total floor area needs to be properly evaluated.

Some studies reported the complex interaction between journeys made by people on days when they are working in the office, and journeys made on days working from home. Some displacement of travel from work-related to travel for domestic chores or to leisure travel is observed. This means that while model scenarios show a strong decrease in emissions relating to WFH, studies based on participants reported behaviour or diaries are likely to indicate a more complex picture.

The LCA study conducted by the team used averaged data representing the full range of dwellings and offices, with a wide range of thermal efficiencies (i.e. equivalent to full range of energy performance certificate ratings). In specific cases, it may be that a dwelling has particularly poor EPC while the office is more energy efficient, or vice versa. A more detailed analysis would be beneficial.

Overall, the dominance of space heating and travel within the carbon footprint of working is very clearly demonstrated by all reviewed LCA studies. Therefore any improvement in energy efficiency of buildings (home or office) will assist in reducing the GHG emissions – and such measures should continue to be promoted in addition to any shift towards WFH or flexible working.

3. DISCUSSION

3.1 Summary of the findings

3.1.1 GHG emissions from LCA and from review

The high-level LCA study clearly showed a reduction in GHG emissions when moving to working from home, compared to an office working scenario with car commute. The benefit for train commute was more muted, but significant benefits in other environmental indicators were seen for this scenario.

It is clear from the LCA study, and from other papers discussed in the rapid review, that **energy for space heating (both at home and in the office) and transport dominated the GHG emissions profile**. There is therefore scope to address these through other means – such as improving energy efficiency of houses or altering the energy consumed by road travel. A switch to public transport compared to private vehicle use is also beneficial.

There is considerable scope to investigate further, for example a switch to part-week working from home or flexible working. However, studies using primary data would be advised to investigate reported complexities, such as a displacement of travel from commuting to other forms of travel by those who are working from home, or the possible trend to travel further due to relocating to more remote or rural locations with the rise of e-working.

3.1.2 Energy from review

Data reporting the change in energy usage by domestic customers from the UK and other EU nations indicated a flattening of demand throughout the day, but an increase in energy consumption with working from home.

The increase in energy for WFH can be offset by a decrease in energy used for heating office areas, in a lockdown scenario. In a post-COVID working scenario the magnitude of benefit relating to displacement of energy from the workplace to the home for remote working depends on whether the office premises are shut completely, or some reduction in floor area and space heating of the workplace occurs, for example if a smaller number of hot desks are provided for workers working part of the week in the central office.

3.1.3 Transport from review

Transport is a significant portion of the GHG emissions of commuting to work, and its dominance increases where private vehicles are used, or where long distances are travelled.

Some studies reported changes in traffic levels relating to lockdown, but it was possible to extract information about the working from home component through evaluation of the pre-lockdown shift to WFH where possible, or the period of easing after lockdown.

Other studies used model data or bottom-up calculations of distances and transport modes to derive typical GHG emissions values and indicate the benefits of shifting to fewer commutes per week, or to different modes of transport, such as passenger trains (long distances) or buses.

However, it is clear that **the pandemic has had a detrimental effect of willingness to travel by public transport,** which will have had a negative effect on GHG emissions, with many commuters using private vehicles to reduce infection risk where commuting resumed as restrictions were eased.

3.1.4 Air quality from review

Air quality is reported to have been affected by the lockdown period, but **no studies have directly evaluated the WFH component of this.**

It does appear that traffic-related emissions were a significant component within the reductions reported for Wales and the UK, so a future trend towards WFH could be associated with a reduction in NO_x and $PM_{2.5}$. However, further study is required to confirm this.

3.2 Limitations of the available evidence

Limitations of the evidence base for this rapid review came from two sources.

Many reports, scientific papers and grey literature have considered the lockdown period (including furlough, industrial shut down and closure of much of the service economy) rather than directly accessing the working from home component of the behaviour change due to the COVID control measures. This was particularly the case for the air quality studies, where even studies during full lockdown contained only mixed or weak trends within data.

Secondly, a general paucity of scientific studies reported in peer reviewed journals was found to date. This may be improved by further widening the number of countries accepted for inclusion within the study, however such a move would further increase the need to critically evaluate the similarities and differences in climate, population behaviour and wider economic context of the country in question compared to Wales and the UK. Trends in air quality for example may have been considerably larger in areas with higher initial air pollution levels, but not reflect the magnitude of changes expected for a nation such as Wales for change in traffic levels. As a second example, countries with warmer temperatures and a greater reliance on air conditioning for cooling, rather than space heating would reveal different energy trends on a move to WFH.

The decision to limit the countries covered by this study to the UK and those within the EU-27 appears a reasonable decision. Both to ensure the context for trends reported is understandable, and that the differences from UK conditions (environmental, economic or social) are within reasonable levels to allow parallels to be drawn.

In terms of evaluating GHG emissions reductions relating to WFH, it is clear that energy and travel emissions can be reduced through changes towards WFH or flexible working, and through related measures such as switching mode of transport. However, the interactions between transport options, distances, energy efficiencies, and office or workspace occupancy levels are complex. Further studies exploring these scenarios is greater detail, and using primary data are needed.

3.3 Implications for policy and practice

The COVID-19 period has provided a unique opportunity, prompting widespread switch to remote working in a very short space of time. It has been demonstrated that many workers can work from home, or work remotely for a portion of the week. Therefore, it is possible to consider the wider usage of remote working for post-pandemic policy, such as to reduce GHG emissions or to reduce road congestion or air pollution.

The studies reviewed by the team, and the high-level LCA both indicated that transport emissions and space heating energy were the dominant components of office working. It was also clear that savings could be made in both areas, with the magnitude of the saving relating to the type of transport avoided, or the specific details about heating required in the home and the office.

The information gathered does indicate that GHG emissions savings can be made through reducing commuting by working from home, or through switching to less emitting forms of transport. However, studies also indicated that some complexities and competing effects may arise, as workers displace travel for one part of their like (commuting) into other activities such as household chores or leisure. Further investigations using primary data re therefore advised.

For the energy component of the GHG emissions relating to remote work there are also complexities relating to occupancy levels or how fully the company or organisation switches their way of working, and whether this is associated with reduction in total space heating required at the company offices. Further investigation is therefore advisable before drawing conclusions based upon a lockdown where many business premises were fully closed.

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5. RAPID REVIEW METHODS

5.1 Eligibility criteria

	Inclusion criteria	Exclusion criteria
Participants	Environmental criteria	
Settings	The home and the office	
Intervention / exposure	Working from home Flexible working (including telecommuting, e-working, remote working)	Mobile working where this means travelling to clients or patients.
Comparison	Working as normal before the pandemic (predominantly office-based roles)	
Outcomes	Greenhouse gas emissions Energy-related component of GHG emissions Travel-related component of GHG emissions Associated effects e.g. air quality and water	Wildlife Waste Food
Study design	Use of the early, mid or late stages of pandemic control measures to evaluate changes in GHG emissions relating to working in different locations	Full lockdown (where changes in industrial activity are likely to mask the effects of working from home)
Countries	UK/GB/England/Wales/Scotland/Northern Ireland Republic of Ireland EU-27	Rest of the world
Language of publication	English	
Publication date	1 Jan 2020 to 17 Feb 2022	
Publication type	Published and preprint scientific literature Grey literature	

5.2 Literature search

The literature search within this study was carried out using Web of Science (WOS) and records were exported to Excel for further analysis. The filtering process used Python routines to interrogate the Title, Abstract, Keywords or other fields of the WOS records.

The date range covered for the WOS search was 1st January 2020 to 17th February 2022.

Search terms for extracting the three over-arching sets of papers (flexible working, pre-COVID and working from home (WFH)) from WOS were shown in Table 1 (in Section 2.1).

Clouds of keywords were generated to cover as many aspects of the environmental attributes as possible. These were tested and refined to maximise the usefulness for the parameters of the review topic, and to eliminate words which had a prolific usage for unrelated reasons. A python script was used to interrogate the title and abstract within the WOS records to identify keywords. A matrix of correlations (i.e. co-occurring keywords) was also generated to provide information on frequency and combinations which occurred within the set of papers searched.

The keyword search strings used in the final sets for this study for the five broad topics are listed below. Within Python all strings were converted to lower case and compared with extracted data, which was also in lower case, to minimise issues with capitalisation.

Air quality:
key=['Air quality', 'air pollution', 'traffic pollution', 'pollutant', 'IAQ', 'Indoor air quality', 'Outdoor air quality', 'air-quality', 'ppm', 'ppb', 'concentration', 'formaldehyde', 'HCHO', 'NOx', 'NO2', 'VOC', 'VVOC', 'SVOC', 'TVOC', 'Volatile organic compounds', 'dioxide', 'monoxide', 'CO2', 'SO2', 'nitrogen', 'gas-phase', 'gas phase', 'humid', 'ventilation', 'atmosphere', 'atmospheric', 'troposphere', 'tropospheric', 'hydrocarbon', 'submicron', 'ultrafine', 'HVAC', 'POM', 'Particulate', 'organic', 'Emission', 'CO2 concentration', 'Particulate matter', 'PM2', 'PM10', 'PM1', 'ozone', 'O3', 'aerosol', 'particle', 'molecular', 'molecule', 'Ambient air', 'Ventilation', 'air circulation', 'air conditioning', 'air flow', 'haze', 'smoke', 'respiratory', 'gases', 'gaseous', 'inhalation', 'inhale', 'Air changes per hour', 'radon', 'Airborne', 'Fine particulate', 'Smog', 'Fly ash', 'Gaseous contaminants']

Energy:
key=['Energy', 'Heating', 'Housing', 'Energy consumption', 'Household energy', 'workplace', 'Office', 'Domestic', 'energy-related', 'Electricity demand', 'Electric', 'Coal-fired', 'Gas-fired', 'power station', 'Power', 'Natural gas', 'Fuel', 'Oil', 'photovoltaic', 'Insulation', 'insulate', 'retrofit', 'thermal efficiency', 'Biomass pellet burner', 'thermal', 'geothermal', 'heat pump', 'Renewable', 'Solar', 'Wind', 'Grid', 'kWh', 'TWh', 'tera watt', 'terawatt', 'GWh', 'Gigawatt', 'giga watt', 'fuel bill', 'Renewable energy', 'Energy load', 'energy demand', 'space heating', 'heating and lighting', 'cooking', 'occupant', 'inhabitant', 'dwelling', 'residence', 'residential', 'supply', 'burden', 'infrastructure', 'cooling', 'air conditioning', 'battery storage', 'battery', 'batteries', 'array', 'power interruption', 'power outage', 'voltage', 'wattage']

GWP:
key=['emissions', 'greenhouse gas', 'CO2', 'dioxide', 'monoxide', 'GWP', 'GHG', 'global warming', 'lifecycle assessment', 'LCA', 'EPD', 'reductions', 'transition', 'net-zero', 'low carbon', 'carbon footprint', 'hydrocarbons', 'ozone', 'O3', 'O2', 'NOx', 'NH3', 'NH4+', 'HCHO', 'SO2', 'sulphur','sulfur', 'oxidation', 'mitigat', 'climate change', 'abatement', 'intensity', 'anthropogenic', 'offset', 'extreme weather', 'kyoto gases', 'radiative forcing', 'environmental']

Travel:
key=['Commute', 'Car ', 'Traffic', 'Public transport', 'Train', 'Bus ', 'buses', 'Tram', 'Underground', 'Tube', 'Rail', 'Pedestrian', 'workplace', 'Commute', 'distance', 'transport network', 'transportation network', 'Bus passengers', 'Commuter', 'Road traffic', 'road noise', 'traffic noise', 'traffic-related', 'trunk road', 'motorway', 'freeway', 'dual-carriageway', 'dual carriageway', 'autobahn', 'urban', 'suburban', 'rural', 'airport', 'Rail passengers', 'Travel', 'Transport', 'Commuting', 'Mobility', 'Vehicle', 'Vehicle ownership', 'Bicycle', 'Cycle to work', 'biking', 'cycling', 'pedestrianised', 'highway', 'Cycle lanes', 'Pedestrianisation', 'Outdoor dining', 'E-bike', 'E-bicycle', 'Scooter', 'E-scooter']

Water quality:
key=['water', 'water-quality', 'pollutant', 'Pollution', 'polluted', 'Organic pollutant', 'toxic', 'ecotoxicity', 'hazardous', 'run-off', 'Fish', 'Water quality', 'Effluent', 'Sewage', 'Waste water', 'waste-water', 'wastewater', 'water-ways', 'sulfur', 'sulphur', 'nitrate', 'ammonia', 'NH3', 'nitrite', 'NH4+', 'Eutrophication', 'Oxygen demand', 'BOD', 'TOD', 'AOD', 'dispersion', 'suspension', 'submicron', 'concentration', 'molecule', 'compounds', 'groundwater', 'Water treatment',

'Treatment works', 'Anaerobic', 'Controlled releases', 'Greywater', 'Sediment', 'water table', 'rainwater', 'rainfall', 'hygiene', 'ecosystem', 'soil', 'polluting', 'nutrient cycling', 'Organic matter', 'Disinfectant', 'Soap', 'Aqueous', 'Plastic', 'microplastic']

Within the thematic sets of records from the keyword search step, a country search was conducted. This Python script interrogated the Title field for each WOS record to recognise countries in the text. The script reported all papers associated with a country, or with multiple countries. These were exported into worksheets within an Excel spreadsheet for the parent population of records. All papers in which no country was detected in the Title were listed in a separate worksheet to enable manual checking of the abstract for indications of the country of study. Papers relating to the UK, ROI or EU27 countries were added to the relevant country sets.

The review team manually reviewed the relevance and strength of all papers within the UK and ROI group, the EU27 group.

5.2.1 Other evidence sources

Grey literature was consulted where studies had been recommended by stakeholders, or where referred to from within the peer reviewed papers identified by the rapid review process. These provided contextual information, and in some cases filled gaps within the scientific literature, for example on the water quality question.

Several COVID review databases (L*VE COVID-19, VA-ESP) were searched and no relevant studies were identified. Additionally, the SAGE group papers were searched, and no relevant information found.

Data for the LCA exercise were gathered from national statistics and from other published UK government reports. Supplementary data, for example giving energy and environmental impact of electrical appliances, were used from scientific papers as appropriate.

5.3 Study selection process

All citations retrieved from the WOS database searches were exported directly to Excel retaining all fields of information.

Irrelevant citations were removed by keyword searches using Python to identify keywords within the titles and abstracts of the records. To assist with an intermediate evidence mapping stage in the rapid review process, the keywords were grouped into five themes to reflect areas where relevant information was anticipated: GWP (relating to GHG emissions or carbon footprints), energy, transport, air quality and water quality. This resulted in five cohorts of papers being identified, including some duplication between sets – to reflect the expected overlap between these closely connected topics.

A further screening process used Python to segregate the records by any country named in the title field, and retaining all records with no country mentioned in the title retained for manual checking. Reviewers checked the title and abstract for all papers with no country listed for relevance, while assessing indications of which country/ies their study covered. Any relevant records for UK, ROI and EU-27 countries were added to the cohort for evaluation.

Reviewers screened the titles and abstracts of records for the UK, ROI, EU27 countries for relevance and awarded initial scores to the papers by relevance (yes, no, maybe), and by strength of evidence for any trend (strong, weak, positive, negative, null). Papers ranked as ‘maybe’ include were included to allow evaluation based on the full text. Due to the time constraints of a rapid review, full double screening was not possible, however a sample of citations were double screened as a result of duplication of records between the five thematic sets. These duplicates were identified and cross-referenced by the project lead.

The papers from the five themes were combined on the basis of location to form a cohort of UK and ROI papers, and a cohort of EU-27 (excluding ROI) for study. The full texts of these papers were shared between the five reviewers for data extraction.

5.4 Data extraction

Data was extracted into text form by the allocated reviewer. Key findings, location, type of study, method of analysis and author conclusions were identified. Reviewers also noted any gaps in the study, or whether the paper addressed WFH directly or indirectly via lockdown data or other approaches.

5.5 Quality Assessment

All papers reviewed in this rapid review were from peer reviewed journals and were used on this basis.

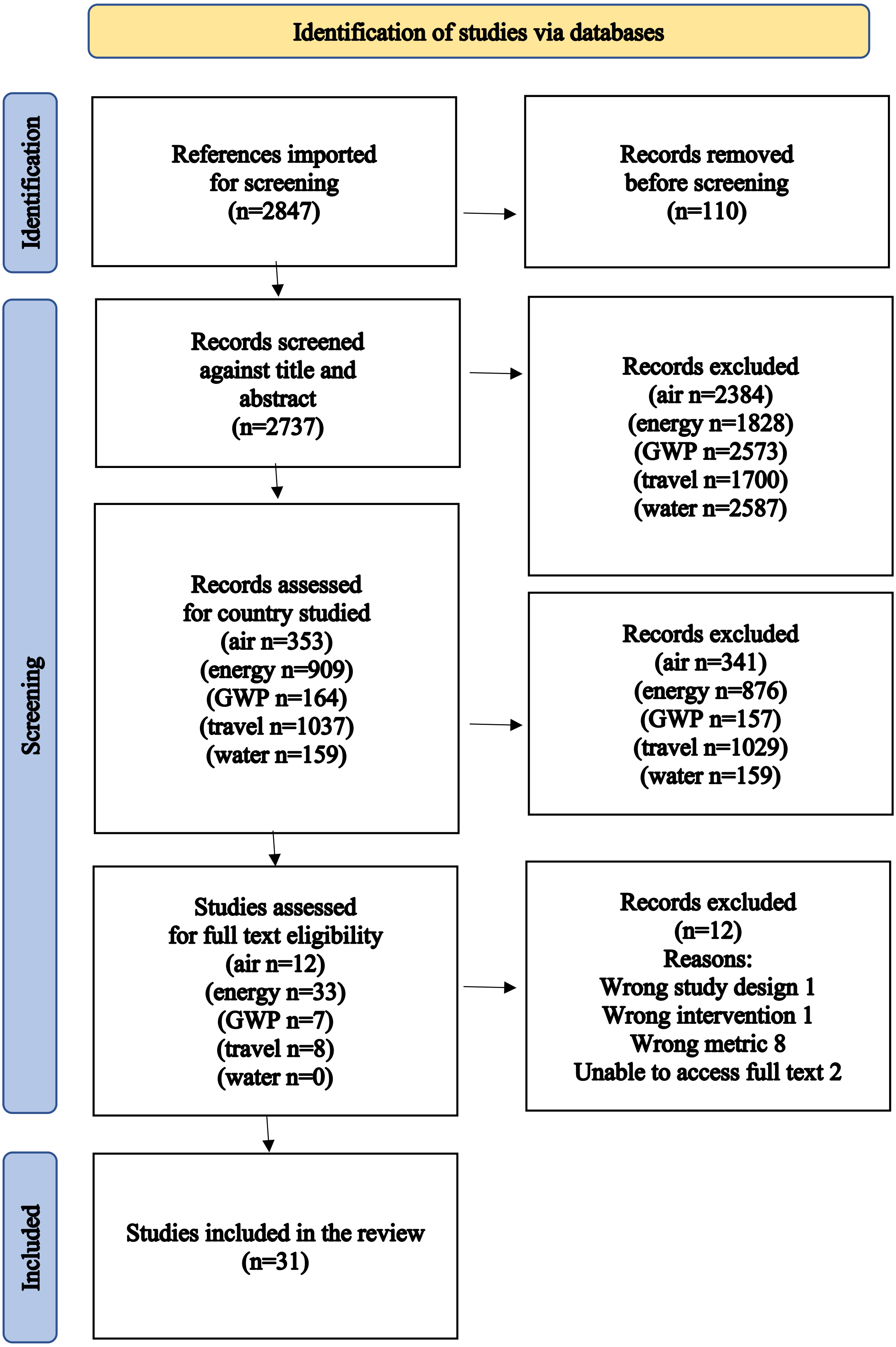
5.6 Assessment of body of evidence

Due to time constraints the rapid review section of this work (Sections 2.3-2.4) presents the original scientific paper authors' own interpretation of the quality of evidence.

The LCA exercise (Section 2.2) using secondary data (national level for UK) explored the GHG emissions for the UK context, to fill the gap identified in the available published reports for the UK. Based on comparison with the observations reported in papers from elsewhere in Europe, the results of the LCA exercise are acceptable as a high level indication of the effects of WFH as compared to commuting to an office. Further work is recommended to conduct a more detailed study using primary data to verify these findings and to explore the different effects observed in greater detail.

6. EVIDENCE

6.1 Study selection flow chart



6.2 Data extraction tables

Table 8: Web of Science search terms.

Flexible working	https://www.webofscience.com/wos/woscc/summary/2c51fba3-bbda-4f65-aadd-5cd2c13aa702-2413ee6c/date-descending/1 "hybrid working" or "at home working" or hybrid near/2 work* or "remote working" or Flexi-work* or "mobile work" or "flexible working" or "dynamic working"	821 hits	0 to 820
Pre-COVID	https://www.webofscience.com/wos/woscc/summary/a1a25e02-d131-450b-8c2b-787f791796ee-24140314/date-descending/1 work or working and pre-covid or pre-pandemic	802 hits	821 to 1622
WFH	https://www.webofscience.com/wos/woscc/summary/f5de2a0c-3b7a-4d60-95c6-0168e0f48ad7-2413bf54/date-descending/1 "working from home" or WFH or working near/2 home or telecommute* or tele-commute*	1224 hits	1623 to 2846

Date range for all searches: 01-01-2020 to 17-02-2022

For the above three streams of data, duplicates between sets are indicated below:

7 duplicates between flexible working and pre-COVID
76 duplicates between flexible and WFH
27 duplicates between pre-COVID and WFH

The numbers of papers containing keywords relating to the five themes were as shown below (duplicates between flexible, pre-COVID and WFH sets have been eliminated from sets further down the table, i.e. are only recorded at their first occurrence). However records may occur in more than one thematic group.

Table 9: Numbers of papers in each thematic group

	Air quality	Energy	GWP	Travel	Water quality
Flexible	93	311	52	324	48
Pre-COVID	79	277	40	316	44
WFH	181	321	72	397	67
All sets	353	909	164	1037	159

Duplicates between the five themes were not removed at this stage in the analysis, but quantities are listed in the matrix table below. The greatest level of overlap between keyword sets occurred between energy and travel.

Table 10: Duplicate matrix

	Energy	GWP	Travel	Water quality
Air quality	154	74	148	75
Energy		89	573	63
GWP			106	37
Travel				64

After manual checking of allocation to country of study, the set relating to the UK and ROI is as shown in the table below. Total of 13 records. Total number of records in horizontal row for All sets exceeds the total number of papers, as some papers contained multiple themes.

Table 11: Numbers of papers for UK and RPI in each thematic group

	Air quality	energy	GWP	travel	Water quality
Flexible	2	2		2	
Pre-COVID	1		1		
WFH	1	8	1	2	
All sets	4	10	2	2	0

After manual checking of allocation to country of study, the set relating to the EU27 (excl ROI) is as shown in the table below. Total of 30 records. Total number of records in horizontal row for All sets excludes the total number of papers, as some papers contained multiple themes.

Table 12: Numbers of papers for EU-27 countries in each thematic group

	Air quality	energy	GWP	travel	Water quality
Flexible	3	8	2	1	
Pre-COVID	2	5	2	3	
WFH	3	10	1	2	
All sets	8	23	5	6	0

The papers from the above two tables were then read in full to verify relevance and findings. A small number were further excluded from the set where the metric, design or intervention did not fall within scope (10 papers), or where we were unable to access the full text (2 papers).

7. ADDITIONAL INFORMATION

7.1 Conflicts of interest

The WCEC, the BioComposites Centre and authors of this work declare that they have no conflict of interest.

7.2 Acknowledgements

Personal communication with Dŵr Cymru allowed the team to have sight of unpublished reports on water consumption data, which are referred to in this document. We would like to thank Wouter Poortinga, Emma Roberts, Miranda Morton, Andrew Kibble, Lucy Corfield and members of the Welsh Government TAG Environment Subgroup for their contributions as stakeholders to this work.

7.3 Disclaimer

The views expressed in this publication are those of the authors, not necessarily the BioComposites Centre or the University of Wales.

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8. ABOUT THE WALES COVID-19 EVIDENCE CENTRE (WCEC)

The WCEC integrates with worldwide efforts to synthesise and mobilise knowledge from research.

We operate with a core team as part of Health and Care Research Wales, are hosted in the Wales Centre for Primary and Emergency Care Research (PRIME), and are led by Professor Adrian Edwards of Cardiff University.

The core team of the centre works closely with collaborating partners in Health Technology Wales, Wales Centre for Evidence-Based Care, Specialist Unit for Review Evidence centre, SAIL Databank, Bangor Institute for Health & Medical Research/ Health and Care Economics Cymru, and the Public Health Wales Observatory.

Together we aim to provide around 50 reviews per year, answering the priority questions for policy and practice in Wales as we meet the demands of the pandemic and its impacts.

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Website including report library:
https://healthandcareresearchwales.org/about-research-community/wales-covid-19-evidence-centre

9. APPENDIX

The Life Cycle Assessment can be accessed here: LCA