November 2023

Evaluation of the environmental impacts of the Superfast Broadband Programme

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Contents

Executive Summary

The Building Digital UK (BDUK) executive agency within the Department for Science, Innovation and Technology (DSIT) commissioned Ipsos and partners to undertake a final impact evaluation of the State-Aid Evaluation of the Superfast Broadband Programme. This environmental impact evaluation report accompanies the main evaluation report, which follows on from two previous evaluations of the Superfast Broadband Programme, led by Ipsos, published in 2018 and 2021. This report sets out the results of an environmental evaluation study exploring the environmental impacts of the programme in terms of carbon costs, land use and other environmental outcomes.

Where possible quasi-experimental design (QED) methods are applied, aligning with those used in the main evaluation. In the absence of QED methods, quantitative evaluation techniques using modelling estimates or benefit transfer from the wider literature are applied.

This report addressed four key research questions:

- **Research question 1:** Has the increased ability to work from home associated with the roll out of superfast broadband led to changes in travel behaviour?
- **Research question 2:** Has the increased ability to work from home associated with the roll-out of superfast broadband led to changes in domestic energy consumption, and have these been offset by equivalent changes in non-domestic usage?
- **Research question 3:** Has the increased ability to work from home associated with the roll out of superfast broadband led to land use change and associated habitat disruption?
- **Research question 4:** Has the increased ability to work from home associated with the roll out of superfast broadband led to environmental impacts through traffic disruption?

Research question 1: Has the increased the increased ability to work from home associated with the roll out of superfast broadband led to changes in travel behaviour?

This research question is explored via two approaches:

1. A case study approach to compare road traffic levels around business parks that are located near the Strategic Road Network (SRN).
2. A difference-in-difference analysis on the change in number of people that report working from home between the 2011 and 2021 Census.

Traffic levels around business parks

Traffic levels around business parks that are located near the SRN were targeted to try to reduce noise in the data as business parks are predominately single use, and road traffic data is less likely to be agglomerated with other forms of travel such as retail or leisure parks.

Using a pipeline model, estimated using fixed effects, the long timeframes over which the Programme was delivered were exploited. This enabled comparisons to be made between the levels of road traffic around business parks local to the areas that benefitted from the Programme first to those that received the intervention later. In this approach, areas receiving subsidised coverage at later stages act as a comparison group for those that receive the intervention earlier.

The analysis **failed to find any significant impact between the intervention and the level of traffic on the road around business parks.** This suggests that superfast broadband roll-out has not significantly reduced levels of commuting behaviour for those who work in a business park, by allowing residents to work more from home.

It is possible that the nature and/or type of work undertaken at business parks may not be conducive with working from home, and focusing the search on traffic levels around business parks has therefore meant we were unable to detect a significant impact on the level of traffic around business parks – as such a second approach to addressing this research question was pursued.

Change in the number of people that report working from home

Data which explores peoples commuting patterns, taken from the Census, was used to explore whether the provision of enhanced connectivity had an impact on individuals working from home and their commuting patterns, and the environmental impact of changes to commuting patterns. One of the questions in the 2011 and 2021 Census asked residents of Great Britian a question on their home address and place of work. This allowed an estimate of the distance travelled to work to be produced – or classify the respondent as someone that works from home.

It should be noted that the **ONS recommend against comparing changes in work from home behaviour** between 2011 and 2021 due to the disruption caused by the COVID-19 pandemic (and the lockdowns that were subsequently introduced). As such, **estimated impacts should be interpreted with caution**. There are also additional limitations with this analysis, set out in Section 3.3.2, which prevent the estimated impacts adopting a causal interpretation.

Changes in response to this question can be compared between the postcodes that were part of the Superfast Programme, and a set of postcodes which were identified as not being covered by the commercial plans of network providers over the next three years (white postcodes). The group of white postcodes used to compare against the treated postcodes was selected using propensity score matching, to ensure that comparisons were made between postcode areas that shared similar characteristics when the programme was rolled out. The effects of the change in work from home behaviour was estimated using a difference-in-difference framework. Assuming that the effects of national lockdowns were homogenous across treated postcodes and the matched white postcodes – the impact on home working should somewhat be held constant.

The results suggest that **the rollout of superfast broadband is associated with a 9.3% increase in work from home behaviour per treated output area**, statistically significant at the 99% confidence level. However, this result should be interpreted with caution.

Research question 2: Has the increased ability to work from home associated with roll-out of superfast broadband led to changes in domestic energy consumption, and have these been offset by equivalent changes in office energy usage?

Energy consumption data for areas that have benefitted from the Superfast Broadband Programme, provided by the BEIS sub-national energy consumption statistics, was explored to examine whether enhanced connectivity has led to changes in domestic and non-domestic energy consumption. Due to data limitations, the analysis is undertaken at two different geographical levels: domestic energy analysis is undertaken at the postcode level and non-domestic energy analysis is undertaken at the Middle Super Output Area (MSOA) level.

Using a pipeline model, estimated using fixed effects, the long timeframes over which the Programme was delivered were exploited. This enabled comparisons to be made between the levels domestic and non-domestic energy consumption for those that benefitted from the Programme first to those that received the intervention later. In this approach, areas receiving subsidised coverage at later stages act as a comparison group for those that receive the intervention earlier.

Positive statistically significant effects were detected for domestic consumption in both electricity and gas, as well as non-domestic electricity and gas consumption – suggesting that receiving superfast broadband led to an increase in energy consumption. The magnitude of the estimated impacts is presented in the Tables below.

Estimated marginal change in domestic energy consumption associated with superfast roll-out

Domestic Consumption	Estimated percentage increase per additional connection	Estimated annual increase In kWh
Urban electricity consumption	0.01%***	0.36kWh
Rural electricity consumption	0.04%***	1.3kWh
Urban gas consumption	0.02%***	2.5kWh
Rural gas consumption	0.05%***	7.3kWh

*** represents statistically significant difference at the 99% confidence level; ** represents statistically significant at the 95% confidence level; * represents statistically significant at the 90% confidence level.

Estimated marginal change in non-domestic energy consumption associated with superfast roll-out

Non Domestic Consumption	Estimated percentage increase per additional connection	Estimated annual increase In kWh
Electricity consumption	0.004%***	0.29kWh
Gas consumption	0.001%**	0.17kWh

*** represents statistically significant difference at the 99% confidence level; ** represents statistically significant at the 95% confidence level; * represents statistically significant at the 90% confidence level.

For domestic energy consumption, the results suggest that:

- **Each additional connection in a postcode leads to an increase in domestic electricity consumption of 0.1% for an urban property**; the equivalent to 0.36kWh per connection per year[1].
- **Each additional connection in a postcode area leads to an increase in domestic electricity consumption of 0.04% for a rural property**; equivalent to 1.27kWh per connection per year[2].
- **Each additional connection results in a 0.02% increase in domestic gas consumption, for an urban property**, equating to an additional 2.5kWh of gas consumption[3].
- **Each additional connection results in a 0.05% increase in domestic gas consumption, for a rural property**, this is equivalent to an additional 7.3kWh[4].

For non-domestic energy consumption, the results suggest that:

- **Each additional connection in an MSOA area increases non-domestic energy consumption by 0.004%** (equivalent to annual increase of 0.29kWh per connection to the superfast broadband network[5]).
- **Each additional connection made in an MSOA area is associated with a 0.001% increase in non-domestic gas consumption;** this is equivalent to approximately 1.68kWh of additional gas per connection to the superfast broadband network[6].

Research question 3: Has the increased ability to work from home associated with the roll-out of superfast broadband led to land use change and associated habitat disruption?

The impact of the Superfast Broadband Programme on land use was explored using the UK Centre for Ecology and Hydrology Land Cover Maps.

Untreated white postcodes were used as a comparator group for areas where the Superfast Broadband Programme had delivered connectivity. To make meaningful comparisons to the treated areas, propensity score matching was used to identify the white postcodes that can be considered similar with respect to the probability of receiving the treatment based on a set of observable characteristics. The same matching model is used as in RQ1.

A key limitation of this analysis is that due to the intensive computational nature of the Geographic Information System (GIS) work, only the pixel value of the postcode centroid can be extracted. It would be preferrable to understand the area around the postcode, and how the land use in areas of close proximity to the postcode centroid have evolved over time. As such, this analysis shows how the land use had evolved over time between treatment and comparator areas, but this cannot be directly attributed to the Programme as the land use would necessarily have to be for residential housing in order for the broadband to be installed.

The analysis shows that the percentage of pixels that are classified as urban in the treatment and comparator areas has increased between 2007 and 2020, with a larger increase in the comparator areas. However, since 2015, the land use change has been lower in the comparison group compared to the

[1] Based on median total consumption figure from domestic electricity consumption dataset, equivalised at the household level
[2] Based on median total consumption figure from domestic electricity consumption dataset, equivalised at the household level
[3] Based on median total consumption figure from domestic gas consumption dataset, equivalised at the household level
[4] Based on median total consumption figure from domestic gas consumption dataset, equivalised at the household level
[5] Based on the average consumption per non-domestic property as per the sub-national domestic electricity consumption statistics, equivalised to the individual non-domestic premises level.
[6] Based on the average consumption per non-domestic property as per the sub-national domestic gas consumption statistics.

treatment group (with the interventions starting in 2016), which suggests that **there has been more change in land use in treatment areas than comparator areas over the course of the Programme.** However, given the fact that the allocation of the treatment is dependent on the area being built, it does not fully explain the extent to which the roll out of superfast broadband *caused* the land use to change.

Research question 4: Has the disruption caused by the roll-out of superfast broadband led to environmental impacts through traffic disruption?

To explore the environmental impacts of traffic disruption, permit data (data which shows where and when roadworks were taking place to install broadband infrastructure) was analysed. Permit records provide a rich data source for the type of work undertaken to install the fibre optic cables. However, due to inconsistencies in data formatting, a limited number of traffic count points[7] around roadworks, and the labour-intensive process of manually entering permit data, a **case study modelling approach** was used to understand the congestion (and resultant carbon) costs associated with broadband deployment funded by the Programme for 52 sites. The case study approach makes use of the QUADRO (Queues And Delays at Roadworks) modelling tool maintained by Highways England. QUADRO provides a method for assessing the total cost of major road maintenance works[8].

Due to a limited sample of sites, the outputs produced by QUADRO are unlikely to be representative of all works. As such, an assumption-based approach was used to extrapolate the environmental effect of roadworks to the treatment area as a whole.

Permit data pre-2020 is not available for the purposes of the evaluation, nor is the complete permit data available post-2020. As such assumptions are used to estimate the number of permits over the course of the Programme:

- It is assumed that each postcode where new connections were made in each phase required one permit each. A total of 538,067 permits were submitted across the UK from 2013 to 2021.
- The percentage of permits that require carriage way closures, and are not considered part of routine maintenance, are then accounted for. This ranged from 10% to 1% when using the permit data from two providers – these will be treated the upper and lower bounds, which a central estimate of 5% used. This produces an estimated number of relevant permits of 28,403 (3,140 – 53,665) in the UK between 2013 and 2021.
- Next, the additionality of the Programme is considered, to account for what would have happened in the absence of the intervention. Additionality assumptions are based on the analysis in the State Aid report.[9] The analysis only covers 2017 – 2021, and so the average additionality percentage is applied to treated postcodes between 2013 and 2016. Estimated additionality rates range from 49% to 81%, which an average rate of additionality of 67%. When the additionality rates are applied the estimated number of relevant permits is 18,268. This yields the number of permits which are expected to generate £140 of additional greenhouse gasses per permit.

The total present value cost in terms of greenhouse gas emissions is estimated to be **£2.3 million (£0.3 million - £4.4 million)** over a 17 year-appraisal period (2013 – 2030).

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[7] A key parameter for QUADRO
[8] https://www.tamesoftware.co.uk/manuals/QUADRO2021_Full.pdf
[9] See section 6.2 of *Evaluation of the Superfast Broadband Programme State aid evaluation: Main Report February 2023* (2023) Ipsos

Economic Value of Estimated Impacts

The economic impacts within this report are limited only to those which indicate a change in environmental conditions, and as such does not consider the broader cost/benefits of the Programme, nor does it attempt to undertake a full cost benefit analysis. For the purposes of this analysis, the monetised impact has been estimated over a 17-year evaluation period (2013 – 2030), to remain consistent with the main report.

The table below presents the estimate economic value of the estimated impacts of the Superfast Programme, where economic costs and disbenefits have a negative value, as they reduce societal welfare.

Economic Impacts – Total Prevent Value

Economic Impact	2013 – 2022	2023-2030
Reduced greenhouse gas emissions through reduced commuting through increased **working from home**	£1,837m (£918m to £2540m)	£1,668m (£834m to £2,045m)
Increased domestic energy consumption through working from home	-£9.9m (-£4.9m to -£14.8m)	-£8.2m (-£4.1m to -£12.1m)
Increased non-domestic energy consumption associated with superfast broadband rollout	-£4.0m (-£6.0m to -£2.0m)	-£3.6m (-£5.4m to -£1.8m)
Increased greenhouse gas emissions through road works/ closures when installing cables	-£2.3m (-£4.4m to -£0.3m)	NA
Total economic impact	**£1,820m (£903 - £2,523)**	**£1,657m (£825m - £2,031m)**

Note: Table may not sum due to rounding

The results above suggest that the Superfast Broadband Programme yielded estimated present value environmental benefits that totalled £3,477m (£1,728m - £4,554m) over the evaluation period. This was primarily driven through reduced greenhouse gas emissions through reduced commuting, enabled by increased working from home (noting the uncertainty in the estimated impacts). It is important to note that key environmental impacts (e.g. land use change and associated biodiversity impacts, embedded carbon in the fibre network, etc.) have not been estimated, nor monetised and so the estimated benefits present a partial view of the economic value of the associated environmental impacts.

1 Introduction

The Building Digital UK (BDUK) executive agency within the Department for Science, Innovation and Technology (DSIT) commissioned Ipsos and partners to undertake a final impact evaluation of the State-Aid Evaluation of the Superfast Broadband Programme. This environmental impact evaluation report accompanies the main evaluation report, which follows on from two previous evaluations of the Superfast Broadband Programme, led by Ipsos, published in 2018 and 2021. This report sets out the results of an environmental evaluation study exploring the environmental impacts of the Programme in terms of carbon costs, land use and other environmental outcomes.

As highlighted in the Invitation to Tender, His Majesty's Government's recent strategy for delivering Net Zero commitments underlines the importance of understanding the environmental impacts of superfast broadband deployment. These aspects have not been addressed by prior evaluation studies and it will be important to elaborate a Theory of Change explaining the potential environmental impacts of superfast broadband deployment and develop robust empirical strategies for assessing the scale of these effects.

1.1 Approach

To prepare the environmental evaluation study, the following research tasks have been undertaken:

- A literature review and scoping study to develop a set of Theories of Change (ToC) and evaluation plan to measure the environmental impacts of the Superfast Broadband Programme.
- An inception meeting with stakeholders from DSIT to explore the key requirements and focus of the evaluation.
- A review of the availability of data to assess the environmental outcomes of the project, both internal data (held by the Programme) and secondary data sources (including exercises to explore the feasibility of collecting secondary pricing data).
- An evaluation of environmental impact of the Superfast Broadband Programme. This report focuses on the outcomes which can be evaluated using quantitative impact evaluation and monetisation techniques. These outcomes were identified in the ToC and evaluation plan. The methodology used to evaluate each of the outcomes using current and historic data has been described, where possible applying quasi-experimental design (QED) methods, aligning with those that will be deployed in the main evaluation. In the absence of QED methods, quantitative evaluation techniques using modelling estimates or benefit transfer (using information from the wider literature) have been used. Qualitative approaches to environmental evaluation have not been used. These approaches were assessed as being infeasible since for many of the outcomes identified in the ToCs, people are unlikely to be able to articulate the environmental impacts in meaningful ways.

1.2 Structure of the report

The remaining sections of this report follow the structure outlined below:

- **Section 2** presents a ToC for overarching environmental impact, and three channels of environmental impacts stemming from working from home, enabled technology and infrastructure, and sets out research questions associated with the environmental impacts of the Superfast Broadband Programme.

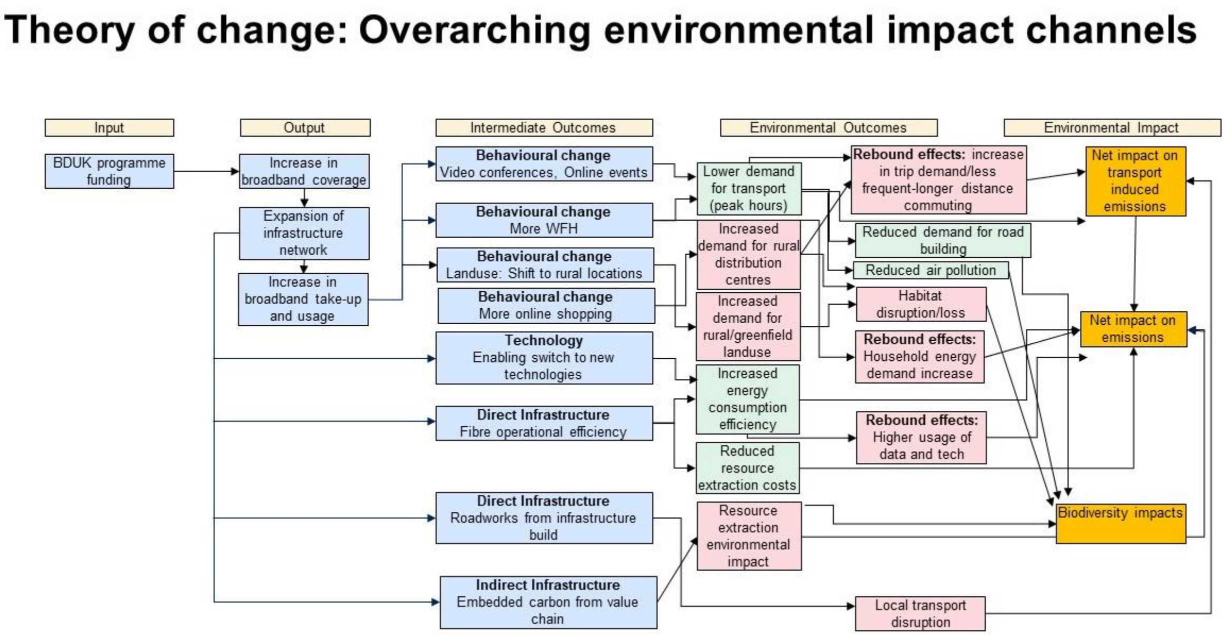
- **Section 3** presents the analysis of the data collected for each of the environmental impact channels, focusing on the more detailed set of outcomes outlined in the ToC:
    - Direct effects on the behaviour of households and firms benefitting from the Programme that can be established using econometric methods.
    - Local impacts on the behaviour of households and firms that can be established using econometric methods.
    - Impacts that will require the application of analytical analysis (for example QUADRO analysis rather than statistical modelling).
- **Section 4** presents the economic value of the estimated impacts
- **Section 5** discusses future research questions, and what an analytical framework may look like to address the questions.
- **Appendix A** provides a detailed literature review of the environmental impacts associated with the Superfast Broadband Programme.

2 Theory of Change

The Theories of Change explore three channels through which the Superfast Broadband Programme could be expected to result in environmental impacts: behavioural change, enabled technologies and infrastructure. Ipsos UK has developed this analysis by undertaking a broad literature review (detailed in full in Annex A). In particular, the Theories of Change have been developed with a specific focus on the context of BDUK interventions, which are typically located in more rural areas and businesses are often smaller. This may require in some cases a different set of assumptions relevant and logical channels than in the context of an urban location.

2.1 Overarching environmental impact channels

Figure 2.1: Theory of change: Overarching environmental impact channels



A core assumption of this report is that upgrading to faster internet speeds changes social behaviour by increasing the feasibility of working from home (videoconferencing, online events etc.), which consequently results in fewer commutes to the individual's office / workplace leading to reductions in carbon emissions and air pollution, and positive impacts on human health and biodiversity.

In the longer term this may lead to reduced demand for road transport, with an associated impact on net emissions. However, rebound effects may also exist if there is an increase in trip demand or a shift to less frequent but longer distance commuting[10], which would reduce the net impact on transport induced emissions. More working from home may also result in rebound effects in household energy consumption, with higher net energy demands across multiple households working from home, compared to the energy economies of scale in an office setting (noting that offices may not immediately close or downsize in

[10] As workers are no longer required to live as close to the office as the frequency in which they are physically in the office has reduced. See O'Brien, W. and Aliabadi, F. (2020) Does telecommuting save energy? A critical review of quantitative studies and their research methods, *Energy and Buildings*, 225(15). DOI: https://doi.org/10.1016/j.enbuild.2020.110298.

response to working from home, meaning that workers will be contributing to energy demands both at home and in the office during the period where firms adjust to increased levels of remote workers).

In the longer-term, there may also be net emissions impacts from the increased demand for rural/greenfield land away from the cities, as people are able to work from home and base themselves further from geographic clusters of offices in cities. This could have impacts on emissions, as well as habitat loss and biodiversity.

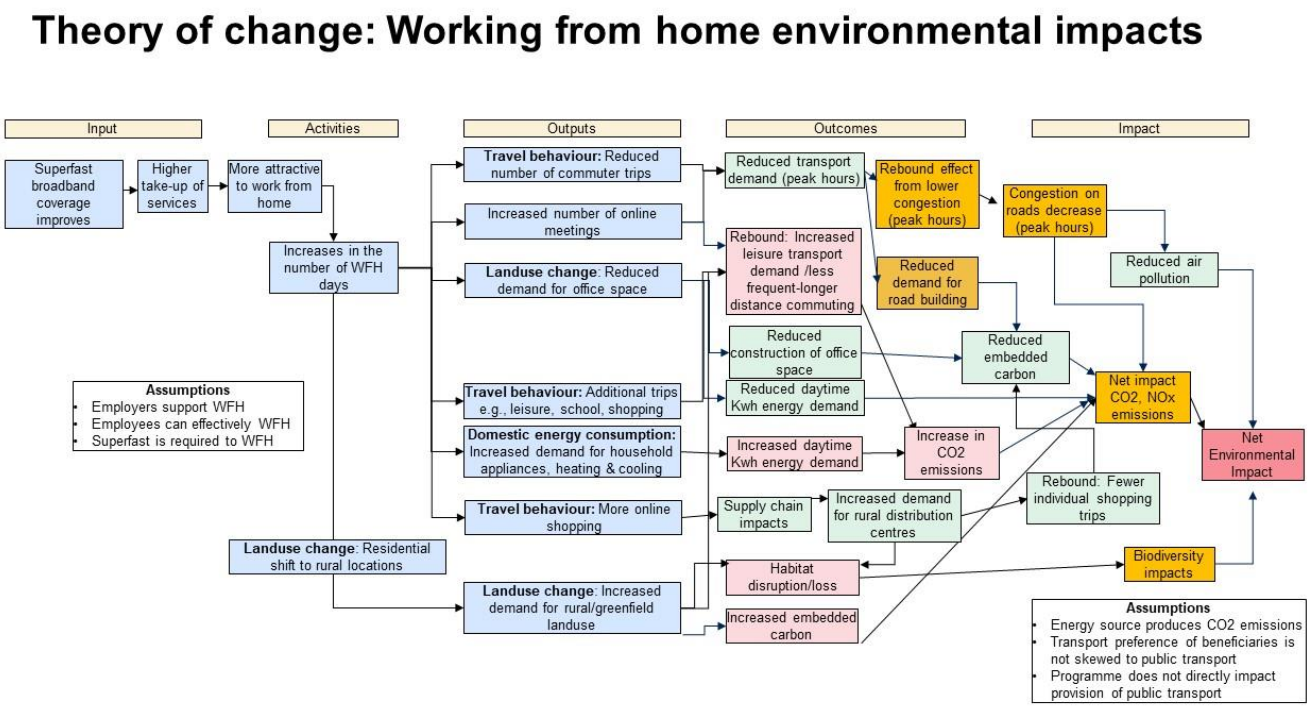
There are also emission impacts from the infrastructure works required for the installation of fibre cables, leading to local transport disruption and a negative impact on transport induced emissions in the short-term.

However, the shift to new infrastructure materials can be expected to reduce the number of repair trips (based on evidence that fibre networks require fewer repair trips than copper cable networks, and a switch to new technology (e.g., cloud computing) which has been found to be more energy efficient). However, this could lead to rebound effects if higher usage of data and technology follows, with implications for the net impacts on emissions. It is also necessary to account for the embedded carbon from the value chain.

The following section explores these three channels of working from home, enabled technology and infrastructure in more detail in the sections below.

2.2 Behavioural change: increased ability to work from home

Figure 2.2: Theory of change: Working from home environmental impacts



Improved broadband infrastructure is expected to increase the number of days that people work from home (relative to areas where internet speeds are lower). Working from home reduces the number of commuter trips (by car, as well as public transport), and increases the number of online meetings (decreasing the number of journeys required to attend meetings, including those taken by plane). This reduced transport demand leads to reduced net GHG emissions.

This is in part supported by the literature. There have been some studies based on observational data that have shown that improvements in internet access increase the rate of teleworking, but they have not made the additional link to estimating the environmental impacts. There is also a body of assumptions-based research on different scenarios of work/travel behaviour and their associated carbon emissions, (partly a consequence of the fact that large-scale working from home patterns is a very recent post-COVID-19 occurrence). Since then, ONS statistics show that a large proportion of the UK workforce has relied on working from home during the COVID-19 pandemic.[11] Superfast broadband is likely to play an enabling effect on this shift to working from home but may not have been the only driver of this broader shift in working patterns.[12] These changes in travel behaviour after introduction of superfast broadband should be detectable in changes in traffic count data to business destinations between the treatment and control areas.

There is also potential for rebound effects. Reduced congestion for commuter traffic may encourage more travel for leisure/recreational trips. More time spent working from home may also allow people to take more leisure trips, or pick up their children in the car, during the time they would otherwise have been commuting to the office. An increase in working from home may also increase the demand for household energy consumption, leading to an increase GHG emissions that would offset some of the savings in reduced trips. As above, changes in travel behaviour after introduction of superfast broadband should be detectable in changes in traffic count data to leisure destinations between the treatment and control areas.

Other potential rebound effects may relate to an increase in home delivery service use associated with people working from home. These could also have wider impacts though the supply chain if it leads to logistical changes such as greater use of large distribution centres to cater for increased demand for home delivery.

There is growing evidence that home delivery may be more efficient than multiple households going to individual shops which would all need to be individually stocked and in this way home delivery could be resulting in cutting out a step of the logistic chain. A study by Amazon (not peer-reviewed) found that US customers ordering groceries online (assuming the goods are not driven in chilled vehicles), averaged across all basket sizes, generated 43% lower carbon emissions per item compared to shopping in stores. However, these statistics depend on the nature of the physical trips: visiting multiple physical stores in one journey, or a shop on a journey they are already making, will have lower environmental impacts as a reference case. Any evaluation of these rebound effects would have to isolate those trips which directly replaces explicit trips to the shops.[13] These impacts would not be evaluable without collection of primary survey data among employees who work from home and those who do not. It may be possible to link travel behaviour along those roads which connect distribution centres and compare the changes in number of trips before and after broadband roll-out in the treated vs control areas, but this is speculative and beyond the scope of this study.

The impacts of home working on household and office energy consumption may be able to be accounted for through changes in home working emissions, energy use from office equipment, and home heating

[11] https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/bulletins/coronavirusandhomeworkingintheuk/april2020

[12] https://committees.parliament.uk/committee/460/covid19-committee/news/156095/covid19-and-employment-in-towns-and-cities/

[13] Based on figures from Ocado and Sainsbury's, Atrato estimates that the journey time for delivery vans travelling from central distribution centres – including via the 'spoke sites' – to the end customer takes between one and two hours. By comparison, store pick fulfilled journeys typically only take 25 to 45 minutes, meaning far less road time for the delivery vehicles per customer. Furthermore, vans from CFCs make on average two drops per hour, versus the four made by those carrying store-picked baskets

and cooling which would not have occurred in an office-working scenario, defined as the incremental energy change from homeworking. A detailed methodology is outlined by the EcoAct Homeworking Emissions Whitepaper[14] based on estimated emissions, and this informs the methodology in Section 3.3.

The demand for more working from home could also lead to land use changes if people are encouraged to live further away from urban centres (where offices have historically clustered). This could create pressure to develop greenfield land (leading to habitat and biodiversity loss) and bounce back effects, if people are commuting less often, but having to commute further due to their changed land use options.

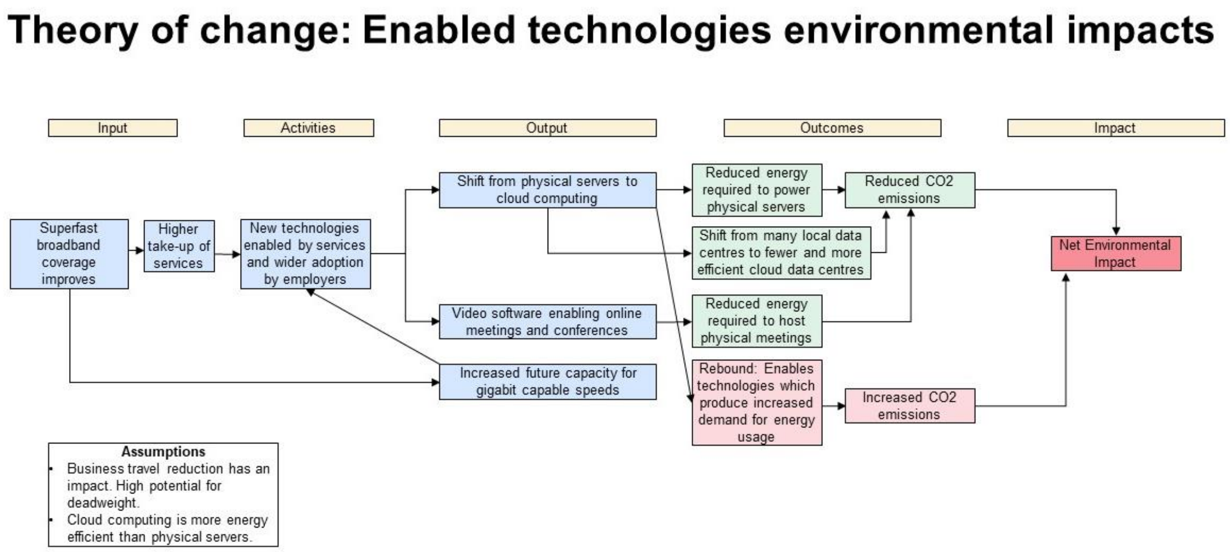
Other longer-term outcomes (outside of the scope of this evaluation) include a reduction in demand for road building, as well as reduced demand for office space, leading to lower environmental impacts in the embedded carbon used to construct roads and offices.

The environmental impacts associated with the increased ability to work from home enabled by superfast broadband roll-out are summarised in the following research questions:

- **Research question 1: Has the increased ability to work from home associated with roll-out of superfast broadband led to changes in travel behaviour** (congestion, trip volumes, and traffic volumes, as well as rebound effects on leisure travel and home deliveries)?
- **Research question 2: Has the increased ability to work from home associated with roll-out of superfast broadband led to changes in domestic energy consumption**: Through increased demand for household appliances, heating & cooling - and have these been offset by equivalent **changes in office energy usage**?
- **Research question 3: Has the increased ability to work from home associated with roll-out of superfast broadband led to land use change:** Increased demand for rural/greenfield land use (likely to be longer term and not detectable within this evaluation)?

2.3 Enabled technology

Figure 2.3: Theory of change: Enabled technologies environmental impacts



[14] https://info.eco-act.com/hubfs/0%20-%20Downloads/Homeworking%20emissions%20whitepaper/Homeworking%20Emissions%20Whitepaper%202020.pdf

As firms obtain access to faster and more reliable networks, it is expected that there will be a trend away from physical servers to more efficient cloud computing. Evidence from the literature shows that there has been, and continues to be, a shift towards cloud computing evidenced by trends in cloud computing uptake in the Cisco (2018) report. While the efficiency of cloud computing is somewhat backed up by the literature, this remains a nascent topic of academic study, and there are few sources from which to draw confident conclusions on the energy, cost, and environmental savings that may be borne from greater cloud computing adoption.

Currently, the literature review suggests there is evidence from several sources that cloud servers are more efficient compared to physical servers and therefore likely to reduce the impact on the environment through lower CO_2 emissions. Google estimates that switching from physical servers to cloud based servers can reduce energy consumption by 68 to 87 percent. An additional factor also to consider is that Google powers its computing infrastructure through renewable energy and also commits to net zero sustainability targets. Therefore, businesses switching to cloud computing will reduce their CO_2 emissions by 68-87% or where cloud providers use renewable energy, this could be up to 100%.

Note, however, that there could be potentially negative environmental outcomes if higher data demand for cloud computing enables certain technologies which produces a rebound effect resulting in higher net energy usage. This kind of rebound effect is characterised by the 'Jevons Paradox', referring to a situation in which an efficiency improvement leads to an even greater proportionate increase in total demand, with the result that resource requirement goes up rather than down, as is often assumed. When energy efficiency is improved, the available energy becomes more productive and therefore more valuable, leading to increased use.[15] This is because any energy saved bounces back as additional energy elsewhere, either because: 1) efficiency makes the use of the resource cheaper (e.g. cloud storage of more data than with traditional file storage), 2) the savings are spent on other activities with a carbon footprint, 3) lower resource use leads to lower prices which increases demand for the resource elsewhere, or 4) knock-on effects in other areas of the economy (see Berners-Lee and Clark, 2013[16]).

There are also benefits in terms of future capacity, since superfast broadband supports the shift towards the gigabit capable speeds required by cloud computing, as well as supplying the demand among companies for an increasing trend to access/use big data as part of their business. **However, in many cases, these would be longer-term impacts which are unlikely to be detectable within the current evaluation.**

It should be noted that the proponents of cloud computing are typically the benefactors of its use, and environmental benefits are often clouded by carbon offsetting pledges, shifting the focus away from the energy demands of cloud computing itself. Nonetheless, the findings illustrated in the Lawrence Berkely National Laboratory (2013) provided convincing evidence on the energy savings that can be realised from cloud computing adoption, and one can expect significant economies of scale savings to be realised if cloud computing is adopted on a large scale.

[15] https://arxiv.org/ftp/arxiv/papers/2102/2102.02622.pdf

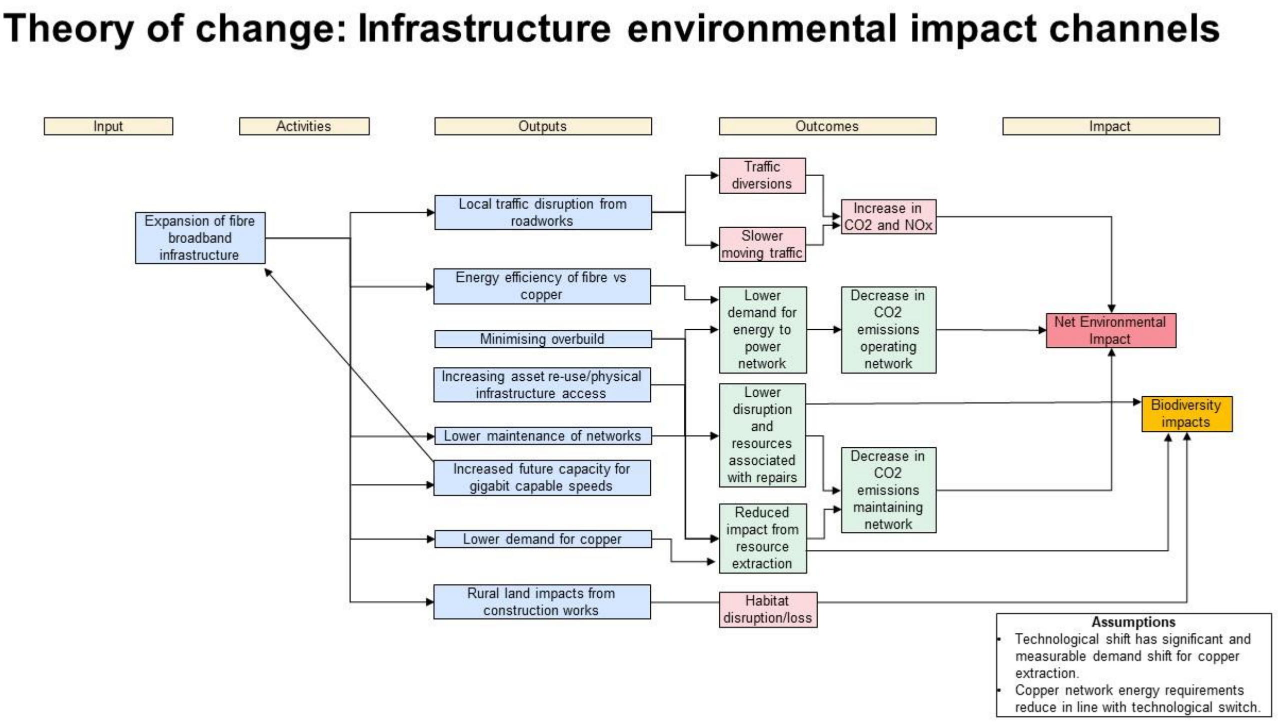
[16] https://books.google.co.uk/books?hl=en&lr=&id=K0S0o8mmw5QC&oi=fnd&pg=PT11&dq=Berners-Lee+and+Clark%E2%80%99s+book+The+Burning+Question+(2013)&ots=Yt7a1bd3Kw&sig=-DC4Vxs4Vx0BLn439vM2VbxPBK8&redir_esc=y#v=onepage&q=Berners-Lee%20and%20Clark%E2%80%99s%20book%20The%20Burning%20Question%20(2013)&f=false

The key outcome areas related to the environmental impacts from superfast-enabled technology are outside the scope of this report, but future avenues of research are summarised in the following future research questions:

- **Future research question 1a: Has the roll-out of superfast broadband led to a shift from physical servers to cloud computing leading to reduced energy consumption?**
- **Future Research question 1b: Has the roll-out of superfast broadband led to an increase in video software enabling online meetings and conferences leading to reduced energy consumption?**

2.4 Infrastructure impacts

Figure 2.4: Theory of change: Infrastructure environmental impact channels



Several positive technological outputs are expected to be produced through infrastructure investments in fibre cable installation, such as minimising overbuild and increasing asset re-use or physical infrastructure access. Installation of fibre cable will also lead to increased consistency /standardisation of technologies used to reach gigabit capable speeds.

In terms of environmental impacts, the deployment of fibre broadband infrastructure is expected to lead to short-term local traffic disruption from roadworks. This will cause traffic diversions and slower moving traffic which will increase vehicle emissions (CO_2 and NOx). This will be measured using permit data logged by providers when installing fibre cables, linked to the Highways England QUADRO tool using a case study approach of affected roads in a subset of local authority areas.

At the same time, fibre cables are assumed to be more energy efficient, have lower maintenance requirements, and less impacts in their extraction, leading to a decrease in CO_2 emissions maintaining network. Although the analysis will not be able to evaluate these outcomes directly, there have been studies undertaken in other countries which may provide results that could be transferred to the

Programme area. Europacable commissioned a Prysmian Group study (2021) investigating the relative energy demands of three network access technologies. The research modelled typical rural or urban settlement structures based on six regions in Germany, assuming a ubiquitous rollout and a minimum of 50Mbit/s for every connection within these regions. Compared to VDSL2[17] and HFC[18] networks (both using existing copper networks), the study found that FTTP/H (Fibre to the Premises/Home) is the most energy efficient consumer fixed-line technology. FTTP Gigabit Passive Optical Network (GPON) in particular, was shown to be far less energy intensive, requiring an annual energy value of 3,156MWh compared to 3,465MWh for VDSL2 and 4,987MWh for HFC. The study estimated the CO_2 emissions of fibre to be between 10% and 37% lower than emissions associated with copper networks. It has been assessed that undertaking this analysis is beyond the scope of this report but remains an interesting area of future research none the less.

There may also be habitat disruption associated with the laying of fibre cables, leading to biodiversity impacts, but nascent guidance in the DEFA ENCA Databook on measuring and monetising impacts puts this outside of scope of this report. This is further discussed in Section 3 of the report.

The key outcome areas related to the environmental impacts from the infrastructure roll-out of superfast broadband are summarised in the following research question:

- **Research question 4: Has the disruption caused by the roll-out of superfast broadband led to environmental impacts through traffic disruption?**

The below research questions may also present avenues of future research to better understand the impacts of the rollout of superfast broadband, but are beyond the scope of this report:

- **Future research question 2: Has the disruption caused by the roll-out of superfast broadband led to environmental impacts through habitat disruption?**
- **Future research question 3a: Has the shift from copper to fibre cables associated with the roll-out of superfast broadband led to a decrease in CO_2 in the operating network?**
- **Future research question 3b: Has the shift from copper to fibre cables associated with the roll-out of superfast broadband led to a decreased demand for copper in the supply chain?**
- **Future research question 3c: Has the shift from copper to fibre cables associated with the roll-out of superfast broadband led to a decrease in CO_2 in maintenance costs?**

2.5 Research questions

Below are the research questions associated with the environmental impacts of the Superfast Broadband Programme as outlined in the Theories of Change.

- **Research question 1:** Has the increased ability to work from home associated with roll-out of superfast broadband led to changes in travel behaviour (congestion, trip volumes, and traffic volumes, as well as rebound effects on leisure travel and home deliveries)?

[17] Very High Bit Rate Digital Subscriber Line uses copper networks https://ask.trustpower.co.nz/app/answers/detail/a_id/78/~/differences-between-adsl-and-vdsl

[18] Hybrid Fiber-Coaxial combines fibre optic and coaxial (copper) cable-based transmission https://www.techopedia.com/definition/25805/hybrid-fiber-coaxial-cable-hfc-cable

- **Research question 2:** Has the increased ability to work from home associated with roll-out of superfast broadband led to changes in domestic energy consumption - through increased demand for household appliances, heating & cooling - and have these been offset by equivalent changes in office energy usage?
- **Research question 3**: Has the increased ability to work from home associated with roll-out of superfast broadband led to land use change: Increased demand for rural/greenfield land use (likely to be longer term and not detectable within this evaluation)?
- **Research question 4:** Has the disruption caused by the roll-out of superfast broadband led to environmental impacts through traffic disruption?

There also are a number of research questions that are beyond the scope of this report, but may represent avenues of future research to better understand the longer-term environmental impacts of the Superfast Broadband Programme:

- **Future research question 1:**
  - **Future research question 1a:** Has the roll-out of superfast broadband led to a shift from physical servers to cloud computing leading to reduced energy consumption?
  - **Future research question 1b:** Has the roll-out of superfast broadband led to an increase in video software enabling online meetings and conferences leading to reduced energy consumption?
- **Future research question 2:** Has the disruption caused by the roll-out of superfast broadband led to environmental impacts through habitat disruption?
- **Future research question 3:**
  - **Future research question 3a:** Has the shift from copper to fibre cables associated with the roll-out of superfast broadband led to a decrease in CO_2 in the operating network?
  - **Future research question 3b:** Has the shift from copper to fibre cables associated with the roll-out of superfast broadband led to a decreased demand for copper in the supply chain?
  - **Future research question 3c:** Has the shift from copper to fibre cables associated with the roll-out of superfast broadband led to a decrease in CO_2 in maintenance costs?

3 Analysis

This section presents the analysis of the data collected for each of the environmental impact themes, focusing on a more detailed set of outcomes, grouped under behaviour change, enabled technology and infrastructure headings:

- Behaviour change: travel behaviour; household energy consumption; land use change.
- Enabled technology.
- Infrastructure: congestion caused by civil works; maintenance of fibre networks; biodiversity impacts.

The analysis of each research question is presented, after evaluating each using current and historic data. Note that due to some outstanding gaps in the data or questions around availability, access requirements and release dates of some data sources, not all research questions detailed in the plan have been feasible for this evaluation.

3.1 Analysis of the treatment and comparison group

A credible assessment of the environmental impact of the Superfast Broadband Programme requires the selection of appropriate comparison groups of postcodes or areas that did not receive BDUK investment (or the commercial roll out of superfast broadband), to enable an assessment of what may have happened in the absence of the Programme. Ideally, this group should be equivalent to those areas benefitting from the Programme in all relevant respects except their exposure to subsidised broadband coverage. As the Programme was not delivered as a randomised experiment, the selection of these areas involves some challenges:

- **Reverse causality:** Reverse causality is typically a central challenge in the evaluation of the impacts of infrastructure projects. Areas often benefit from enhanced infrastructure investment because they are expected to grow in the future. Comparing areas that do and do not benefit from enhanced infrastructure tends to overstate the effects of investment, as those areas receiving the investment would be expected to grow more rapidly anyway. This problem is less acute in the case of the Superfast Broadband Programme as it was designed to address inclusion objectives (i.e. enabling areas of the UK to obtain superfast broadband services that were being delivered on a commercial basis to denser urban areas) rather than to address specific spatial development priorities. However, several Local Bodies have used the tendering process to align the delivery of the Programme with local economic development priorities and reverse causality problems are likely present in at least some areas benefitting from the Programme.

- **Selection bias:** Selection bias poses a potentially greater threat to robustness. Suppliers chose which premises to upgrade (as a subsidised build via fair procurement processes) based on a list of eligible premises identified as 'white' (i.e. not covered by the commercial plans of network providers over the next three years). As such, there will also be problems of selection bias if those areas that suppliers chose to upgrade differed in systematic ways to those that they excluded from their build plans. It would not be unreasonable to assume that the suppliers chose these premises to maximise their expected returns from investment. This could imply a focus on areas with higher levels of demand density and lower costs associated with delivering superfast broadband infrastructure. This, in principle, could distort comparisons between those areas that benefitted from the Programme and other eligible areas that did not. For example, areas of higher economic density may offer firms superior access to the skilled labour needed to exploit enhanced connectivity (either locally or via better connections to other centres). These features may have enabled these areas to grow more rapidly than areas that did not benefit from the Programme regardless of the broadband infrastructure delivered, leading to comparisons that overstate the impacts of the investment.

3.1.1 Pipeline Design

The issues identified above can be handled by exploiting the long timeframes over which the Programme was delivered. The pipeline design enables comparisons to be made between those areas that benefitted from the Programme first to those that received the intervention later. In this set up, areas receiving subsidised coverage at later stages act as a comparison group for those that receive the intervention earlier. In this design, comparisons are restricted to areas that eventually received the intervention.

The principal advantage of a pipeline design is that comparisons should be robust to problems caused by systematic differences (i.e. selection bias) between areas that do and do not benefit from subsidised broadband coverage, as comparisons are restricted to the 'only treated'. Other counterfactual approaches that rely on using non-treated areas may exhibit biases as unobserved characteristics between the treated and comparison groups cannot be controlled for. However within a pipeline design, there is greater confidence that these unobserved biases are reduced given all units were eventually treated.

The pipeline model was implemented using the following generic econometric model:

$$y_{it} = \alpha_i + \beta T_{it} + \gamma X_{it} + \alpha^i + \alpha^t + \varepsilon_{it}$$

This model links the outcome of interest for area *i* in period *t* (y_{it}) to whether the area has benefitted from subsidised coverage in period t (T_{it}). The coefficient β captures the effect of subsidised coverage on the outcomes. Models will also generally include a vector of time varying control variables describing other characteristics of the areas that may also influence the outcome of interest (X_{it}). Econometric models will also be developed to allow for unobserved but time invariant characteristics of the areas of interest that could bias results (α^i) as well as unobserved but time specific shocks (α^t) affecting all areas[19].

3.1.2 Limitations of Pipeline Design

Whilst a pipeline design can help to exploit long timeframes over which the Programme was delivered to identify a causal impact, there are some methodological limitations to this approach:

- **Robustness:** The pipeline design will produce robust estimates of the impact of subsided coverage if the order in which the premises receive upgrades can be considered random in relation to the outcome of interest. Three factors have the potential to influence the timings of upgrades:
  - **Timing of procurement:** The timing of the procurement exercise will partly be determined by the Local Body. It is possible that completing the tendering exercise more rapidly may reflect unobserved managerial characteristics of the Local Body (e.g. greater efficiency and/or internal resources). In turn, this could be reflected in other aspects of the performance of the area. This would be connected to the performance of the public services, but also potentially to economic development outcomes if this reflects the ability of willingness of the Local Body to invest in the promotion of local growth. This could lead to an overstatement of the Programme's effects.

[20] i.e. people are no longer concentrated in one specific area, and instead are dispersed across different locations.

  - **Order of upgrades:** The network provider selects the order in which postcodes benefit from subsidised upgrades. If they adopt a profit maximising strategy, it would be anticipated that they would be delivered to the most profitable postcodes first. If selection is positively correlated with underlying economic performance, or other outcomes of interest, then this could lead to an overstatement of the impacts of the Programme.

  - **Timeliness of delivery:** Finally, the order in which postcodes benefit from subsided upgrades will be influenced by how rapidly the network provider brings forward delivery. This could potentially be linked to the capacity of the local economy to provide the necessary resources (e.g. skilled labour) to do so. Constrained capacity could reflect the wider growth of the local economy. If so, the economies of those areas upgraded later may be more likely to expand in the absence of subsided coverage (in which case, the pipeline design would understate the impacts of the Programme).

- **Direct and indirect effects:** The pipeline design does not discriminate between the direct and indirect effects of superfast broadband coverage on the outcomes of interest. This will not create problems with biased results however, can create some challenges for interpretation. For example, superfast broadband coverage may have a direct effect enabling people to work from home, resulting in fewer commuting trips. Simultaneously, a rebound effect may be that people begin to take more leisure trips; where both trips will be captured in road traffic count data. As such, the data will not allow the model to differentiate between direct and indirect effects, rather reporting a total effect, which would be the net marginal change of the direct and indirect effect.

3.2 RQ1. Behaviour change: Travel behaviour around businesses parks

Research question 1: Has the increased ability to work from home associated with roll-out of superfast broadband led to changes in travel behaviour?

The environmental impacts of the Superfast Broadband Programme via travel behaviour are likely to be complex. On the one hand, superfast broadband deployment may reduce travel demand and associated emissions by increasing the prevalence of homeworking or reducing trips to retail centres. However, evidence from prior studies also indicates that superfast broadband has encouraged the ‘disagglomeration’ of the economically active population[20] – with the potential to increase congestion on rural road networks and/or increase the length of commuting trips.

As outlined in the literature review (see Appendix A), the majority of studies on the environmental impact of faster broadband through behaviour change (increasing the feasibility of working from home and fewer commutes to the individual’s office / workplace) have been assumption-driven. These have been based on different scenarios of work/travel behaviour and their associated carbon emissions, rather than on observable data, although in part this is a consequence of the fact that large scale patterns of working from home are a recent occurrence since COVID-19. There have been some studies based on observational data that have shown that improvements in internet access increase the rate of teleworking, but they have not made the additional link to estimating the environmental impacts.

3.2.1 Methodology

The objective of this analysis is to use observable data to identify and monetise the environmental impacts associated with travel behaviour, linked to the increased ability to work from home due to faster internet connections. A pipeline design is used, as discussed in section 3.1.1. The pipeline design is estimated using fixed effect techniques, which allows us to estimate the causal effect of the Programme in terms of the

[20] i.e. people are no longer concentrated in one specific area, and instead are dispersed across different locations.

number of journeys made in the roll-out areas, compared to the comparator group. If significant effects are identified, the Department for Transport's (DfT) Transport Appraisal Guidance (TAG)[21] values for air pollution and Greenhouse Gas emission reductions associated with these journey savings can be applied to monetise the impact[22].

To explore the effect of superfast broadband on travel behaviour, the research team used National Highways Strategic Road Network (SRN) traffic count data[23] to target count points in close proximity to business parks. Consultation with National Highways analysts indicated that a significant challenge to isolating changes in commuting behaviour is that many of the locations where people commute to are mixed function locations, containing both business, educational, and leisure destinations. This introduces considerable noise into the data when seeking to analyse commuting traffic only. Targeting business parks allows the analytical approach to reduce noise in the data because business parks are predominantly single use (the research targeted roads leading to business parks which are typically not agglomerated with other forms of travel such as retail or leisure parks, to further minimise noise in the data)[24]. The research team obtained Geographical Information System (GIS) dataset containing 567 business park locations across the whole of the UK. The dataset was constructed by undertaking vast amounts of desk-based research to identify the existence and location of the business parks. This is a unique dataset in terms of the comprehensiveness of the coverage provided – although the extent to which this represents a fully comprehensive list of UK business parks is unknown due to lack of existing research in this area. This dataset provided a sample base of business parks in which the commutable behaviour of workers can be tested.

The business park data also has the advantage that business parks are more likely to have access routes along the SRN – and therefore utilising the traffic count points along the SRN. The SRN data set includes stretches of road which are closer, and more likely to be used by individuals commuting to business parks than the Local Authority data set. Using traffic count data from the SRN provides three distinct benefits over traffic count data provided by Local Authorities[25]. 1) it helps to eliminate noise as it is less likely to include people using the road for purposes other than commuting (e.g. the people on the school-run); 2) the quality of data from local authorities is lower compared to the SRN; Local Authority traffic counts often include manual count points, and are not necessarily repeated every year, nor under the same conditions (leading to problems comparing yearly data within a given location). Targeting business parks is therefore likely to reduce noise in the data, whilst simultaneously increasing data quality; and 3) the coverage of traffic count points is greater along the SRN – allowing a more precise targeting of the traffic in and out of business parks.

However due to the unknown representativeness of the coverage, the research team has only been able to adopt a **case study approach** within this analysis, using the business parks as commuter destinations. The research team created inclusion criteria (detailed below) which allows us to target business parks which are close enough to the SRN to provide relevant data, as well as within an appropriate distance from the treatment and control area. The inclusion criteria evolved over a number of iterations to find the optimal

[21] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1126348/TAG_Unit_A1.1_-_Cost_Benefit_Analysis_Nov_2022_Accessible_v1.0.pdf.pdf

[22] The DfT produce values to aid the monetisation of environmental impacts, reflecting the societal benefit of improving given conditions.

[23] Available through the WebTRIS API: https://webtris.highwaysengland.co.uk/

[24] With thanks to the British Council for Offices and Perkins & Will for providing a detailed GIS dataset on the location of business parks across England

[25] https://roadtraffic.dft.gov.uk/about

balance between specificity of the data, and sample size; where tighter inclusion criteria led to more specific data, but at a reduced sample size. The inclusion criteria can be seen below:

- **Within a commutable distance (20km) of the treatment/ control area:** A commutable distance of 20km was used from treatment/control areas. Research undertaken by Milton Park[26] and consultation with transport economists at the consultancy Perkins & Will suggest that a commuting distance of 20km is not uncommon for those travelling to business parks. Whilst this distance may introduce some noise in the data (the wider the distance, the more traffic that is unconnected to the business park in question), it also helps to increase the sample size, therefore providing a more representative assessment of commuting behaviour overall.

- **Within 500 meters of the SRN:** Ensuring that the business park sits close to the SRN will limit the noise from other road users. After experimenting with various distances, the research team identified that 500 meters was the minimum distance that produced a sufficient number of business parks in scope. This distance provided the best balance between sample size and introducing additional noise into the analysis.

- **Within 1000 meters of the traffic data count point:** As well as ensuring that the business park is within 500 meters of the SRN, the business park needs to be within 1000 meters of the traffic data count point (which is located on the SRN). This approach allows a greater distance between the count point and the business park, compared to the business park and the SRN, to account for the distribution of automatic count points across the SRN. At this distance, the count point is close enough to the business park to be considered plausible business park traffic, yet far enough away to help to increase the sample size. Various distances were tested, in a bid to optimise the trade-off between sample size and increased noise.

Ensuring the above criteria are met when choosing the business parks in scope of the analysis allowed a comparison of traffic counts on these journeys in areas benefitting from the Programme and a set of comparison areas; whilst mitigating noise from other types of road traffic. After the application of the inclusion and exclusion criteria, 32 business parks were identified as being in scope, yielding 260 traffic counters and 1,496 observations of traffic count data.

The pipeline design is applied to the case studies of 32 business parks in scope, to exploit the long-time frames over which the Programme was delivered, enabling comparisons traffic on SRN roads around business parks in those areas that benefitted from the Programme first to those that received the intervention later. In this set up, traffic on roads around business parks in areas receiving subsidised coverage at later stages act as a comparison group for traffic on roads around business parks in areas that receive the intervention earlier; restricting comparisons to areas that will eventually receive the intervention. The econometric model used for this analysis can be seen below:

$$ln(road\ traffic_{it)} = \beta_1 Cummulative\ Connections_{it} + \beta_2 rural_i + \beta_3 COVID_t + \beta_4 2013 + \beta_5 2014 + \beta_6 2015 + \beta_7 2016 + \beta_8 2017 + \beta_9 2018 + \beta_{10} 2019$$

This is an adaption of the pipeline model outlined in section 3.1.1, with $Cumulative\ Connections_{it}$ used in place of the binary variable (T_{it}). The advantage of using a cumulative number of connections over using a binary treatment/control variable is that the binary variable assumes the same fixed effect on the travel patterns in an area, regardless of the number of connections in each postcode, whereas the

[26] Internal unpublished report from Milton Park (2022)

$Cumulative\ Connections_{it}$ variable allows for the additional effect of each premise receiving superfast coverage.

Dependent Variable

The dependent variable used in the analysis is $ln(road\ traffic_{it})$. This represents log of the number of non-heavy goods vehicles[27] on the road, at each count point around the business parks. Statistics on the average number of heavy goods vehicles are provided for each count site, for each year as part of the WebTRIS data download. Netting off the number of heavy goods vehicles helps reduce noise in the data, by limiting the road traffic to only commuting vehicles. The log is used, opposed to the level value, to address non-normalities in the data which can lead to incorrect model interpretation of hypothesis tests and confidence intervals. The 12-hourly (07:00 – 18:59) average weekday traffic count data is used, as opposed to wider time intervals (e.g., the 18hour or 24 hour) as a means of eliminating noise from the data, by focusing on periods of time where commuting traffic is more likely to be made of workers travelling to business parks.

Variable of interest

The key independent variable, and the one that will identify any statistical impact of the Programme is $Cummulative\ Connections_{it}$. This variable represents the number of cumulative connections in each commutable area around the business parks (see below for a discussion around inclusion criteria for business parks). The advantage of using a cumulative number of connections over a binary treatment/control variable is that the binary variable assumes the same fixed effect on the level of road traffic, independent of the number of connections made within the commutable distance from the business park. In contrast, the cumulative number of connections assumes a fixed effect (in terms of effect on road traffic levels) for *each additional connection* made. In this way, the research aimed to establish the degree to which the additional connections have led to a causal effect on levels of road traffic.

Controls

In the pipeline model, control variables are added to hold constant a number of potential confounding variables on the analysis, including;

- $rural_i$ – This is a count of the number of treatment postcodes classified as rural within 20km radius of the business park (defined as the commutable distance above). This controls for business parks that reside in more rural locations, and are potentially likely to have people commuting from further out. However, it is also likely that there is a correlation between distance to work and propensity to work from home. Due to difficulty in interpreting the interaction of a count variable[28] and a continuous variable, the interaction of $rural_i$ and $cummulative\ connections_{it}$ has not been included within the econometric model. As such, there exists the possibility that the model does not fully control for the effects of urban and rural location and therefore over-estimates the impact of traffic behaviour in more urban locations, meaning that the results should be interpreted with some caution.

- $COVID_t$ – A binary variable that controls for the potentially unrepresentative changes in commuting behaviour during the Covid-19 pandemic. Due to the lockdowns imposed, working from home became common-place, and a significant number of workers were furloughed, meaning most were not travelling to work. Including the COVID variable avoids over-estimating the impact of the Programme

[27] HGVs, as defined by the Department for Transport includes all goods vehicles over 3.5 tonnes gross vehicle weight: https://roadtraffic.dft.gov.uk/about

[28] Otherwise known as a discrete variable

(e.g. attributing decreased road traffic to the ability to work from home, rather than being told to work from home). The $COVID_t = 1$ where $t \geq 2020$, reflecting the fact that COVID-19 led to significant changes in commuting behaviour, both during and after the lockdowns.

- *Year dummy variables* – The use of year dummy variables is to control for variation in the commuting behaviour across the control period. For example, the opening (or closing) of a local business/industrial park that may lead to changes in road users, which would be attributed to the intervention without controlling for confounding variables.

3.2.2 Limitations

An important consideration is that not all employment types will be able to switch to working from home as a result of superfast broadband. Some types of employment are inelastic in their choice of location and require workers to be present on site, meaning these jobs, or the commuting behaviour in these locations, will not be affected by broadband roll-out. By limiting the number of road traffic counting sites to those close to the SRN, the analytical approach aims to minimise the noise introduced by jobs which are inelastic in their choice of location.

One of the challenges of this analysis has been to distinguish the traffic count data between a potential reduction in commuting, versus the rebound effect of an increase in leisure trips, as outlined in the Theory of Change. Unfortunately, estimating the rebound effect has not proved viable for the purpose of this evaluation. There does not exist a pre-made GIS dataset containing retail parks, shopping centres or other leisure sites. Without prior experience in economic geography techniques which would be required for this task, creating such a dataset would be a very labour-intensive process. As such, the analysis was unable to feasibly estimate the rebound effects associated with changes in commuting behaviour in this report.

In addition to the limitations mentioned above, the analysis of travel behaviour has a number of other specific limitations which must be considered in the analysis:

- Traffic count data includes only motorised journeys by road, as this is the behaviour which is observed in the available datasets. This analysis is therefore unable to comment on changes in commuting behaviour using other means of transport (e.g. trains). There may also be impacts in terms of increased longer-distance train journeys. These trips are not captured in the available datasets, but it can be assumed that the Green House Gas (GHG) impacts of train journeys are considerably lower than car journeys.

- The analysis is also not able to comment on the nature of the trips – e.g. people may now work from home, but may still use their car to drop their children at school. In instances such as this – the use of the car would still show up in the count data. Business parks were specifically targeted to minimise this, however this is still likely to introduce additional noise into the analysis.

- Working patterns have changed significantly due to COVID-19 social lockdowns, which have accelerated the use of work from home technologies. ONS statistics show that a large proportion of the UK workforce has relied on working from home during the COVID-19 pandemic[29]. Superfast broadband is likely to play an enabling effect on this shift to working from home, but may not have been the only driver of this broader societal shift. Within the econometric model, the inclusion of the

[29] https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/bulletins/coronavirusandhomeworkingintheuk/april2020

$Covid_t$ variable controls for the societal shift in work from home behaviour, isolating the effects of the superfast broadband on employees' work from home behaviour.

3.2.3 Estimated impact on travel behaviour

The results of the fixed effects regression are presented in Table 3.1. The results suggest that the variable of interest, $cumulative\ connection_{it}$, is statistically insignificant. **This suggests that superfast broadband roll-out has not significantly reduced levels of commuting behaviour for business purposes, by allowing residents to work more from home**. One explanation for this lack of significance in the findings could be that people's ability to work from home was relatively inelastic prior to the COVID-19 Pandemic, meaning that little variation would be detectable in the data in the evaluation area over time. Until the COVID-19 Pandemic, the social norm was to work in the office; where working from home could be seen as a privilege. Whilst access to superfast broadband would enable employees to work from home, employers' attitudes on working from home may ultimately dictate where an employee works from. From 2006 to 2019, the percentage of employees working from home[30] only increased from 12.6% to 14.7%[31]. In a pre-COVID world, the rate at which home working increased was modest[32], suggesting reluctance from employers to allow employees to work away from the office. COVID-19 accelerated the prevalence of homeworking, due to the lockdown restrictions. However, evidence suggests that firms have yet to adapt to the post-COVID 'hybrid' working style. The Business Insights and Conditions Survey from the ONS found that in 2021 24% of businesses surveyed intended to use a hybrid work force, whilst 28% remained unsure of future work from home policies[33].

Table 3.1: Regression output for estimated impact on travel behaviour

Variables	Coefficient	P-Value
Cumulative Connections	0.0000	0.1356
Covid	-0.7514	0.1253
Rural	0.0002	0.2943
2014	-0.3138*	0.0685
2015	-0.2775	0.2882
2016	-0.3829	0.3166
2017	-0.4586	0.2919
2018	-0.6171	0.1669
2019	-0.6641	0.1543
2020	-0.1824*	0.0845
Constant	11.2442***	0
Number Of MSOA Areas	32	
R-Squared	0.1166	

**** p<0.01, ** p<0.05, * p<0.1. Robust p-values used.*

The Null Hypothesis of the Hausman Test is rejected at the 99% confidence level, suggesting the fixed effects model is preferred to the random effects model.

[30] Defined as those who usually spend at least half their time working from home

[31] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1049877/Homeworking_Jan_2022_final.pdf

[32] Noting that his increase cannot be attributed to improved broadband

[33] https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/articles/businessandindividualattitudestowardsthefutureofhomeworkinguk/apriltomay2021

Despite a reasonable model fit (R^2 of 11.7%), the model exhibits poor external consistency, given the $Covid_t$ variable is statistically insignificant on travel behaviour. During the COVID-19 lockdowns, road traffic significantly reduced, compared to pre-pandemic levels[34]. Whilst this is detected in the model, it is not statistically significant, suggesting that COVID-19 lockdowns had no detectable statistical effect on the level of road traffic around the business parks in the evaluation area. Given this discrepancy, it suggests that there is either an issue with the underlying model, or the data supporting the model.

One possible explanation for this finding is that the traffic on roads leading to business parks remained essential even during Covid lockdowns. Research undertaken by Milton Park Retail Park, explores commuting behaviour (and work from home behaviour) of those who use Milton Park as a place of work. They surveyed 914 employees of various businesses who use the retail park and found that a substantial number of employees still work from the office, rather than from home. Of the employees surveyed, 29% never work from home, and a further 23% only occasionally work from home. Of the 914 employees that work at the business park, 75% work at least three days in the office per week. Whilst this is not representative of all business parks, nor all places of work, this does suggest that the shift to home working has not become as prevalent as first hypothesised; at least around business parks. This could suggest that the nature and/or type of work undertaken at business parks may not be conducive with working from home. Future research into the commuting behaviour impacts of superfast broadband roll-out would require alternative commuting destinations to be included in analysis, either by expanding the list of business parks, or finding a way to isolate business commuting traffic into town centre areas, which is challenging due to the levels of noise introduced by other travel purposes in the same area.

3.2.4 Recommendations for Future Research

Despite failure to detect an impact on the level of commuting traffic around business parks due to the increased propensity to work from home, this does not mean there are not causal links between the broadband coverage and working from home. Failure to detect a statistically significant impact could be an artifact of the type of work undertaken at business parks, meaning working from home is not as viable as hypothesised. As such, broadening the search beyond business parks may yield fruitful results. Adequate control variables would need to be included, to hold confounding factors constant, allowing the effects of subsided broadband coverage to be isolated. A longer time frame may also need to be considered, to allow employers to fully adapt to the post-Covid landscape (where dummy variables could be used to control for post-Covid observations, such as is used in this report).

It is also important to consider that whilst there was no observable change in the traffic levels around the business parks, it does not mean that the ability to work from home has not been created (given the installation of superfast broadband). There may be factors beyond the provision of superfast broadband that prevent homeworking (e.g. requirement for some office working, other issues unrelated to broadband that require office working), however the option for someone to take a remote role in the future now exists. Further research, including qualitative interviews of business park workers and potential remote employers, would be required to fully understand the extent to which superfast has provided remote working as an option.

[34] https://www.gov.uk/government/statistics/transport-use-during-the-coronavirus-covid-19-pandemic

3.3 RQ1: Change in Travel Behaviour (Census Data)

Research question 1: Has the increased ability to work from home associated with roll-out of superfast broadband led to changes in travel behaviour?

Additional analysis was undertaken that explores that change in work from home behaviour, as reported in both the 2011 and 2021 Census (the limitations of making direct comparisons is discussed in Section 3.3.2). The purpose of this analysis was to explore the impacts on wider populations and therefore across different industries and types of work – which was not possible when targeting areas around business parks.

3.3.1 Methodology

Both the 2011 and 2021 Census collected data on both the home address and the location of the respondent's place of work.[35] Estimates of the distance travelled to work can therefore be generated.[36] The dataset also released accounts for those that work from home – where Census respondents are classified as working from home based on answers from the address of workplace and method of travel to work question, choosing the 'work mainly at or from home' option.

Changes in the proportion of those that work from home across the two Censuses may provide insights into the extent to which superfast broadband has enabled working from home. The analysis is undertaken at the output area level.[37]

In the absence of available population data at the output level, the number of people that work from home are normalised by the population of economically active. This helps to control for any increases in the number of people that work from home by virtue of the population of the economically active increasing.

Propensity Score Matching

To test the hypothesis described above, the change in work from home behaviour for the treatment and comparable white postcodes (that did not benefit from the Programme) can be compared. To ensure that comparisons are made between comparable units, propensity score matching is used to 'match' treatment and untreated white postcodes based on a set of observable characteristics. The propensity scores (i.e. the probability of receiving the treatment based on observable characteristics) was estimated using a probit model:

$$P(D_i = 1 | X_{it}) = \Phi(X_{it}\beta)$$

Which estimates the probability, P, of a postcode being in the treatment group, $D_i = 1$, given a set of baseline characteristics X_{it}. Φ is the cumulative distribution function of the standard normal distribution, which gives the probability that a variable following the standard normal distribution.

The variables used to estimate the propensity score (included in X_{it}) were chosen among factors that are assumed to influence both the selection into the intervention and outcomes of interest, and mimic the matching approach used in the Superfast Broadband Programme Evaluation 2020 (for the Reducing the Digital Divide analysis).38 Variables were selected so that the characteristics of the postcodes prior to the roll out of Phase 3 were informing the estimate of the propensity score:

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[35] https://www.ons.gov.uk/census

[36] Formally, the distance is calculated as the straight line between the postcode centroids of the place of work and home address.

[37] Output areas are geographical regions comprising 40 to 250 households (between 100 and 625 people).

[38] https://assets.publishing.service.gov.uk/media/601ac0e8d3bf7f70bc2e1ef8/Technical_Appendix_1_Reducing_the_Digital_Divide_V2.pdf

- **Next Generation Access[39] coverage between 2012 and 2016:** Pre-programme levels of connectivity. Average and maximum available download speeds in 2013 was also included. This gave a measure of pre-programme supply.

- Number of premises with exchange only lines: Premises that are connected directly to the Exchange will cost more to enable with superfast broadband speeds as this requires the installation of a new cabinet. The prior expectation was that postcodes with a higher number of premises with exchange only lines would be less likely to be included within the build plans of local schemes owing to these additional costs.

- **Delivery points at the serving Cabinet and the serving Exchange:** The attractiveness of upgrading available broadband services to superfast broadband speeds will also be linked to the number of premises that benefit from the upgrade. As such, it was anticipated those postcodes with fewer delivery points at the serving cabinet and exchange would be less commercially attractive and carry a lower likelihood of being included within the build plans of local schemes, relative to other white postcodes.

- **Whether the postcode was in the Virgin Media footprint in 2013:** Data was made available on whether the postcode was within the Virgin Media footprint in 2013. The availability of Virgin Media at a postcode could reduce the likelihood that it was included in local schemes – signalling the presence of a competitor and reducing the commercial benefits associated with providing upgraded services. However, when comparing white postcodes, to which Virgin Media may have had no immediate plans to roll out superfast broadband services, competing providers may see an attraction in providing superfast broadband to the postcodes to enable them to gain a competitive advantage, increasing the likelihood that the postcode was included in the build plans for local schemes.

- **Estimated cost to upgrade the serving cabinet or exchange only lines:** BDUK developed estimates of the cost of upgrading the cabinets or exchange only lines in 2013 to support the resource allocation process. The expectation was that those cabinets with higher predicted upgrade costs (or higher upgrade costs per premises upgraded) would be less likely to be included within the build plans for local schemes (or at least those that involved higher upgrade costs per premises upgraded).

- **Factors affecting demand:** Demand for superfast broadband was assumed to be linked to the characteristics of the local economy (at the LSOA level). Information on gross weekly earnings, employment rates, unemployment rates and urban/rural status was included in the matching model.

After the propensity score is estimated, a nearest neighbour with replacement matching algorithm is used:

- This matches each treated postcode to the nearest untreated white postcode, in terms of their estimated propensity scores.

- 'With replacement' means that each untreated white postcode can be used as a control for more than one treated postcode.

The common support assumption is also imposed, requiring that treated postcodes whose estimated propensity score is higher than the maximum, or less than the minimum, estimated propensity score of the

[39] Includes fixed-line broadband access technologies capable of achieving download speeds meeting at least 30Mbps coverage.

untreated white postcodes are dropped from the analysis. This further ensures that the treatment and comparison groups are as similar as possible in terms of their observed covariates.

After the matching process, there were a total of 192,276 postcode areas, 147,894 of which are treatment areas and 44,382 of which are matched white postcodes.

Difference-in-Difference

Difference-in-difference (DiD) is based on comparing changes in outcomes between pre- and post-intervention periods and a treatment and comparison group. In the context of the Superfast Broadband Programme, it compares changes in work from home behaviour over time between treated output areas and matched comparison output areas.

This design exploits the longitudinal nature of the data, and as such it can account for unobserved, time-invariant sources of bias that affect between treatment and control groups.[40] It is more robust than evaluating treatment effects with propensity score matching alone, as propensity score can only account for biases due to systematic differences in observable characteristics. Importantly for this analysis, the DiD estimator may be able to control for some of the time fixed effects brought about by the COVID-19 pandemic, assuming the effect of the pandemic was homogeneous across all units (see limitations below for more detail).

To estimate the effect of the rollout of superfast broadband, the following econometric model is used:

$$\Delta Y_{it} = \beta D_i + \gamma X_i + \epsilon_{it}$$

Where the change in the outcome of interest (working from home as a percentage of the economically active within an output area), ΔY_{it}, is regressed on a binary variable indicating whether the output area was part of the treatment group D_i. The estimated effect of the rollout of superfast broadband on change in work from home behaviour is captured by the coefficient β.

The control variables, X_i, can be used to control for confounding factors. However, the availability of control variables is limited at the output area due to associated disclosure risks. The control variables used within the regression are:

- **Change in the nature of work over time:** The Census estimates the number of people undertaking different typologies of work – based on their reported occupation at the time of data collection: Higher and intermediate management administrative/ professionals; supervisory, clerical and junior managerial administrative/ professionals; skilled manual labour professions; and semi-skilled and unskilled manual labour. Those from the 'professional' jobs are more likely to be able to work from home compared to those that undertake manual labour. Including these within the regression will help to account for differences in the nature of work overtime that otherwise would affect the propensity to work from home.

The key identifying assumption under which DiD produces robust estimates of the treatment effects is parallel trends. This assumption states that, in the absence of the intervention, differences in the outcome between treatment and comparison groups would have remained constant during the post-intervention period. To improve the chances that this assumption is credibly met, a matched comparison group was used

[40] Noting that the gaps between observations are 10 years apart, representing an unbalanced panel.

to reduce differences in observable characteristics. However, this could not be formally tested given there are only two data points within the analysis.

3.3.2 Limitations

There are several key limitations associated with the analysis, that are likely to pose a threat to the robustness:

- **Effects of COVID-19:** The 2021 Census was conducted during the COVID-19 pandemic, which saw a series of unprecedented actions taken: national lockdown, non-essential businesses and shops forced to close, 5.6 million people supported by the Furlough Scheme, etc. Specific to this research question, this would have induced a change in the way that the Travel to Work question in the Census was answered, with more people working from home, or not working due to the Furlough Scheme. The ONS specifically caution against using the Census data to measure change in pre- or post-pandemic travel patterns, identifying that changes over time could be due to either furloughed populations, pandemic related behaviour changes or long-term trends.[41] These time-fixed effects would only be eliminated from the estimated impact assuming that the effect of the pandemic were homogenous across the entire treatment and control group. This is a particularly strong assumption given the treatment and control groups are comprised of output areas from different occupations, industries, or parts of the UK (each country within the UK had their own COVID-19 response) would likely have experienced differing effects of the pandemic.

- **Lack of temporal variation:** The Census data used limits the analysis to examining the changes over two points in time – which are 10 years apart. This limits the ability to understand how work from home behaviour trended in the interim period in both treatment and control areas. This is significant as it means that parallel trends are explicitly assumed; where the use of event study analysis cannot be used to test the plausibility of this assumption. Given the 10-year gap between the data points, parallel trends in outcomes can be considered a very strong assumption that underpins the analysis. The lack of temporal variation also makes it increasingly difficult to control for the time-variant effects that may exist and influence the outcome of interest.

- **Limited control variables at output area level:** The variables which can be used to control for confounding factors is limited due to the low level of geography (output area) and associated disclosure risks. In the absence of appropriate control variables, the effect on work from home is not isolated to whether the output area received the treatment; other factors (such as socio-economic demographics, household composition, caring responsibilities, etc.) could be driving changes in work from home behaviour that are otherwise being attributed to the treatment effect (omitted variable bias). There are also other factors that do not exist within the data- such as distance to the office, should the respondent not work from home, or exact nature of work[42]- which may also influence the ability to work from home which are not being accounted for.

- **Non-work related trips:** Whilst the Census data can help to identify how commuting behaviour and place of work have changed, they do not account for instances where other trips (e.g. dropping

[41] https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/methodologies/traveltoworkqualityinformationforcensus2021

[42] Whilst partially captured within the ONS classification of a respondents job, there would still exist significant differences within each classification that determines a persons ability to work from home – e.g. someone handling personal information is more likely to be required to work from an office than a researcher using secondary data sets – despite both falling under the same ONS classification in terms of the nature of their work

children at school, or going to the shops) would also be undertaken as part of a commute to/from work. In these instances, the non-work trips would still be occurring, despite working from home. Therefore, the analysis is likely to represent an upper bound in terms of estimated reduction in greenhouse gas emissions.

3.3.3 Estimated impacts

The result of the first DiD analysis can be seen in the regression output below**. The results suggest that the rollout of superfast broadband is associated with a 9.3% increase in work from home behaviour per treated output area, statistically significant at the 99% confidence level**. However, as noted in the limitations above, this **result should be interpreted with caution**. The significant impacts of the COVID-19 pandemic means that the ONS advises against such comparisons to understand changes in work from home, where more robust higher frequency longitudinal data would be required to confirm causal impacts arising from the roll out of superfast broadband.

Table 3.2: Results of DiD analysis

Variable	Coefficient	P-value
Treatment	0.09315***	0.000
Change in higher/ intermediate occupations	0.01659***	0.000
Change in supervisory/ clerical/ junior management occupations	-0.01413**	0.001
Skilled manual labour occupations	0.00074	0.760
Semi-skill or unskilled manual labour professions	-0.00183	0.493
Constant	1.75158***	0.0000
Number of observations	130,123	
R^2	0.0075	

**** p<0.01, ** p<0.05, * p<0.1. Frequency weights used to estimate the standard errors.*

The econometric model exhibits a low R^2 – which is a measure of the extent to which the independent variables explain the variability in the dependent variables. At 0.7%, the R^2 of the model indicates that the control variables used do not help to explain the change in work from home behaviour over time. This is likely due to two issues (both discussed in more detail in Section 3.3.2):

- Lack of temporal variation.

- Lack of available control variables at output level.

This suggests that biases have been introduced into the analysis which could misrepresent the true impact of the Superfast Broadband Programme on the change in work from home behaviour. As such, the results presented above should be interpreted with caution.

3.3.4 Recommendations for Future Research

Whilst the analysis of Census data presented weak evidence that there may be an underlying relationship between areas that were recipients of the Superfast programme and the ability to work from home, the analysis was not robust enough to understand the extent to which Superfast *caused* this change in behaviour.

To further explore the extent to which superfast enabled people to work from home, datasets which are both granular and regularly updated should be exploited. There exist two further potential datasets that may be able to address this research question, although it should be noted both would require further scoping work to fully understand feasibility:

- **Estimated train station usage by the Office of Rail Road** – These statistics present entries, exits and interchanges for each station around Great Britain. The change in passenger volumes over time, between treatment or control areas, could be explored. A key consideration of this analysis would be the extent to which a train station solely services a treated area – or are there contamination effects from untreated areas using the same train station. Defining ‘catchment areas’ for train stations may also pose some challenges, and require the use of assumptions.

- **Understanding Society** – This longitudinal study contains a question relating to working from home in every other wave (waves 2, 4, 6, 8, 10 and 12). Given the longitudinal nature of this dataset, the analysis has the potential to offer robust results. A key consideration would be the extent to which data can be obtained at a low enough geographical level to fully understand changes over time between a treatment and control area.

3.4 RQ2. Behaviour change: Household energy consumption

Research question 2: Has the increased ability to work from home associated with roll-out of superfast broadband led to changes in domestic energy consumption, and have these been offset by equivalent changes in office energy usage?

The hypothesis that superfast broadband enables people to work from home as opposed to working in the office has been tested. There is thin evidence in the academic literature highlighting the environmental benefits of videoconferencing and teleworking. Research using more rigorous methodologies highlight marginal environmental benefits to videoconferencing (Helimen and Ristimaki, 2005), and the more optimistic research findings often omit rebound effects, such as a teleworker travel behaviour. More research considering these effects are needed to fully address the effect of videoconferencing on the environment, however, when considering the emissions savings stemming from heavily-emitting business air travel, corroborating the reduced air transport mandated by the COVID-19 pandemic with Hernandez et al.’s (2021) findings, showcases the significant positive environmental benefits that may arise from a wide uptake in videoconferencing technology.

There is growing evidence that net energy usage per worker is higher among home-workers than those in the office, referred to as the incremental energy. As outlined by the EcoAct Homeworking Emissions Whitepaper[43], to properly account for home working emissions, energy use from office equipment, home heating and cooling (where appropriate), which would not have occurred in an office-working scenario, should be accounted for. This method takes three input data sources: office equipment, heating energy, and cooling energy. Assumptions are also made around number of days working from home, percentage of gas consumption spent on heating the home during these periods, and electricity required for office equipment and lighting.

This study improves on these assumptions-led studies by using observable energy (gas and electricity) within treatment areas who have access to superfast broadband, compared to comparator areas in the pipeline design. Assuming other factors are constant in the treatment and comparator samples, any estimated differences in energy usage can be interpreted as an indication of the impact of superfast-enabled working from home on domestic energy usage.

3.4.1 Methodology

The objective of this part of the study was to analyse observational data to test whether the provision of faster broadband has the potential to lead to changes in the working patterns (e.g. via teleworking) that could be associated with some adverse environmental impacts via increased household energy consumption.

BEIS (now DESNZ) sub-national electricity consumption data, compiles meter records of domestic electricity and gas consumption (provided by energy suppliers) and is available for postcodes annually. Matching exercises undertaken to identify the proportion of treatment area postcodes that are covered by the statistics identify that 26% and 27% of treatment postcodes for domestic electricity and gas consumption respectively were covered by the sub-national energy consumption data. Whilst there is a moderately low level of coverage, this still yields over one million observable data points for both domestic gas and electric consumption; providing a sufficient sample to estimate the effects of working from home on domestic energy consumption. The total energy consumption by postcode was analysed, whilst controlling for the number of properties in each postcode area. Different postcode areas contain a different number of properties, and hence varying levels of consumption. Controlling for the number of properties will prevent over-attributing changes in energy consumption to the Superfast Broadband Programme.

Similarly, BEIS (now DESNZ) produce sub-national non-domestic energy consumption datasets, however these are only at the Middle Super Output Area (MSOA).[44] A similar methodology can be applied to evaluate the effect of superfast broadband installation on non-domestic buildings. One of the main concerns is that the higher geographical area may introduce more noise, particularly for treatment and control areas that lie on, or close to, the boundary. Another main consideration is that people do not necessarily work in their immediate MSOA, and it is not uncommon for individuals to travel between MSOA areas for work. Therefore, businesses outside treatment areas may be affected by installation of superfast broadband in a geographical location.

To address this, the analytical framework ensured that coverage of the gas and electric consumption data was representative of the treatment areas. The research team assessed if there were disproportionate areas that were not covered by the consumption datasets compared to the treatment area. Table 4.2 compares

[43] https://info.eco-act.com/hubfs/0%20-%20Downloads/Homeworking%20emissions%20whitepaper/Homeworking%20Emissions%20Whitepaper%202020.pdf

[44] MSOAs are constructed from groups of LSOAs and are designed to contain between 2,000 to 6,000 household (or 5,000 to 15,000 residents).

the proportion of postcodes covered in the consumption data, to the regional distribution of postcodes across the entire Superfast Broadband Programme. Table 4.2 shows that the coverage of the energy consumption data broadly matches the regional distribution of postcodes that have had superfast broadband installed. Scotland exhibits a slight over-representation in the consumption data, however the consumption data coverage of all other regions appears to broadly match the distribution of the programme.

Table 3.3: Proportion of energy data coverage compared to the distribution of superfast broadband rollout by NUTS1 Regions

	Domestic Electricity		Domestic Gas		Non-Domestic Electricity		Non-Domestic Gas	
Region Name	Consumption Data Coverage	Superfast Program Coverage	Consumption Data Coverage	Superfast Program Coverage	Consumption Data Coverage	Superfast Program Coverage	Consumption Data Coverage	Superfast Program Coverage
Scotland	19.0%	15.2%	16.4%	15.2%	18.8%	11.3%	16.6%	11.3%
Wales	0.8%	0.7%	0.7%	0.7%	3.9%	4.5%	3.8%	4.5%
East Midlands	10.2%	9.4%	10.8%	9.4%	8.7%	8.6%	9.1%	8.6%
East of England	14.1%	14.7%	12.0%	14.7%	10.7%	11.9%	10.6%	11.9%
London	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
North East	4.3%	4.2%	4.3%	4.2%	4.4%	4.8%	4.6%	4.8%
North West	9.3%	10.0%	11.3%	10.0%	12.1%	12.3%	12.9%	12.3%
South East	14.0%	15.7%	15.8%	15.7%	14.7%	16.9%	15.4%	16.9%
South West	13.4%	14.7%	12.3%	14.7%	9.0%	11.4%	8.8%	11.4%
West Midlands	7.5%	8.7%	7.9%	8.7%	8.4%	8.5%	8.7%	8.5%
Yorkshire and The Humber	7.3%	6.7%	8.4%	6.7%	9.4%	9.9%	9.4%	9.8%

3.4.2 Pipeline Design

The pipeline model (as described in Section 3.1.1) was implemented using the following generic econometric model:

$$y_{it} = \alpha_i + \beta T_{it} + \gamma X_{it} + \alpha^i + \alpha^t + \varepsilon_{it}$$

This model links the outcome of interest for area *i* in period *t* (y_{it}) to whether the area has benefitted from subsidised coverage in period t (T_{it}). The coefficient β captures the effect of subsidised coverage on the outcomes. Models will also generally include a vector of time varying control variables describing other characteristics of the areas that may also influence the outcome of interest (X_{it}). Econometric models were developed to allow for unobserved but time invariant characteristics of the areas of interest that could bias results (α^i) as well as unobserved but time specific shocks (α^t) affecting all areas[45].

[45] All models will be estimated with robust standard errors. Hausman tests will be applied to determine the use of Fixed or Random Effects.

The econometric model used can be seen below:

$$log(energy\ consumption_{it}) = \beta_1 Cumulative\ Connections_{it} + \beta_2 Cumulative\ Connections_{it} Urban_i + \beta_3 Number\ of\ Meters_i + \beta_4 COVID_t + \beta_5 Covid_t Urban_i + \beta_6 2013_t + \beta_7 2014_t + \beta_8 2015_t + \beta_9 2016_t + \beta_{10} 2017_t + \beta_{11} 2018_t + \beta_{12} 2019_t$$

Dependent Variable

The dependent variable used in the analysis was $log(energy\ consumption_{it})$. Energy consumption was input into the models as the total energy consumption for each postcode area: one of either total domestic electricity consumption, total domestic gas consumption, total non-domestic electricity consumption or total non-domestic gas consumption. For each of the four different outcome measures of energy consumption, the logged value was used, to address non-normalities in the data[46]. The econometric model remained the same through the analysis of domestic and non-domestic energy usage. This allowed an estimate of the association between the Programme roll-out and different measures of energy consumption to be made.

Variable of interest

The key independent variable, and the one that identifies any statistical impact of the Programme is $Cumulative\ Connections_{it}$. This variable represents the number of cumulative connections in each postcode. This is an adaption of the pipeline model outlined in section 3.1.1, with $Cumulative\ Connections_{it}$ used in place of the binary variable (T_{it}). The advantage of using a cumulative number of connections over using a binary treatment/control variable is that the binary variable assumes the same fixed effect on the energy consumption of a postcode area, regardless of the number of connections in each postcode. The cumulative number of connections assumes a fixed effect in terms of energy consumption for each *additional* connection made in a postcode area, better controlling for the variation in the number of connections in each postcode area. In this way the analysis establishes the degree to which the additional connections have led to a causal effect on energy consumption.

The interaction of $Cumulative\ Connections_{it} Urban_i$ accounts for the difference in the marginal change in total energy consumption that may arise due to an additional connection between urban and rural properties; where $Urban_i = 1$ if the postcode area is classified as urban. This helped to control for differences between urban and rural properties that may have confounding impacts on any detected marginal change, e.g., the expectation that properties in urban environments would be more energy efficient due to heat island effect (i.e., being closer together so hold heat better) compared to rural properties. Note, this variable is only included in the domestic regressions due to the different form the $Urban_i$ variable takes in the non-domestic regressions, caused by higher levels of geography. This is discussed further in Section 3.4.3.

Control Variables

In the pipeline model, control variables were added to hold constant a number of potential confounding variables on the analysis, including;

- $Number\ of\ Meters_{it}$ – This controls for the varying number of electricity meters by each postcode. This helped to account for the different reported levels of total energy consumption within each postcode level, preventing over-attribution of any detected change to the Superfast Broadband

[46] The use of non-normally distributed data can lead to the incorrect interpretation of hypothesis tests and confidence intervals

Programme by equivalising by the number of meters within each postcode area. Note, this also is dependent on time due to inconsistencies in year-on-year reporting.

- $COVID_t$ – A binary variable that controls for the potentially unusual and unrepresentative changes in domestic and non-domestic energy consumption during the Pandemic. Due to the lockdowns imposed, people were mandated to stay at home and working from home became common place, and a significant number of workers were furloughed, meaning most were not travelling to work. Including the COVID variable avoids over-estimating the impact of the Programme (e.g., attributing increased domestic electricity consumption to the ability to work from home, rather than being told to work from home). The $COVID_t = 1$ where $t \geq 2020$, reflecting the fact that COVID-19 led to significant changes in work from home behaviour, both during and after the lockdowns.

- $urban_i COVID_t$ – This is an interaction between whether a postcode is classified as urban, and when the meter reading has been affected by COVID-19. This variable controls for differences between the energy consumption of urban and rural households during the various lockdowns of 2020 and 2021. It was expected that the properties in urban environments would be more energy efficient due to heat island effect (i.e., being closer together so hold heat better) compared to rural properties.

- *Year dummy variables* – The use of year dummy variables was to control for variation in the weather, and therefore energy usage, across the control period. For example, a particularly cold year may result in a higher energy consumption across both treatment and control group, however without controlling for this, it would be attributed to increased energy consumption due to working from home. The inclusion of year dummies also controls for variation in energy price and the extent to which this influences consumption, although this would require the assumption that there are homogenous effects on energy consumption from a change in price across all units. Given the pipeline design used to evaluate this research question, it would be expected that differences between early and late adopters are marginal – so a plausible assumption to make.

3.4.3 Evaluation Limitations

BEIS (now DESNZ) datasets are in experimental format, and guidance is provided for sub-national analysis which takes into account limitations, coverage and comparability.[47]For instance, electricity consumption is not weather-corrected (i.e., does not control for the fact that energy consumption increases in colder weather and reduces in warmer weather, adjusting the consumption figure accordingly) while gas consumption is weather corrected. However, this weather-correction is more relevant for short-term analysis where problems of prediction arise from the multiple seasonal components. This would be less of an issue for this analysis since it compares multi-year periods, assuming that there were no significant changes in annual seasonal weather patterns over that period. Furthermore, the inclusion of dummy variables for each year helps to control for variation in weather conditions across the evaluation period.

One proviso is that household consumption data can suffer from high levels of statistical noise, due to the myriad of factors (property and household characteristics, and the infrequency of consumption reporting which varies between properties depending on how often they submit metre readings) that drive differences in energy consumption, over and above the teleworking context. The research team were unable to control for household characteristics, due to the lack of postcode level data[48]. Therefore, the estimated marginal impact of an additional connection on the energy consumption does not account for differences in household

[47] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1050290/subnational-methodology-and-guidance-2022.pdf

[48] At the time of writing, the 2021 Census data has not been released at the postcode level. Future work in this space could seek to utilise the low levels of geography of the Census data to better control for statistical noise.

characteristics (e.g., number of bedrooms, floor space, number of occupants) or socio-economic factors. To overcome the inability of being able to match on household and socio-economic characteristics, the analysis assumes that the factors are randomly allocated across the treatment and control areas with no significant selection effects, meaning the statistical noise is held constant in the analysis.

A further challenge, for the estimation of the impact on non-domestic premises, is incremental energy usage in offices. This challenge, which has not been satisfactorily resolved in the literature, is whether remote working has net positive or net negative energy consumption impacts, since it may be that offices are more efficient places for people to work, benefitting from economies of scale (a lower energy consumption cost per head to keep the lights on for a team of people in an office compared to lots of individuals lighting their own homes). This is further complicated by the potential lag effects between an uptake in working from home and a downsizing of office space. This means that offices have the lights on for a smaller number of workers who locate in the office, while the remainder work from home using energy in their own homes while still contributing to energy consumption pressures in absentia from their offices.

It is likely that any increases in household energy consumption are at least partly driven by home working (implying there may be offsetting effects in non-domestic settings that may be difficult to capture). The analytical framework used MSOA level data on non-domestic energy consumption to identify if a relationship exists between an increase in domestic consumption and a change in non-domestic energy use in the workplaces to which these households commute. However, the households in the treatment and comparator areas only make up a small proportion of the labour force in that workplace, and there may be a large number of workplaces in any one MSOA area (which is a large geographic area, containing thousands of postcodes) meaning that this analysis would be susceptible to considerable contamination effects. These effects may be exacerbated in the recent past by the fact that offices may have stayed open during the COVID-19 pandemic, even whilst the majority of their staff were isolated at home. As such, companies may not yet have adjusted to the post-Covid demands for office space.

Furthermore, there is the added complication that it is feasible that individuals from treatment areas may travel outside of the treatment or control areas for work. One likely scenario would be commuting from a treated area to an office/workspace in a major city (which was not eligible for the Superfast Broadband Programme). In this instance, the statistical matching between the connected postcodes and MSOA non-domestic consumption would exclude changes in non-domestic consumption in the workspaces not included in the treatment or comparator area. Another challenge exists in that it is also feasible for individuals to live and work in different MSOA areas. In instances like this, the analysis would be unable to identify the impacts of superfast broadband installation in one MSOA area to changes in non-domestic energy consumption in another area.

3.4.4 Impact of Working from Home on Energy Consumption

The results of the analysis can be broken down into four components: domestic electricity consumption, domestic gas consumption, non-domestic electricity consumption, and non-domestic gas consumption. For each component, fixed effects regression were run. The results for each component are presented below:

Domestic Electricity Consumption

The results of the pipeline model regression can be seen in Table 4.3 below. The results suggest that an increase in the **number of cumulative connections in a postcode area leads to an increase in the domestic electricity consumption.**

- It is estimated that each **additional connection in a postcode leads to an increase in domestic electricity consumption of 0.01% for an urban property**; the equivalent to 0.36kWh per connection per year[49].
- Likewise, it is estimated that **each additional connection in a postcode area leads to an increase in domestic electricity consumption of 0.04% for a rural property**; equivalent to 1.27kWh per connection per year[50].
- **This supports the hypothesis that an increase in work from home behaviour (enabled by increased accessibility of superfast broadband) has led to an increase in domestic electricity consumption**.
- In both cases, the variables of interest are individually statistically significant at the 99% confidence level, and jointly significant at the 99% confidence level[51].

For comparison, switching from a D rated fridge freezer to an A rated fridge freezer, would save approximately 206kWh of electricity per year[52], equating to an annual saving of approximately £70 for the household (based on the October 2022 price per kWh of electricity).

Interestingly, there are statistically insignificant effects on domestic electricity consumption identified in the model due to COVID-19. It was expected that the lockdowns during the Pandemic would have led to an increase in domestic electricity consumption, given most people were confined to their home for extended periods of time during 2020 and 2021. Detecting a lack of significance of this variable could suggest that there is an underlying issue with the model, or data provided to the model. However, the urban COVID-19 interaction term yields a negative coefficient, which is statistically significant at the 99% confidence level, confirming the notion that rural homes would have used more electricity during the various lockdowns of 2020 and 2021.

The model achieves an overall R^2 of 60%[53], suggesting that independent variables explain 60% of the variation observed in the total energy consumption. The within R^2 reports how much of the variation within the dependent variable is captured by the model (i.e., how much variation in total energy consumption *within* each postcode area is explained by the independent variables). The within R^2 is reported as 17%. The between R^2 reports how much variation in total postcode area electricity consumption is captured for different postcodes, reported at 58%. The reported R^2 values suggest that the model does a good job at accounting for variation in total domestic electricity consumption, both within postcode areas, and between different postcode areas.

[49] Based on median total consumption figure from domestic electricity consumption dataset, equivalised at the household level
[50] Based on median total consumption figure from domestic electricity consumption dataset, equivalised at the household level
[51] Joint statistical significance of variables is tested using an F-test.
[52] https://www.confused.com/gas-electricity/guides/appliances-how-much-do-yours-cost-to-run
[53] Within a fixed effect framework, the overall R^2 is a weighted average of the 'between' and 'within' R^2 metrics.

Table 3.4: Regression output for domestic electricity consumption

Variable	Coefficient	P-value
$Cumulative\ Connections_{it}$	0.0004***	0.0000
$Cumulative\ Connections_{it}urban_i$	-0.0003***	0.0000
$Number\ of\ Meters_{it}$	0.0300***	0.0000
$Covid_t$	0.0011	0.2065
$urban_iCovid_t$	-0.0118***	0.0000
2015	0.0107***	0.0000
2016	-0.0132***	0.0000
2017	-0.0237***	0.0000
2018	-0.0498***	0.0000
2019	-0.0578***	0.0000
Constant	10.5318***	0.0000
Number Of Observations	1,088,066	
Number Of Postcodes	252,559	
R-Squared - Within	0.171	
R-Squared - Between	0.583	
R-Squared - Overall	0.600	

******* *p<0.01, ** p<0.05, * p<0.1. Robust p-values used.*

The Null Hypothesis of the Hausman Test is rejected at the 99% confidence level, suggesting the fixed effects model is preferred to the random effects model.

Domestic Gas Consumption

Table 4.4 presents the results of the pipeline model for domestic gas consumption. The results suggest that **an increase in the cumulative number of properties connected to the superfast broadband network increases the consumption of domestic gas**. Results are significant at the 99% confidence level[54].

- **Each additional connection results in a 0.02% increase in domestic gas consumption, for an urban property**, equating to an additional 2.5kWh of gas consumption[55].
- **Each additional connection results in a 0.05% increase in domestic gas consumption, for a rural property**, this is equivalent to an additional 7.3kWh[56].
- **These results further support the notion that working from home increases domestic energy consumption**.

The impact of the connection in a rural area yields a similar impact on the level of gas consumption, as was seen for domestic energy consumption. It was estimated that for each additional urban connection, on average, the increase in gas consumption is 64% less when compared to a rural property. Once again this can likely be attributed to the energy efficiency gains from smaller, more compact urban housing, compared to rural housing.

[54] Cumulative Connections and Cumulative Connections Urban Interaction are jointly significant at the 99% confidence level
[55] Based on median total consumption figure from domestic gas consumption dataset, equivalised at the household level
[56] Based on median total consumption figure from domestic gas consumption dataset, equivalised at the household level

Due to multi-collinearity, both the $Covid_t$ and $urban_i Covid_t$ variables are omitted from the regression. There is also a poor model fit in the regression, with an overall R^2 of 3%; suggesting that the independent variables only account for 3% of the variation in the domestic gas consumption. The model copes relatively well in handling changes in the level of domestic gas consumption between different postcode areas, reporting a between R^2 of 16%. This is particularly important for a pipeline design, as areas that benefitted from the Programme first are compared against those that received the intervention later (i.e., a comparison *between* postcodes). However, the model is relatively weak at accounting for variation in domestic gas consumption within each postcode area; reporting a within R^2 of 2%. This suggests that the model is missing key explanatory variables that capture changes in domestic gas consumption, both within and between postcodes. It could therefore be suggested that the model could be improved to better estimate the impact of the Superfast Programme on household electricity consumption through the use of appropriate control variables, which is further discussed in Section 3.4.

Future work could also seek to link other data sources, such as Smart meter data. This would allow researchers to dig further into gas consumption results to be certain that the lack of significant effect is borne out in more sensitive household-level data, and not an artefact of limitations in the data.

Table 3.5: Regression output for domestic gas consumption

Variable	Coefficient	P-value
$Cumulative\ Connections_{it}$	0.0005***	0
$Cumulative\ Connections_{it} urban_i$	-0.0003***	0
$Number\ of\ Meters_{it}$	0.0000***	0
$Covid_t$	-	-
$urban_i Covid_t$	-	-
2015	-0.0293***	0
2016	-0.0254***	0
2017	-0.0022***	0.0035
2018	-0.0084***	0
2019	0.0022***	0.0061
2020	0.0188***	0
Constant	12.3056***	0
Number Of Observations	1,148,511	
Number Of Postcodes	170,502	
R-Squared - Within	0.021	
R-Squared - Between	0.161	
R-Squared - Overall	0.033	

**** p<0.01, ** p<0.05, * p<0.1. Robust p-values used.*

The Null Hypothesis of the Hausman Test is rejected at the 99% confidence level, suggesting the fixed effects model is preferred to the random effects model.

Non-Domestic Electricity Consumption

As previously discussed, analysis of non-domestic energy consumption was undertaken at a higher level of geography (MSOA level compared to the postcode level) due to data limitations.

Due to higher levels of geography, the $urban_i Covid_t$ term has been transformed; a dummy variable for *urban* was not appropriate as all MSOA areas in the treatment group have at least one urban area. As such, the $urban_i$ variable is transformed from a binary variable to a count of the number of connected urban postcodes in the MSOA area, now represented as $urban_{it}$, given it is dependent on time. Whilst the $urban_{it}$ variable can be used to interact with the $Covid_t$ variable, it is no longer feasible[57] to interact the $urban_{it}$ variable with $Cumulative\ Connections_{it}$. Table 4.5 presents the output for the non-domestic electricity regression.

The $urban_{it}Covid_t$ coefficient is statistically significant at the 99% confidence level, and suggests that during the pandemic, non-domestic electricity consumption is lower in places that have more urban postcodes. This may be likely explained by the type of non-domestic properties in urban and rural areas. For example, office blocks in urban areas could close and enforce work from home during the pandemic, but factories or warehouses (which often remained open during the pandemic depending on their role) could not allow employees to work from home.

The variable of interest, $Cumulative\ Connections_{it}$, is a cumulative count of the number of connections in each MSAO area.

- The results of the analysis suggest that **the level of non-domestic electricity consumption increases as the number of connections to the superfast broadband network increase** (statistically significant at the 99% confidence level).
- **For every additional connection in an MSOA area, non-domestic energy consumption increases by 0.004%[58]** (equivalent to annual increase of 0.29kWh per connection to the superfast broadband network[59]).
- This also suggests that increases in domestic electricity consumption are not offset by decreases in non-domestic consumption.

The coefficient of $Cumulative\ Connections_{it}$ in both the domestic and non-domestic regressions is positive, suggesting that an increase in the ability to work from home is not being offset by a reduction in non-domestic electricity consumption. One possible explanation for not seeing a reduction in non-domestic electricity consumption is that non-domestic premises, for example office blocks, have not yet identified a way to fully adjust to a hybrid style of working. That is to say that the number of employees in an office may be independent to the energy consumption of a building, as lighting, maintaining temperature, running servers, etc takes a given amount of energy regardless of the number of employees in the building.

An explanation for the positive impact on non-domestic electricity could be improved connectivity leading to productivity gains among industrial businesses. Better access to superfast broadband may have enabled business expansion, and hence an increased use of electricity, which would swamp any offsetting effects of residents in the area being able to work from home. This would especially be the case if the businesses in the area were large industrial users of electricity, at a magnitude much greater than offices whose staff may be able to work from home.

However, caution is required in comparing the magnitude of energy increases from the two sets of results (domestic and non-domestic), since the difference in magnitude could be driven by differences in the method/data, specifically the geographical scale of postcode level vs MSOA. Further research would be

[57] Namely due to the abstract interpretation associated with the interaction

[58] Note Table 4.4 rounds to 4 decimal places, so is reported as a zero impact

[59] Based on the average consumption per non-domestic property as per the sub-national domestic electricity consumption statistics, equivalised to the individual non-domestic premises level.

required to understand in what direction the data bias would be expected to lead, and to what extent this can be quantified and adjusted to improve comparability of the results.

There is an improved model fit for the non-domestic regression compared to the domestic one. The overall R^2 is 68% for the non-domestic electricity model, compared to 60% for the domestic electricity consumption model, suggesting that the independent variables explain more of the variation in the measures of non-domestic electricity usage compared to the domestic electricity use model. Most notably, there were significant improvements in the within R^2, estimated to be 74%. A higher R^2 for higher levels of geography[60] was not anticipated. Further work would be needed to better understand the drivers behind the within R^2 and how the level of geography interacts with the underlying econometric model.

Despite concerns over the reported model fit, internal consistency is exhibited within the regression outputs. The $Covid_t$ dummy variable shows that during the Covid-19 Pandemic, non-domestic electricity consumption decreased by 57% and is also statistically significant at the 99% confidence level. This is likely driven by the various lockdowns and restrictions preventing a lot of non-domestic properties (and therefore places of work) from opening.

Table 3.6: Regression output for non-domestic electricity consumption

Variable	Coefficient	P-value
$Cumulative\ Connections_{it}$	0.0000***	0.0000
$Number\ of\ Meters_{it}$	0.0019***	0.0000
$Covid_t$	-0.5717***	0.0000
$urban_i Covid_t$	-0.0007***	0.0000
2014	0.0405***	0.0000
2015	-0.0101***	0.0024
2016	-0.2182***	0.0000
2017	-0.3196***	0.0000
2018	-0.3803***	0.0000
2019	-0.4159***	0.0000
Constant		
Number Of Observations	49,922	
Number Of Postcodes	6,241	
R-Squared – Within	0.744	
R-Squared – Between	0.744	
R-Squared – Overall	0.684	

***** p<0.01, ** p<0.05, * p<0.1. Robust p-values used. The Null Hypothesis of the Hausman Test is rejected at the 99% confidence level, suggesting the fixed effects model is preferred to the random effects model.*

Non-Domestic Gas Consumption

Table 4.6 presents the results of the pipeline model for the non-domestic gas regression. The variable of interest, $Cumualtive\ Connection_{it}$, is statistically significant at the 95% confidence level.

- **The results of the regression suggest that each additional connection made in an MSOA area is associated with a 0.001% increase in non-domestic gas consumption[61];** this is equivalent to

[60] Higher R^2 is typically driven by lower levels of variation exhibited in MSOA data compared to postcode level data, because of significantly higher sample sizes of MSOA.

[61] Note Table 4.6 rounds to 4 decimal places, so is reported as a zero impact

approximately 1.68kWh of additional gas per connection to the superfast broadband network[62]. This means that there is not an observed accompanying decrease in non-domestic gas consumption, which would offset the increase in domestic consumption; as originally hypothesised.

One possible explanation for this increase in non-domestic consumption in superfast broadband roll-out areas may be that the improved connectivity leads to productivity gains among gas users, leading them to expand their business and use more gas. This in turn swamps any gas reduction impacts that may be produced by the increased ability of residents in the area to work from home. This would be especially the case if the businesses in the area were large industrial users of gas, at a magnitude much greater than offices whose staff may be able to work more from home, but whose gas use is predominantly for heating.

The overall model R^2 is 40%, however there is a comparatively low within R^2 of 8%, suggesting variation in the level of non-domestic gas consumption within each postcode area is not fully explained by the control variables. This is similar to the domestic regression, in that the gas statistics are not as well captured to their electricity counterpart. This suggests that additional control variables will be needed to better understand the drivers of non-domestic (as well as domestic) gas consumption.

Table 3.7: Regression output for non-domestic gas consumption

Variable	Coefficient	P-value
$Cumulative\ Connections_{it}$	0.0000**	0.0388
$Number\ of\ Meters_{it}$	0.0205***	0.0000
$Covid_t$	-0.0427***	0.0000
$urban_i Covid_t$	0.0003**	0.0288
2014	-0.002	0.5651
2015	-0.023***	0.0000
2016	-0.043***	0.0000
2017	-0.0167***	0.0017
2018	-0.0188***	0.0010
2019	0.0002**	0.0400
Constant	15.378***	0.0000
Number Of Observations	46,587	
Number Of Postcodes	5,947	
R-Squared - Within	0.075	
R-Squared - Between	0.422	
R-Squared - Overall	0.403	

**** p<0.01, ** p<0.05, * p<0.1. Robust p-values used. The Null Hypothesis of the Hausman Test is rejected at the 99% confidence level, suggesting the fixed effects model is preferred to the random effects model.*

3.4.5 Recommendations for Future Research

Throughout the analysis, areas of future research have been identified that would help to further contribute to the research question. Due to limitations in data availability, the proposed future avenues of research were out of scope for this report, but may be possible to explore in the future as/if data becomes more available:

- **The use of Smart meter data:** Smart meter data could allow for matching on actual household characteristics, but was outside of the scope of the current evaluation given the difficulties of obtaining

[62] Based on the average consumption per non-domestic property as per the sub-national domestic gas consumption statistics.

consent from all of the required households. Matching on household characteristics would allow for confounding variables (such as number of bedrooms, where one would expect a larger number of bedrooms to be associated with increased energy usage) to be held constant in the analysis. This would help to overcome any omitted variable bias that may be present in the existing model due to the lack of inclusion of these variables.

- **Use of the National Energy Efficiency Data-Framework (NEED) dataset:** Use of the NEED dataset was beyond the scope of this report due to data accessibility restrictions. Using unique property reference numbers within the dataset may present data linking opportunities to identify further control variables that could be used in the analysis; which would hold confounding variables constant and reduce bias that may have arisen due to omitted variables.

3.5 RQ3. Behaviour change: demographic and land use change

Research question 3: Has the increased ability to work from home associated with roll-out of superfast broadband led to land use change and associated habitat disruption?

The assumption underlying the land use change analysis is that more people have been able to move into the treatment areas because of improvements in broadband speed, allowing them to work, study, and enjoy online recreation in these areas, compared to the comparator group areas, which may be demonstrated through increased housing development in treatment areas. The key data set for this analysis is the monitoring information containing data on treated and white postcodes and the UK Centre for Ecology and Hydrology (UKCEH) Land Cover Maps, which provide detailed UK wide coverage of land use from 2007 to 2020[63].

3.5.1 Methodology

The untreated white postcodes – postcodes where there are no commercial plans to roll out superfast broadband – were used as a comparator group. To make meaningful comparisons to the treated areas, propensity score matching was used to identify the white postcodes that can be considered similar with respect to the probability of receiving the treatment based on a set of observable characteristics. The same matching model is used as in RQ1 – see Section 3.3 for more detail.

Estimating land use change

The UKCEH Land Cover Maps from 2007[64], 2015 and 2020 are available as Raster layers, which are made up of pixels which represent a 25meter x 25meter area.[65] Individual pixels represent 21 different land types[66] (pixel values can be re-coded so that they are consistent across different releases). Individual pixels from the 2007 and 2015 Land Cover Maps can be compared to the 2020 Map to identify changes in land use over time.

The matched sample can then be overlaid on the Land Cover Maps, and the pixel values extracted, providing an indication of the land use for each postcode - where comparisons can be made between treatment and control postcodes in the matched sample.

Guidance from the UKCEH indicates that urban pixels include areas such as towns, city centres, dock sides, car parks and industrial estates. Sub-urban pixels include areas where there is a mix of urban and vegetation signatures. For the purpose of this analysis, urban pixels will refer to those pixels that are classified as urban

[63] https://www.ceh.ac.uk/data/ukceh-land-cover-maps
[64] Note, the 2007 map represents the earliest UKCEH Land Cover Map before the intervention in 2013
[65] https://www.ceh.ac.uk/data/ukceh-land-cover-maps
[66] https://www.ceh.ac.uk/sites/default/files/2021-11/lcm2020ProductDocumentation.pdf

and sub-urban; non-urban will refer to pixels that are neither urban nor sub-urban. Comparisons can be made to understand the extent to which pixels changed from a non-urban to urban state. It should be noted that inaccuracies arising from the data collection phase (i.e., the use of satellite imagery) can cause pixel values to change year on year, particularly between urban and sub-urban classification.

3.5.2 Limitations

The main limitation of the analysis is that due to the intensive computational nature of the GIS work, only the pixel value of the postcode centroid can be extracted. It would be preferrable to understand the area around the postcode, and how the land use in areas in close proximity to the postcode centroid have evolved over time, given that the postcode itself is built on and does not change. As such, this analysis shows how the land use had evolved over time between treatment and comparator areas, but this cannot be directly attributed to the Programme as the land use would necessarily have to be for residential housing in order for the broadband to be installed.

3.5.3 Estimated Change in Land Use

Table 4.7 below presents the results from the analysis. This shows that the percentage of pixels that are classified as urban in the treatment and comparator areas has increased between 2007 and 2020, with a larger increase in the comparator areas. However, since 2015, the land use change has been lower in the comparison group compared to the treatment group (with the interventions starting in 2016), which suggests that there has been more change in land use in treatment areas than comparator areas over the course of the Programme. However, given the fact that the allocation of the treatment is dependent on the area being built, it does not fully explain the extent to which the roll out of superfast broadband *caused* the land use to change. Note that these findings are purely descriptive. For instance, the treatment areas may be in areas where housing development is common, due to existing demand to live in an area, unrelated to the rollout of superfast broadband. This means that in the absence of intervention, the number of urban pixels may have increased faster compared to the rest of the UK. Recommendations to improve this analysis are presented in the following section – noting that this analysis was limited by the intense computational nature of spatial analysis.

Table 3.8: Change in pixel classification between 2007 and 2020

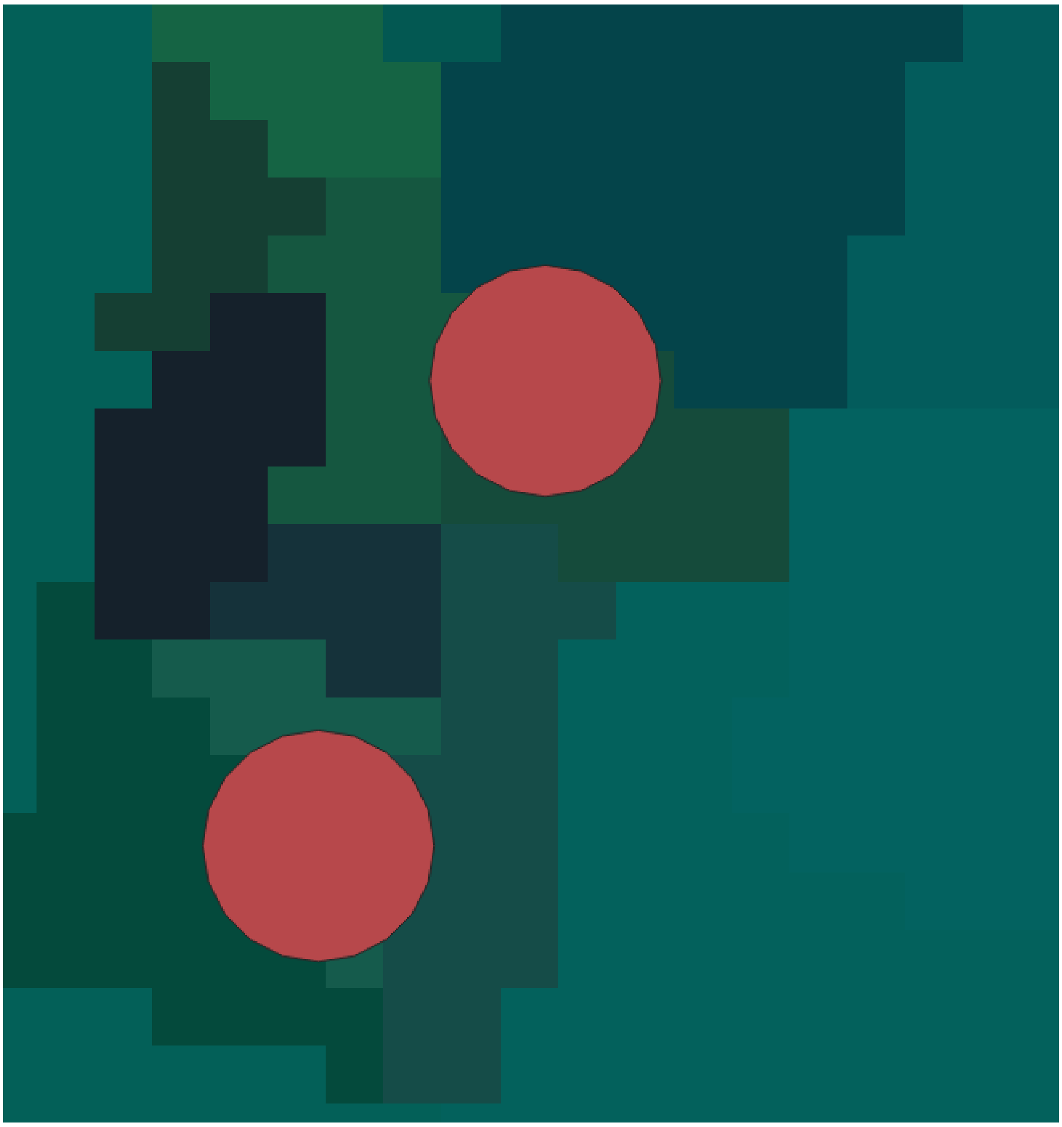
	Pixel change from 2007 to 2020	Pixel change from 2015 to 2020
Percentage change of pixels from a non-urban to urban state – treatment group	8.6%	3.2%
Percentage change of pixels from a non-urban to urban state – matched comparison group	12.4%	2.6%
Statistically significant differences	Yes	Yes

Note: Due to the nature of how the Land Cover Maps are generated (satellite imagery), some changes in pixel values may arise due to inaccuracies in the data collection process, particularly between urban and sub-urban classification. Weighting of the matched sample accounted for in means and significance testing.

3.5.4 Recommendations for future research

Due to computationally intensive analysis, there have been limitations in identifying the extent to which the roll out of superfast broadband caused land use change. Figure 4.2 below provides a visualisation of a possible approach to enhance the analysis, subject to sufficient processing power. To understand how the land around the treatment area changes over time, ‘buffers’ around the postcode centroids could be created – represented by the red circles in the figure below. A 0.05km buffer could be used given the clustering of treated postcodes – this would help to reduce the instances of multiple counts of the same pixel value, as well as reducing the computational burden of running the analysis. The matched sample can then be overlaid on the Land Cover Maps, and the pixel values extracted, providing an indication of the land use around the postcode; i.e. any pixel that is within (either fully or partially) the red circle will be assessed for land use change. This can then be used to estimate how the land use has changed over time around the postcode centroid – where comparisons can be made between treatment and control postcodes in the matched sample.

Figure 3.1: Visualisation of 0.05km buffer overlaid on UKCEH Land Cover Maps



Source: UKCEH Land Cover Map 2020 and BDUK Monitoring data

Additional avenues of future research could also include:

- **Peatland loss:** Peatland act as a ‘carbon sink’, where the carbon contained in the peatland has an associated economic value. If causal impacts of land use change can be identified, the map of the peatlands in England and Scotland could be overlaid with areas of land use change. This would provide an estimate of the value of the carbon released by destroying the peatland and the associated land change use. It should be noted that this would add further layers of complexity to the already computationally intense analysis.

- **The Department for Environment, Food, and Rural Affairs Enabling a Natural Capital Approach Databook to examine biodiversity impacts:** Nascent literature and guidance on assessing and monetising biodiversity impacts at a sub-national level have this avenue of research from scope of this report. However, development in the evidence base of a Natural Capital Approach would enable the biodiversity impacts associated with land change use, enabled by access to superfast broadband to be better explored.

- Assuming the above avenues of future research become feasible, the use of local economic and socio-demographic indicators would help to control for local level characteristics between treatment and control areas that may lead to a different amounts of land use change between treatment and control areas, in the absence of policy. Controlling for these confounding factors would help to increase robustness of and impacts analysis that may become viable within the future.

3.6 RQ4. Infrastructure: Congestion caused by civil works

3.6.1 Methodology

Research question 4: Has the disruption caused by the roll-out of superfast broadband led to environmental impacts through traffic disruption?

To explore the environmental impacts of traffic disruption, a **case study modelling approach** to understand the congestion (and resultant carbon) costs associated with broadband deployment funded by the Programme has been used. This used the QUADRO (QUeues And Delays at ROadworks) modelling tool maintained by Highways England. QUADRO provides a method for assessing the total cost of major road maintenance works[67].

Typically, QUADRO is used for ex-ante analysis, to predict the impact of proposed road works. The QUADRO tool is used here for an ex-post as to the best of the research teams knowledge, it represents the most comprehensive tool for estimating the effect of road works on traffic flow and associated environmental impacts. For ex-post analysis of historic impacts, permit data for individual incident of work between 2020 and 2022, provided by utility companies to input data on where the civil works took place, for how long, and how the road was impacted (how many lanes were closed) etc. was used.

Due to inconsistencies in data formatting, a limited number of traffic count points[68] around roadworks, and the labour-intensive process of manually entering permit data, the QUADRO tool was used on 52 sites, to generate estimates of the environmental impact of the road works. Due to a limited sample of sites, the outputs produced by QUADRO are unlikely to be representative of all works. As such, an assumption based approach has been used to extrapolate the environmental effect of roadworks to the treatment area as a whole. The permit records provide a rich data source of the type of work undertaken to install the fibre optic

[67] https://www.tamesoftware.co.uk/manuals/QUADRO2021_Full.pdf
[68] A key parameter for QUADRO

cables. However, the research team were only able to secure permit records from two providers, meaning that assumptions have to be made around how representative these case studies are. Data included in the permit records includes:

- Street location and town.
- Highway Authority (potentially allowing us to link incidents to local traffic data at the local highways authority level).
- Categorisation of the road affected (numerical in the data scoped so far, so this would require a codebook to interpret and input into QUADRO).
- Time: Proposed start and end date and duration of works.
- Location of the works: E.g. footpath, carriageway, verge.
- Traffic management type: Scope of roadworks and closures required, ranging from some carriageway intrusion to multi/two-way signals and full road closure.
- Works description: This is not categorised, but only provided in open-text format. QUADRO requires data on the scope and impact of the works on traffic movement.
- Activity description: Describes the fibre works, rather than impacts on the road. Categorised as Minor-Major.
- Other variables which will require further clarification/codebook descriptions: Designation applicable to works; traffic management plan required; environmental health notifiable; collaborative working; highway exemption; excavation carried out; modification request details.

Within the permit records available the research team combined several data points to select relevant sites that met the criterial below:

- **Intervention:** The research team excluded repair and maintenance work from the analysis. This was completed by undertaking a manual review of the items in the descriptions provided to mitigate against data inconsistencies to ensure that records that related to repairs rather than fibre installation were excluded from the analysis.
- **Carriageway impacts:** The permit data file included applications which impacted on the verge, footpath, as well as the carriageway. For the purposes of this analysis only the impacts on vehicle traffic were considered. Therefore, disruption to only the verge or footpath were excluded from the analysis.
- **Actual works:** The permit data file included applications which were granted, not granted, cancelled, and did not take place for other reasons. Not granted and cancelled applications were excluded.
- **Other factors:** The dates for which permit data were available spanned from 2020 to 2022. Using DfT Road Traffic Statistics[69], the research team matched traffic counts to the year of the works. This does cause potential problems in extrapolating results to pre-2020 road sites, given the impact of Covid on

[69] https://roadtraffic.dft.gov.uk/#6/55.254/-6.053/basemap-regions-countpoints

the levels of road traffic over this period, meaning road traffic levels between 2020 and 2022 are likely unrepresentative of pre-Covid traffic levels.

Applying the above criteria to the permit records produced a sample size of 52 sites. As discussed above, this is not representative of all treatment areas; therefore, assumptions were required to extrapolate across the whole treatment area. This data can be input into QUADRO at the road location (road name and town) where the incident occurred. In order to model the typical expected congestion impacts of civil works associated with fibre installation, in terms of their total cost, carbon implications, injuries/mortalities etc. QUADRO requires the following input data:

- **Location of road**
- **Duration:** In weeks, with options around working day vs 24 hours, midweek vs weekend etc.
- **Traffic flow:** Traffic count is data provided by DfT Road Traffic Statistics[70]. One challenge that was encountered was that the civil works associated with fibre installation often occur on local roads which are not always covered by count points in the DfT Road Traffic Statistics. In instances where road traffic data is not available, local authorities could be individually contacted, to enquire about local road traffic data they may hold. However, this data is often a manual count, rather than automated traffic count, and there are often long lead times from enquiry and obtaining the data. As such, use of local authority traffic count data is beyond the scope of this evaluation. An alternative method of obtaining traffic count data is using the DfT TAG guidance on how to estimate the capacity of a road[71], through which a low, medium, or high flow designation to non-SRN roads can be assigned.
- **Make-up of traffic:** Percentage heavy goods vehicles. QUADRO has average default of 15 percent. In instances where road traffic statistics recorded this measure, it was incorporated into the analysis.
- **Type of road:** QUADRO provides options to change the type of road within the input file. QUADRO allows users to choose between four types of road: rural, urban, suburban and small town roads. An assessment of the road type for each permit record will be made when inputting data into QUADRO. QUADRO is not equipped to handle access points (such as cul de sacs), which are beyond the scope of this analysis due to a lack of road traffic count data for cul de sac roads.
- **Traffic management type:** On single carriageways these can include shuttle working (traffic lights, one direction allowed through at a time); or narrow lanes; On dual these can include narrow lanes; lane closed; contra-flow (one carriageway closed entirely and other carriageway becomes two direction). QUADRO is able to estimate likely impacts based on the inputted traffic management type.

The main challenge for analytical modelling in this evaluation is mapping traffic management incident data from web providers to the intervention types used in QUADRO. This a labour-intensive process, where inconsistent data causes additional complications; as such a case study approach to model the typical expected congestion impacts of civil works associated with fibre installation has been adopted.

3.6.2 Limitations

A key challenge for the analysis was the lack of permit data for the pre-2020 period. From engagement with network operators it has become clear that only 2020 to present permit data was available. For aggregation

[70] https://roadtraffic.dft.gov.uk/#6/55.254/-6.053/basemap-regions-countpoints
[71] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/938864/tag-m3-1-highway-assignment-modelling.pdf

purposes, it is necessary to make an assumption that disruption levels associated with fibre installation is constant over time, and in this way to 'back-date' disruption data onto pre-2020 treated areas. It will also require assumptions on the number of permits per postcode delivered, as well as the nature of the works (i.e. road excavation, road closure, length of time, etc).

One challenge with only having permit data from 2020 onwards was that this was collected during peak COVID-19 lockdown. It may not therefore be representative of the welfare loss that people experienced under normal circumstances, as the roads were likely not at capacity and in that case congestion impacts would be low. Whilst this does not pose a significant problem for works undertaken during the pandemic, extrapolation to years before the pandemic are likely to be an under-estimate welfare losses as there were reduced levels of traffic on the road. The DfT TAG[72] was used to inform the aggregation process, and assumptions used within the analysis.[73]

3.6.3 Estimated Impacts due to congestion

When assessing maintenance works, the total of the works and road user costs were taken into account by QUADRO to calculate the total cost of the works and were used to compare the full costs of alternative maintenance options and to assess the maintenance implications of different options for road improvements.

For the purposes of this Environmental Evaluation, only the carbon costs have been used, but future avenues of work may seek to better understand the impact of delay costs (value of time), vehicle operating costs and accident costs that are associated with a large-scale infrastructure investment Programme. The Carbon Costs have been taken from the BEIS carbon values tables, in terms of Green House Gas (GHG) emissions produced as a consequence of the civil works, calculated as equivalent tonnes of carbon dioxide (tCO_2e)[74].

Running the sample of 52 sites through the QUADRO tool identified that there are marginal impacts in terms of carbon costs per application. On average, each permit that required installation works on the carriageway yielded an additional £140 worth of greenhouse gasses, in 2020 prices. This does not include the greenhouse gases emitted through the works (i.e. use of machinery to dig the road), rather the additional cost of the greenhouse gases that are emitted due to diverted traffic or temporary traffic lights.

Permit data pre-2020 is not available for the purposes of the evaluation, nor is the complete permit data available post-2020. As such assumptions are used to estimate the number of permits over the course of the Programme:

- It is assumed that each postcode where new connections were made in each phase required one permit each. A total of 538,067 permits were submitted across the UK from 2013 to 2021.
- The percentage of permits that require carriage way closures, and are not considered part of routine maintenance, are then accounted for. This ranged from 10% to 1% when using the permit data from two providers – these will be treated the upper and lower bounds, which a central estimate of 5% used. This produces an estimated number of relevant permits of 28,403 (3,140 - 53,665) in the UK between 2013 and 2021.

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[72] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/938864/tag-m3-1-highway-assignment-modelling.pdf
[73] Where the DfT produce values aid the monetisation of environmental impacts, reflecting the societal benefit of improving given conditions.
[74] The HM Treasury Green Book (2022) provides factors for conversion of other greenhouse gases to a carbon cost: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

- Next, the additionality of the Programme is considered, to account for what would have happened in the absence of the intervention. Additionality assumptions are based on the analysis in the State Aid report.[75] The analysis only covers 2017 – 2021, and so the average additionality percentage is applied to treated postcodes between 2013 and 2016. Estimated additionality rates range from 49% to 81%, with an average rate of additionality of 67%. When the additionality rates are applied the estimated number of relevant permits is 18,268. This yields the number of permits which are expected to generate £140 of additional greenhouse gasses per permit.

The total present value cost in terms of greenhouse gas emissions is estimated to be **£2.3 million (£0.3 million £4.4 million)** over a 17 year-appraisal period (2013 – 2030).

3.6.4 Recommendations for future research

Future developments to this work could include utilising local authority traffic count data, which is not available online, directly through the local authority. This is likely to increase the number of roads in which traffic count information is available for – and may help to target the more residential roads which this Programme specifically targets. Scoping work indicated that some local authorities will charge (approx. £200-£1,000) for administrative time in preparing this data, but others will be free.

For the purposes of this Environmental Evaluation, only the carbon costs will be utilised, but future avenues of work may seek to better understand the impact of delay costs (value of time), vehicle operating costs and accident costs that are associated with a large-scale infrastructure investment Programme.

[75] See section 6.2 of *Evaluation of the Superfast Broadband Programme State aid evaluation: Main Report February 2023* (2023) Ipsos

4 Economic Impacts

Section 4 presents an overarching view of the economic benefits/disbenefits and costs that are estimated in Section 3 of this report. The economic impacts within this report are limited only to those which indicate a change in environmental conditions, and as such does not consider the broader cost/benefits of the Programme, nor does it attempt to undertake a full cost benefit analysis. For the purposes of this analysis, the monetised impact has been estimated over a 17-year evaluation period (2013 – 2030), to remain consistent with the main report.

The environmental economic benefits that are estimated include:

- **Reduced greenhouse gas emissions through increased working from home:** The roll-out of superfast broadband is hypothesised to increase the propensity to work from home, reducing the greenhouse gas emissions through commuting to an office environment. The impact analysis estimated that the treated areas were associated with a 9% increase in work from home behaviour. Although it should be noted that this estimate is subject to significant uncertainties and should not be treated as a causal estimate (see Section 3.3.3).

The environmental economic disbenefits that are estimated include:

- **Increased domestic energy consumption:** Due to the hypothesised increase in working from home, domestic energy consumption is likely to rise consequently. The impact analysis estimated that each additional connection in a postcode leads to an increase in domestic electricity consumption of 0.1% for an urban property; and that each additional connection in a postcode area leads to an increase in domestic electricity consumption of 0.04% for a rural property.

- **Increased non-domestic energy consumption:** It was found that the increase in domestic consumption was not off-set by a decrease in non-domestic consumption. Rather, the impact analysis identified that: For every additional connection in an MSOA area, non-domestic energy consumption increased by 0.004%, and For every additional connection in an MSOA area, non-domestic gas consumption increased by 0.001%.

The environmental economic costs are estimated include:

- **Increased greenhouse gas emissions from a build-up of traffic around roadworks:** Using the QUADRO economic evaluation tool from National Highways, it was possible to estimate the increase in greenhouse gas emissions that were associated with work works/ road closures within the treatment areas. The total present value cost in terms of greenhouse gas emissions is estimated to be **£2.3 million (£0.3 million - £4.4 million)**.

4.1 Economic impact of reduced commuting through increased working from home

Whilst the extent to which the Superfast Programme *caused* a change in work from home behaviour remains unknown, this section provides an illustration of the economic value of the 9.3% reduction in work from home behaviour.

The aggregation process contains several steps:

- **Step 1:** An estimate of the total number of working adults needs to be established. Using the count for the number of postcodes where superfast broadband has been rolled out to (6,465,229) combined with estimates of working adults per household yields the total estimated number of working adults in-scope of the Programme. ONS estimates indicate[76]:

- 59.1% had all household members aged 16 and over in employment;
- 27.2% had a mix of one working adult and one workless adult; and,
- 13.7% of households had no working age adults in employment.

The average household size of 2.36 is used for 'all household members aged 16 and over'.[77]

Combining the above yields an estimated 10,775,985 working adults within the treated areas.

- **Step 2:** The 9.3% increase in work from home is applied, where this increase can be interpreted as the marginal increase in work from home behaviour associated with the Programme, as described in the above sub-section. Applying this marginal increase equates to an estimated additional 1,003,813 people who now work from home rather than commute into an office.
- **Step 3:** To understand the economic value of the environmental impact, the method of travel to work is required – because walking, cycling, driving or using the train will all have different environmental impacts. To account for this, the average from the 2011 Census is used to understand the pre-COVID travel to work behaviour.[78] The average proportion for each method of travel across the treatment areas is used.

Table 4.1: Method of transport to work for treatment areas

Method of transport	Proportion
Underground/ tram	0.4%
Train	3.5%
Bus/ coach	4.1%
Taxi	0.4%
Motorbike	7.2%
Driving car	66.1%
Passenger car	5.1%
Bicycle	2.2%
Walk	10.2%
Other	0.7%

Source: 2011 Census data. Excluding the work from home population

- **Step 4:** The above proportions are applied to the estimated increase in the number of people working from home. This provides an estimate of the method of travel that these people otherwise would have used.

76 https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/bulletins/workingandworklesshouseholds/apriltojune2023

77 https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2022#:~:text=The%20average%20household%20size%20remained,both%202012%20and%20in%202022.

78 https://www.nomisweb.co.uk/census/2011/qs701ew

Table 4.2: Estimated number of individuals in treatment areas that are working from home that would not have been in the absence of the Programme

Method of transport	Proportion	Those that are now working from home that otherwise would not be
Underground/ tram	0.4%	4,477
Train	3.5%	35,629
Bus/ coach	4.1%	41,336
Taxi	0.4%	3,657
Motorbike	7.2%	72,143
Driving car	66.1%	663,425
Passenger car	5.1%	51,390
Bicycle	2.2%	21,975
Walk	10.2%	102,635
Other	0.7%	7,147

Source: 2011 Census data combined with Ipsos analysis of MI data

- **Step 5:** DESNZ publish conversion factors for the level of emissions of greenhouse gasses associated with various methods of transport.[79] These can be used to estimate the environmental impact associated with each mode of transport. A number of simplifying assumptions are made:
  - There are no environmental impacts associated with walking or cycling, hence the shift to home working does not represent a reduction in greenhouse gas emissions for those who used these methods of transport.
  - For simplicity, the greenhouse gas emissions for cars are taken as the average of petrol and diesel vehicles of all sizes. Whilst electric vehicles are becoming increasingly popular, one must consider the additional strain placed on the electricity grid to power these vehicles. This builds additional layers of complexity and uncertainty into the analysis. As such a simplifying assumption has been made.
  - For those that are passengers in cars, there would only be greenhouse gas emissions saving with all other passengers in the car also work from home – otherwise the car would be making the commute regardless. This means that the act of driving the car is captured in the 'driving car' row of the table above. Therefore to avoid double counting, it is assumed that passengers working from home have no impact in terms of greenhouse gas emissions.
  - In the absence of data on what modes of transport 'other' refers to, this is taken as the average reduction in greenhouse gas emissions of the models of transport in the table above.
- **Step 6:** The greenhouse gas emissions are presented in CO_2e (equivalent CO_2 emissions) per km travelled. Therefore, these estimates need to be combined with the average distance travelled to work by transport method – which can be obtained from the 2011 Census.[80] Multiplying the CO_2e by the average distance travelled provides an estimate of the CO_2 emissions per person per mode of transport. This can then be converted to tonnes of CO_2.

[79] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022
[80] https://www.nomisweb.co.uk/census/2011/lc7701ew

- **Step 7:** The tonnes of CO_2e per person can then be multiplied by the number of people that correspond to the method of transport.

Table 4.3: Estimated Carbon emissions saved as a result of working from home per day

Emission Factors	CO_2e emissions in tonnes per person per day	Total tonnes CO_2e per day
Underground/ tram	0.0004	1.763
Train	0.0005	17.653
Bus/ coach	0.0009	35.730
Taxi	0.0029	10.632
Motorbike	0.0051	365.873
Driving car	0.0076	5056.561
Passenger car	0.0000	0.000
Bicycle	0.0000	0.000
Walk	0.0000	0.000
Other	0.0007	4.965
Total Reduction in CO_2e (tonnes)	NA	**6206.213**

Source: 2011 Census data combined with Ipsos analysis of MI data

- **Step 8:** DESNZ publish carbon values that can be applied to the above to estimate the economic value of the greenhouse gas emissions.[81] The accrual of reduced travel behaviour is profiled from 2010 to 2030 – the appraisal period of interest – to yield an estimate of the net present value of benefits. The results are presented in the below table.

Table 4.4: Estimated present value saving through increased working from home

Method of transport	2013 - 2022	2023 - 2030
Underground/ tram	£0.6m (£0.3m - £0.8m)	£0.5m (£0.3m - £0.7m)
Train	£5.9m (£3m - £8.2m)	£5.4m (£2.7m - £6.6m)
Bus/ coach	£11.9m (£6m - £16.5m)	£10.9m (£5.4m - £13.3m)
Taxi	£3.6m (£1.8m - £4.9m)	£3.2m (£1.6m - £4m)
Motorbike	£122.3m (£61.2m - £169.2m)	£111.1m (£55.6m - £136.2m)
Driving car	£1690.5m (£845.3m - £2,338.1m)	£1,535.7m (£767.9m - £1,882.4m)
Passenger car	£0m (£0m - £0m)	£0m (£0m - £0m)
Bicycle	£0m (£0m - £0m)	£0m (£0m - £0m)
Walk	£0m (£0m - £0m)	£0m (£0m - £0m)
Other	£1.7m (£0.8m - £2.3m)	£1.5m (£0.8m - £1.8m)
Total	**£1,836.5m (£918.3m - £2,540m)**	**£1668.3m (£834.2m - £2,044.9m)**

The above table suggests that over a 17-year appraisal period, the estimated total present value benefit of reduced emissions from travelling to work, due to working from home is, £3.5 billion (£1.8 billion - £4.6 billion).

[81] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

4.2 Economic impact of Working from Home on Energy Consumption

From the marginal impact estimated in Section 3.4, lower and upper bound monetised estimates on the levels of Green House Gas (GHG) emissions are generated as a consequence of increased household energy consumption associated with the increased propensity to work from home in areas with superfast broadband, compared to comparator areas. The analysis considers both the impacts of domestic and non-domestic energy consumption for the purpose of this monetisation exercise.

To monetise the impacts, the total change in the level of energy consumption must be identified. Firstly, the estimated coefficient must be converted into a percentage change, this was done by using the following formula, where β_1 is the coefficient of $cummulative\ connections_{it}$ and β_2 is the coefficient of $Cumulative\ Connections_{it} urban_i$. $urban_i$ is equal to 1 if the postcode is classified as urban and 0 otherwise; if the postcode is classified as urban, the estimated coefficient of β_2 must also be accounted for in the aggregation. This can be seen in the equation below:

$$\%\Delta \text{ energy consumption} = \left(e^{\beta 1} - 1\right) * 100 + \beta_2 * urban_i$$

The estimated change in energy consumption for each connection in kWh can then be found by multiplying the marginal percentage change by the median consumption in the sub-national dataset. Multiplying by the median consumption of each property equivalises at the household (or business premises) level. Multiplying this by the total number of connections at a given point in time yields the total change in energy consumption caused by houses having access to superfast broadband. Table 5.5 below presents the total estimated impact on energy consumption for each of the four measures of energy consumption.

- **Across the evaluation period, it is estimated that the Programme has caused an additional 710.6 million kWh of energy use in both domestic and non-domestic properties,** over a 17-year appraisal period**.**

- **A significant proportion (62%) of the estimated increase in energy consumption is driven by increases in domestic gas use.**

Further work would need to be undertaken to better understand this result, with follow up interviews of residents and businesses to explore how the availability of superfast broadband has led to such a large estimated increase.

Table 4.5: Estimated impact on energy consumption (kWh) associated with the installation of superfast broadband over a 17-year evaluation.

	Domestic		Non-Domestic	
	Electricity Consumption (kWh)	Gas Consumption (kWh)	Electricity Consumption (kWh)	Gas Consumption (kWh)
Estimated aggregated impact on energy consumption (kWh) over a 17-year evaluation period	70.5 million	441.7 million	29.4 million	169.0 million

To convert the impact (currently measured in kWh) into equivalent tonnes of carbon dioxide (tCO_2e), BEIS (now DESNZ) Green Book supplementary guidance[82] was used, alongside Data Tables[83], also published by BEIS (now DESNZ). Using Table 1 and Table 2a from the published Data Tables, the impact on domestic energy consumption can be converted into $kgCO_2e/kWh$[84] and then into tCO_2e[85]. From here, BEIS (now DESNZ) Data Table 3 provides low, central and high estimates for the price of one tCO_2e[86]. Multiplying the estimated tCO_2e by the price of carbon yields a costed economic impact, in 2020 prices, of increased household energy consumption associated with the increased propensity to work from home in areas with superfast broadband, compared to control areas. This has then been discounted by a rate of 3.5% per year, as per HM Treasury Green Book (2022) guidance.[87] The results of the monetisation of impacts can be seen in Table 4.8 below.

- **Over a 17-year evaluation period, the cost to society of the Superfast Broadband Programme on energy consumption in present value terms to be £25.6 million (low estimate £12.8 million, high estimate £34.8 million).**

- **In terms of the timing of these impacts, it is estimated £13.8 million of the present value costs are incurred between 2013 and 2022, and the remaining £11.8 million of present value costs incurred between 2022 and 2030.**

- **Overall, this suggests a cost to society of £25.6 million, caused by increased energy consumption, that can be attributed to work from home behaviour, that has been enabled by access to superfast broadband.**

In terms of differential impacts on electricity and gas usage: The £25.6 million total cost to society from increased energy usage associated with the Superfast Programme, is split between:

- Cost to society due to increased domestic energy consumption of £18.0 million (low estimate of £3.8 million, high estimate of £27.0 million) in present value terms; and

- Cost to society of increased non-domestic energy consumption to be £7.6 million (low estimate of £379million, high estimate of £11.4 million) in present value terms.

Table 4.6: Estimated Net Present Value of the economic disbenefit of changes in energy consumption due to superfast broadband over a 17-year evaluation period, 2020 prices

	2013 - 2022	2022 - 2030
Domestic Electricity	£2.1m (£1.1m - £3.2m)	£1.2m (£0.6m - £1.8m)
Domestic Gas	£7.7m (£3.9m - £11.6m)	£7m (£3.5m - £10.4m)
Non-Domestic Electricity	£1m (£0.5m - £1.5m)	£0.9m (£0.5m - £1.4m)
Non-Domestic Gas	£2.9m (£1.5m - £4.4m)	£2.7m (£1.3m - £4m)
Total	£13.8m (£6.9m - £20.7m)	£11.8m (£5.9m - £17.7m)

[82] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal
[83] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal#full-publication-update-history
[84] Kilograms of CO_2 per kWh of energy used.
[85] This is achieved by converting the $kgCO_2e/kWh$ into tCO_2e/kWh (tonnes of CO_2 per kWh). Then multiplying by the number of kWh of energy used. The BEIS Data Tables provide conversion factors to enable this transformation
[86] It should be noted that BEIS Data table 3 only provides £/tCO_2e from 2020 onward. Due to a changed approach in 2021 for calculating the cost of carbon, old data tables do not provide realistic societal costs. As such, values from 2013 to 2019 have been generated for the purposes of this analysis, using the same methodology for 2020 values onwards.
[87] https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent/the-green-book-2020

Note: table may not sum due to rounding

4.3 Economic Impacts

The economic impacts are set out in the table below, where economic costs and disbenefits have a negative value, as they reduce societal welfare.

Table 4.7: Economic Impacts – Total Present Value

Economic Impact	2013 – 2022	2023-2030
Reduced greenhouse gas emissions through reduced commuting through increased **working from home**	£1,837m (£918m to £2540m)	£1,668m (£834m to £2,045m)
Increased domestic energy consumption through working from home	-£9.9m (-£4.9m to -£14.8m)	-£8.2m (-£4.1m to -£12.1m)
Increased non-domestic energy consumption associated with superfast broadband rollout	-£4.0m (-£6.0m to -£2.0m)	-£3.6m (-£5.4m to -£1.8m)
Increased greenhouse gas emissions through road works/ closures when installing cables	-£2.3m (-£4.4m to -£0.3m)	NA
Total economic impact	**£1,820m (£903 - £2,523)**	**£1,657m (£825m - £2,031m)**

Note: Table may not sum due to rounding

The results above suggest that the Superfast Broadband Programme yielded estimated present value environmental benefits that totalled £3,477m (£1,728m - £4,554m) over the evaluation period. This was primarily driven through reduced greenhouse gas emissions through reduced commuting, enabled by increased working from home (noting the uncertainty in the estimated impacts). It is important to note that key environmental impacts (e.g. land use change and associated biodiversity impacts, embedded carbon in the fibre network, etc.) have not been estimated, nor monetised and so the estimated benefits present a partial view of the economic value of the associated environmental impacts.

5 Future Research Questions

This section of the report presents three future research questions which were beyond the scope of this report, but would help to better understand the full spectrum of environmental impacts associated with the Programme. Subject to future data availability, addressing the below research questions would help to fill existing gaps in literature regarding environmental impacts associated with superfast broadband.

5.1 FRQ1. Enabled Technology

Future research question 1a: Has the roll-out of superfast broadband led to a shift from physical servers to cloud computing leading to reduced energy consumption?

Future research question 1b: Has the roll-out of superfast broadband led to an increase in the use of video software enabling online meetings and conferences leading to reduced energy consumption?

An assessment of the environmental impacts associated with enabled technology would have to rely on evidence from secondary literature sources that cloud servers are more efficient compared to physical servers and therefore likely to reduce the impact on the environment through lower CO_2 emissions. The business impacts of enabled technology like cloud computing have been addressed in previous waves of the evaluation through surveys of affected businesses, but not in a way that would enable evaluation within the environmental impact evaluation, coupled with the fact that no reliable evidence exists on the likely carbon savings associated with cloud computing roll-out.

The scoping of existing evidence, such as the primary surveys undertaken in the BDUK economic evaluation, and of the DSIT UK Business Data Survey[88] showed that although questions were asked about levels of cloud computing, that sample sizes of firms in the treatment and control areas were too low to perform reliable statistical analysis.

Evaluability considerations: The shift to enabled technology may also be a longer-term impact which will not be detectable within the current evaluation. In the absence of observable data, an assumptions-led approach informed by literature may present an avenue to explore this in the future. One important consideration would be the potential for bias if basing these assumptions on studies commissioned by technology companies who have a business incentive to over-emphasize the environmental benefits. However, it is possible that cloud computing has become more important post-COVID-19, with the accelerated shift to home working. If this is the case, then this gap could be addressed in future studies provided that the interventions in question have national scale impacts that might influence cloud computing decisions. This is outside the scope of the current evaluation. Future research could be undertaken combining primary data research on cloud usage among businesses in the treatment and control areas.

Future research question 1c: Has the roll-out of superfast broadband led to an increase in the use of smart meters in homes?

The roll out of superfast broadband may enable people to utilise smart meters, potentially allowing for better management of energy consumption.

Evaluating this research question would require a comparisons of smart meter use in the treated and comparison areas – exploring whether installation of superfast broadband has led to a step-change in smart

[88] https://www.gov.uk/government/statistics/uk-business-data-survey-2021

meter use. This would likely rely on utilising data help by energy companies on smart meter installation, and would require them to share data at the postcode level.

5.2 FRQ2. Infrastructure: Biodiversity impacts

Future research question 2: Has the disruption caused by the roll-out of superfast broadband led to environmental impacts through habitat disruption?

The Environment Act 2021 includes provisions on biodiversity which may inform a future evaluation approach. The research team formed a working assumption that the installation of fibre cables is expected to cause minimal impact as digging for new infrastructure happens along existing infrastructure routes, with a small area of ground disturbance less than 500mm in width. Environmental impacts associated with digital infrastructure are low scale in comparison to a) other underground utilities installation b) major project constructions such as Highways and Event Centres. However, there may be impacts in cases where installation works are taking place in previously in developed land. This could be explored through review of the permit data for installation of fibre cables (noting that this level of detail is unlikely to be available pre-2020).

Future research could explore these impacts further by mapping permit data to modelling data for different habitat types. For instance, analysis could map whether superfast broadband delivery was disrupting habitats in/near peatlands, as listed in the UKCEH Landcover maps and link this to the carbon and biodiversity impacts modelled in the Defra ENCA framework. ENCA provides a services Databook with 200 sources of evidence on ecosystem services such as food production, flood regulation and recreation and environmental impacts such as air pollution and noise. This provides biophysical and monetary values where appropriate, with explanatory notes and guidance on use. This is linked to the ENCA assets Databook with UK data sources on natural capital categories. However, this would be an analytically intensive process, and could only be undertaken on a case study basis.

Future research could augment the permit data with data from local authorities for evidence on tree felling permits and/or permits to conservation areas/wildlife conservation areas associated with this delivery. Average values can be assigned based on the characteristics of the trees felled (if data is available in local authority records) or to the likely ecosystem service losses, based on the ENCA Databook described above. However, this would require detailed data collection at the local authority level, which is beyond the scope of this evaluation. The research team concluded that this would be disproportionate to the scale of the environmental impacts from laying fibre cables, which are likely to be low, and which must also be assessed against a counterfactual of the ongoing maintenance and relaying of copper cables in the absence of fibre roll-out.

5.3 FRQ3. Infrastructure: Embedded carbon in fibre networks

Future research question 3a: Has the shift from copper to fibre cables associated with the roll-out of superfast broadband led to a decrease in CO_2 in the operating network?

Fibre cables are assumed to be more energy efficient, have lower maintenance requirements, and less impacts in their extraction, leading to a decrease in CO_2 emissions for maintaining the network. Although these outcomes may not be directly evaluable, there have been studies undertaken in other countries which may provide results that could be transferred to the Programme area. Europacable commissioned a Prysmian Group study (2021) investigating the relative energy demands of three network access technologies. The research modelled typical rural or urban settlement structures based on six regions in Germany, assuming a ubiquitous rollout and a minimum of 50Mbit/s for every connection within these regions. Compared to VDSL2[89] and HFC[90] networks (both using existing copper networks to different degrees in their network mix), the study found that FTTP/H (Fibre to the Premises/Home) is the most energy efficient consumer fixed-line technology. FTTP Gigabit Passive Optical Network (GPON) in particular, was shown to be far less energy intensive, requiring an annual energy value of 3,156MWh compared to 3,465MWh for VDSL2 and 4,987MWh for HFC. The study also estimated the CO_2 emissions associated with each network access type with FTTP emitting 1,685 tons/year – lower than VDSL2 (1,850 tons/year) and HFC (2,663 tons/year).

A recent (2020) peer-reviewed study from Germany[91] found that the kWh/year output per premise for an FTTP connection is 1.55, while for Copper (VDSL) it is 3.1. Applying BEIS (now DESNZ) carbon values of 0.23314 KG per kWh suggests a 50% saving of 0.362KG of CO_2 per premise per year (estimated as the difference between 0.361KG of CO_2 per premise per year for a fibre connection per year compared to 0.723KG of CO_2 per premise per year for copper).

To incorporate into the evaluation these statistics would need to be linked to data on the annual coverage of copper and fibre in the treatment and control areas. This data could not be provided, meaning it has not been possible to estimate the overall savings in energy use associated with the roll-out of fibre cable as part of the BDUK Programme in this iteration of the report.

Future research question 3b: Has the shift from copper to fibre cables associated with the roll-out of superfast broadband led to a decreased demand for copper in the supply chain?

Over time, a shift from copper to fibre cables will lead to reduced demand for copper extraction, and a reduction in its associated environmental impacts in the supply chain. No evidence has been found to inform this analysis.

A future evaluation of this impact would be dependent on an assumptions-led approach using accepted figures (if available) for environmental impacts in the supply chain associated with decreased demand for copper cable. This would need to be based on the likely replacement rate of existing cable, and so this is likely to be a marginal impact. Given that lack of reliable evidence in the literature and the marginal nature of this research questions, this question has been assessed as infeasible for the current evaluation.

Future research question 3c: Has the shift from copper to fibre cables associated with the roll-out of superfast broadband led to a decrease in CO_2 in maintenance costs?

The BDUK Benefits Realisation Framework highlights that switching from copper to fibre networks will result in direct improvements to efficiency via reduced maintenance costs (owing to the improved reliability of fibre). It can be anticipated that this will reduce the environmental costs of inspections and maintenance by reducing the number of vehicle trips made (and possibly reducing the need for street works). However, there are questions regarding how far these effects can be observed (e.g., via Street Manager data, as outlined in the previous sections) or inferred from secondary evidence.

The literature review showed wide agreement that fibre technology is also more reliable[92] and will therefore result in fewer resources being used to maintain the network. In particular, the 2021 TalkTalk and

[89] Very High Bit Rate Digital Subscriber Line uses copper networks https://ask.trustpower.co.nz/app/answers/detail/a_id/78/~/differences-between-adsl-and-vdsl

[90] Hybrid Fiber-Coaxial combines fibre optic and coaxial (copper) cable-based transmission https://www.techopedia.com/definition/25805/hybrid-fiber-coaxial-cable-hfc-cable

[91] https://www.ispreview.co.uk/index.php/2020/11/study-finds-full-fibre-is-the-most-energy-efficient-broadband.html

[92] https://www.cablinginstall.com/cable/fiber/article/16465844/how-fiber-can-help-make-your-network-greener

Carnerstone report referenced above also highlights the superior reliability of fibre optic over copper wire cables. The report identifies faults as one of the largest drivers of customer dissatisfaction and amount to high levels of field engineer visits.

The TalkTalk and Carnerstone report estimated the total distance of field engineer repair journeys to be 740,000 miles a year. However, it does not provide information on the number of repair jobs that need to be undertaken per year to create that footprint, nor the percentage decrease that could be expected with fibre. Instead, the report makes an overarching statement that with "less faults, exchanges and street cabinets, the frequency of engineer visits is expected to fall dramatically, and even if this reduced by a third, the report estimated that "hundreds of tonnes of GHG [emissions] would be saved as fewer journeys would be made."

It is envisaged that a future evaluation would be dependent on an assumptions-led approach using accepted figures (if available) for reduction in repair rate for fibre cables and associated CO_2 and NOx emissions. The literature review did not find any reliable evidence that could be used to develop robust assumptions linking miles saved per repair journey for each mile of fibre laid (replacing copper cable), and as such remains an avenue of future research.

Appendix A – Literature review

Introduction

We build on the DSIT Scoping Study which identified three channels of environment impact associated with the Superfast Programme:

1. Behavioural change
2. Enabled technology
3. Infrastructure

We expand on the initial theories of change proposed by DSIT for each channel. The literature review is comprehensive, and pulls out the key findings from the literature in summary tables at the end of each section.

Summary of main findings

Behaviour change

In sum, the majority of studies on the environmental impact of faster broadband through behaviour change (increasing the feasibility of working from home and fewer commutes to the individual's office / workplace) have been assumptions driven, based on different scenarios of work/travel behaviour and their associated carbon emissions, rather than on observable data, although in part this is a consequence of the fact that large-scale working from home patterns are a very recent post-COVID-19 occurrence. There have been some studies based on observational data that have shown that improvements in internet access increase the rate of teleworking, but they have not made the additional link to estimating the environmental impacts. One challenge that the environmental impact assessment has is that working patterns have changed significantly due to COVID-19 social lockdowns, which have accelerated the use of work from home technologies. ONS statistics show that a large proportion of the UK workforce has relied on working from home during the COVID-19 pandemic.[93] Superfast broadband is likely to play an enabling effect on this shift to working from home, but may not have been the only driver of this broader societal shift.[94] The challenge for econometric analysis will be to isolate the effect of superfast broadband alone.

Environmental impacts from enabled technology

There has been, and continues to be, a shift towards cloud computing evidenced by trends in cloud computing uptake in the Cisco (2018) report. While the efficiency of cloud computing is somewhat backed up by the literature, this remains a nascent topic of academic study, and there are few sources from which to draw confident conclusions on the energy, cost, and environmental savings that may be borne from greater cloud computing adoption. The loudest proponents of cloud computing are the benefactors of its use, and environmental benefits are often clouded by carbon offsetting pledges, shifting the focus away from the energy demands of cloud computing itself. Nonetheless, the findings illustrated in the Lawrence Berkely National Laboratory (2013) cannot be overlooked; their analysis provided convincing evidence on

93 https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/bulletins/coronavirusandhomeworkingintheuk/april2020

94 https://committees.parliament.uk/committee/460/covid19-committee/news/156095/covid19-and-employment-in-towns-and-cities/

the energy savings that can be realised from cloud computing adoption, and one can expect significant economies of scale savings to be realised if cloud computing is adopted on a large scale.

Environmental impacts from Video Conferencing

There is thin evidence in the academic literature highlighting the environmental benefits of videoconferencing and teleworking. Research using more rigorous methodologies highlight marginal environmental benefits to videoconferencing (Helimen and Ristimaki, 2005), and the more optimistic research findings often omit rebound effects, such as a teleworker travel behaviour. More research considering these effects are needed to fully address the effect of videoconferencing on the environment, however, when considering the emissions savings stemming from heavily-emitting business air travel, corroborating the reduced air transport mandated by the COVID-19 pandemic with Hernandez et al.'s (2021) findings, showcases the significant positive environmental benefits that may arise from a wide uptake in videoconferencing technology.

Environmental impacts of Copper vs Fibre networks

The copper extraction landscape accounts for a significant portion of worldwide metal extraction. Although it emits lower levels of environmental damage than the extraction of other metals (e.g., cobalt), the sheer volume of copper demand and levels of production results in significant amounts of health and environmental damage. Copper demand is expected to rise significantly in the future driven by factors such as population growth, and the quality of metal ores has reduced, requiring more energy and subsequent environmental damage to produce less quantities of copper. The widespread adoption of optical fibre networks would offset some of this reliance on copper extraction and the academic literature provides convincing evidence of the benefits that would arise from a shift to fibre. They are not only more efficient in transferring data than copper, but also require less energy to maintain, and are much more physically reliable.

Behaviour Change

A core assumption in the Internal BDUK scoping paper is that upgrading to superfast broadband internet speeds changes social behaviour by increasing the feasibility of working from home and consequently results in fewer commutes to the individual's office / workplace and reductions in carbon emissions.

This is in part supported by the literature. For example, using observational data from multiple waves of the Survey of Working Arrangements and Attitudes, Barrero, Bloom and Davis' (2021) argued that better home internet access increases the propensity to work from home. By adopting a regression approach to analysing the survey data, the paper found that a ten percentage-point rise in home internet access quality would bring about **a 0.8 percentage-point rise in the extent of working from home**. Whilst modest, the effect is statistically significant. However, the paper acknowledges its limitations, one being that it relies on self-reported worker assessments, and another significant limitation being that its projections neglect static general equilibrium effects. This means that the analysis does not account for the possibility whereby better internet access increases remote working, reducing the cost of office spaces in city centres, which may then induce a shift back towards office working.

Despite this, these findings are corroborated by an older 2006 study by Song, Prazem, and Singh. Using observable data from the 2001 UCLA Internet Survey, a nationally representative survey of computer and internet use, the paper developed an empirical model of telecommuting to analyse how broadband access affects the incentives to commute. Their analysis found that **differences in broadband access explained three-quarters of the gap in the probability of telecommuting between urban and rural labour**

markets. This study was restricted to salaried employees, however, which neglects the effect of broadband and higher internet speeds on the ability of self-employed individuals to work from home. Its outdated data also constrains the applicability of the research findings to the types of superior internet speeds we are used to now.

The link between better broadband and a reduction in commutes through an increase in remote working has been difficult to isolate. Most studies assume this relationship implicitly. For instance, a study commissioned by Openreach and carried out by the Centre for Economic and Business Research estimated with radical improvements in connectivity the enhanced opportunities for remote working could reduce transport pressures and **save 300 million commuting trips, representing a carbon reduction of 360,000 tonnes by 2038**. The study has a number of limitations, with the counterfactual being primarily **assumptions-based** and tailored towards future full fibre coverage in the UK.[95] We agree with DSIT's initial assessment that it is not suitable for the evaluation of superfast broadband and lacks a sufficient evidence base to be considered robust.

Additionally, a consortium led by SQW, in partnership with Cambridge Econometrics and Dr Pantelis Koutroumpis (2013) published a study which developed an integrated model projecting the effect of faster broadband in an economic, social and environmental context, within the UK. Using 2008 as a baseline year and extrapolating analysis to 2024, the study estimated that faster broadband **would lead to a reduction in the UK's annual commuting distance of around 2.3 billion kms by 2024**. This would predominantly be via car usage, however, given that teleworking is most common in less densely populated areas – which have larger homes, using more carbon-intensive fuels, as well as having the longest commutes – the study estimated that more than half of the carbon savings from reduced commuting and office energy use would be offset by higher domestic heating emissions. The resulting net annual saving in **CO_2 emissions (CO_2e) through increased teleworking, attributable to faster broadband, rises to 0.24 million tonnes by 2024**. Adding to that the CO_2e savings from the changes in business travel and server emissions, SQW (2013) estimated that the **total net carbon savings from faster broadband would be 1.6 million tonnes of CO_2e per annum by 2024, equating to a value of about £100 million**. While the authors are fair to highlight the study's standing as a particularly in-depth and rigorous analysis of the effects of faster broadband in the UK, the findings from this study are tempered by the heavily **assumptions-based models** used. The authors flagged that uncertainties are inherent to many of the assumptions used to generate the model's analyses, for example, the proportion of telework-eligible employees was assumed to be 40% in 2008 and 72% in 2024, and analysis using a counterfactual was not undertaken, limiting the robustness of the study's findings.

Significant carbon savings arising from teleworking were also found in a Carbon Trust (2021) report which performed predictive analysis of the carbon emissions savings associated with teleworking for four COVID-19 scenarios under different assumptions: before, during, post (2021), and post (2022+). **Findings predicted that total carbon savings per teleworker in the UK during COVID-19 was 889 kgCO_2e a year, compared to 272 kgCO_2e at pre-COVID levels, 429 kgCO_2e post-COVID (2021), and 273 kgCO_2e post-COVID (2022+).** At the country level, the study calculated the potential carbon savings from increased teleworking in a post-COVID (2022+) scenario, where everyone who can work from home does so at an assumed 3 days per week, to be 4.1MtCO_2e each year. Using a combination of national statistics data, research, studies, and media articles, the study made various assumptions to estimate the key

[95] This is based on the assumption that each of the 1,087,074 additional home workers in 2033 works from home instead of commuting to a place of employment 135 days a year (three additional days worked from home per week, 45 working weeks in a year) – therefore they each commute to or from work 270 times fewer per year; 63.7% of these journeys would have been by car and their average distance would have been 15.9 kilometres; Average CO_2 emissions per kilometre of 121.3g55.

variables used to calculate carbon savings. For example, in each scenario, the average number of days worked from home by a teleworker, the proportion of teleworkable jobs, average commuting distances, and average commuting, office- and domestic-related emissions were all assumed from secondary sources. The calculation of carbon should be interpreted with caution as the authors omitted emissions produced from internet related activities of working (such as videoconferencing), small domestic appliances for heating or cooling (such as desk fans), as well as larger domestic appliances (such as dishwashers), from their calculations. While the report argued that the emissions impact of these components is negligible or similar whether being at home or in an office, trends in increased energy usage at home during COVID (electricity consumption rose by more than 15 per cent on weekdays in the UK)[96] suggest that this omission may have had a larger effect on findings than the study presents. Projections of post-COVID (2022+) calculations are also highly uncertain. The report underlines this point, stating that predictions are sensitive to changes in future behaviour away from those assumed by the Upwork report on the future workforce used to inform the calculations.

A study by Fuhr and Pociask (2011) examined the reduction in greenhouse gas emissions in the US following a widespread delivery of broadband services and the consequent expansion in telecommuting. By undertaking a purely literature-based review analysis, the study provided simple estimations of the environmental effects telecommuting would have. The authors argued that telecommuting could reduce greenhouse gas emissions (GHGe) over the subsequent decade from the study's publish date, by approximately **588.2 tonnes. Of this, 247.7 million would be attributable to less driving, 28.1 million tonnes because of reduced office construction, and 312.4 million tonnes because of less energy usage by businesses**. However, the study omits reductions in GHGe stemming from the reductions in public transport that would arise from greater teleworking.

Acknowledging the impact of COVID-19 on promoting teleworking and assuming this practice would continue beyond the pandemic, Abulibeh (2020) presented a **literature review-based analysis** on the interventions and subsequent recommendations necessary to maximise the potential gains from widespread telework. The report argued that access to digital infrastructure and technologies and to fast broadband are necessary facilitators to the adoption of teleworking which can facilitate other policy goals like reducing carbon footprints, transport and traffic congestion, and occupational health and safety. Taking a similar literature review-based approach, other papers, notably an OECD productivity working paper by Criscuolo et al. (2021) and a 2021 paper by Milasi et al. argue that better quality internet connections have enabled the adoption of teleworking in cities and more densely populated areas, highlighting that telework uptake before and during the COVID-19 pandemic is correlated with ICT infrastructure quality.

Summary

In sum, the majority of studies on the environmental impact of faster broadband through behaviour change (increasing the feasibility of working from home and fewer commutes to the individual's office / workplace) have been assumptions driven, based on different scenarios of work/travel behaviour and their associated carbon emissions, rather than on observable data, although in part this is a consequence of the fact that large-scale working from home patterns are a very recent post-COVID-19 occurrence. There have been some studies based on observational data that have shown that improvements in internet access increase the rate of teleworking, but they have not made the additional link to estimating the environmental impacts. One challenge that the environmental impact assessment has is that working patterns have changed

[96] https://blogs.lse.ac.uk/covid19/2021/09/21/does-working-from-home-cut-carbon-emissions-not-necessarily-in-fact-it-can-have-the-opposite-effect/

significantly due to COVID-19 social lockdowns, which have accelerated the use of work from home technologies. ONS statistics show that a large proportion of the UK workforce has relied on working from home during the COVID-19 pandemic.[97] Superfast broadband is likely to play an enabling effect on this shift to working from home, but may not have been the only driver of this broader societal shift.[98] The challenge for econometric analysis will be to isolate the effect of superfast broadband alone.

97 https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/bulletins/coronavirusandhomeworkingintheuk/april2020

98 https://committees.parliament.uk/committee/460/covid19-committee/news/156095/covid19-and-employment-in-towns-and-cities/

Table A1: Behaviour change literature review: Key findings

Title	Citation	Link	Methodology	Values / Results
Can COVID-19 mitigation measures promote telework practices?	Abulibdeh, A., 2020. Can COVID-19 mitigation measures promote telework practices?. Journal of Labor and Society, 23(4), pp.551-576.	https://onlinelibrary.wiley.com/doi/pdf/10.1111/wusa.12498	Literature review	Access to digital infrastructure and technologies and to fast broadband are necessary facilitators to the adoption of teleworking which can facilitate other policy goals like reducing carbon footprints, transport and traffic congestion, and occupational health and safety.
Internet access and its implications for productivity, inequality, and resilience	Barrero, J.M., Bloom, N. and Davis, S.J., 2021. Internet Access and its Implications for Productivity, Inequality, and Resilience (No. w29102). National Bureau of Economic Research.	https://www.nber.org/system/files/working_papers/w29102/w29102.pdf	Regression analysis using survey data	A ten percentage-point rise in home internet access quality would bring about a 0.8 percentage-point rise in the extent of working from home.
The Homeworking Report	Carbon Trust. 2021. Homeworking report: An assessment of the impact of teleworking on carbon savings and the longer-term effects on infrastructure services.	https://www.carbontrust.com/resources/the-carbon-savings-potential-of-homeworking-in-europe	Predictive analysis using national statistics data, academic research findings, and media articles	Total carbon savings per teleworker in the UK during COVID-19 was 889 kgCO_2e a year, compared to 272 kgCO_2e at pre-COVID levels, 429 kgCO_2e post-COVID (2021), and 273 kgCO_2e post-COVID (2022+).
Full Fibre broadband: A platform for growth Cebr report for Openreach	Cebr. 2019. Full Fibre broadband: A platform for growth Cebr report for Openreach	https://www.openreach.com/content/dam/openreach/openreach-dam-files/images/hidden-pages/full-fibre-impact/CebrReport_online.pdf	Assumptions based	Reflecting trends in increasing home working, there would be an estimated 300 million fewer commuting trips, representing a carbon reduction of 360,000 tonnes by 2038.
The role of telework for productivity during and post-COVID-19	Criscuolo, C., Gal, P., Leidecker, T., Losma, F. and Nicoletti, G., 2021. The role of telework for productivity during and post-COVID-19: Results from an OECD survey among managers and workers.	https://www.oecd-ilibrary.org/content/paper/7fe47de2-en	Literature review	Telework uptake before and during the COVID-19 pandemic is correlated with ICT infrastructure quality.
Broadband and Telecommuting: Helping the U.S. Environment and the Economy	Fuhr, J.P. and Pociask, S., 2011. Broadband and telecommuting: Helping the US environment and the economy. Low Carbon Economy, 2(01), p.41.	https://www.scirp.org/html/4227.html	Literature review based analysis	Telecommuting could reduce GHGe by approximately 588.2 tonnes between 2011-2021. Of this, 247.7 million would be attributable to less driving, 28.1 million tonnes because of reduced office construction, and 312.4 million tonnes because of less energy usage by businesses.
Telework before the COVID-19 pandemic: Trends and drivers of differences across the EU	Milasi, S., González-Vázquez, I. and Fernández-Macías, E., 2021. Telework before the COVID-19 pandemic: Trends and drivers of differences across the EU.	https://www.sipotra.it/wp-content/uploads/2021/01/TELEWORK-BEFORE-THE-COVID-19-PANDEMIC-TRENDS-AND-DRIVERS-OF-DIFFERENCES-ACROSS-THE-EU.pdf	Literature review	Telework uptake before and during the COVID-19 pandemic is correlated with ICT infrastructure quality.
Broadband Access, Telecommuting and the Urban- Rural Digital Divide	Singh, R., Orazem, P.F. and Song, M., 2006. Broadband Access,	https://ageconsearch.umn.edu/record/18214/files/wp060002.pdf	Empirical modelling using observable survey data	Differences in broadband access explained three-quarters of the gap in the probability of telecommuting

	Telecommuting and the Urban-Rural Digital Divide (No. 1043-2016-85314).			between urban and rural labour markets.
UK Broadband impact study	SQW & Cambridge Econometrics. 2013. UK Broadband Impact Study.	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/257006/UK_Broadband_Impact_Study_-_Impact_Report_-_Nov_2013_-_Final.pdf	Assumptions based model	Faster broadband would lead to a reduction in the UK's annual commuting distance of around 2.3 billion kms by 2024. Net annual savings in CO_2 emissions (CO_2e) through increased teleworking, attributable to faster broadband, would equate to 0.24 million tonnes by 2024 Including CO_2e savings from the changes in business travel and server emissions, total net carbon savings from faster broadband would be 1.6 million tonnes of CO_2e per annum by 2024, equating to a value of about £100 million.

Enabled technology

The assumed driver of environmental impact from enabled technology is that as firms obtain access to faster and more reliable networks, there will be a trend away from physical servers to more efficient cloud computing.

There is evidence from a number of sources that cloud servers are more efficient compared to physical servers and therefore likely to reduce the impact on the environment through lower CO_2 emissions, summarised in the DSIT Superfast Broadband Programme – Synthesis Report (Ipsos MORI 2021[99]). This report is cited as a major source by the DSIT scoping study, but we note that this report only mentions the cloud 11 times, and only once was this related to efficiency:

“Subsidised coverage may allow public sector organisations to benefit from the faster broadband connectivity. This will potentially allow them to generate efficiency gains or realise cost savings by adopting cloud computing and allowing public sector workers to work more flexibly” (page 27)

Using qualitative interviews to inform its discussion, the report dug deeper into the operational efficiency of ultrafast connectivity, addressing considerations around the usage of cloud computing, but that these were not relevant to the evaluation of cloud vs physical servers. Given that the link between cloud computing vs physical servers and efficiencies cannot be observed directly, we will instead focus in this section on the wider literature.

Relevant literature on the apparent greater efficiency of cloud servers over physical servers is thin. Most academic literature focusses on the relative improvements in physical data centres which has allowed global data centre energy consumption to plateau, with Masanet et al.’s (2020) paper often being cited. They argue that since 2010, the **four-fold drop in electricity use per computation of a typical volume server** – the workhorse of the data centre – is largely owing to processing efficiency improvements and reductions in idle power. However, this observation is purely **correlational**, and the report does not attempt to isolate the impact of cloud computing in a causally robust way.

Despite this, there is a small body of literature that assess the superior efficiency gains that can be made from wider adoptions of cloud-based computing. A 2013 report titled, ‘The Energy Efficiency Potential of Cloud-Based Software: A U.S. Case Study’ by the Lawrence Berkely National Laboratory, represents a particularly notable source. The organisation developed an **open-access model for assessing net energy and emissions implications of cloud** services in different regions and at various levels of market adoption. Titled, CLEER (Cloud Energy and Emissions Research), the model is openly accessible and provides full transparency and allows for further refinement by the global research community. Applying this model to the US, the report performed **predictive** analysis of the effect of moving three common business applications – email, productivity software, and customer relationship management (CRM) software – used by tens of millions of US workers, to cloud servers. Their analysis found substantial potential for energy savings from this shift, amounting to **326 Petajoules, or an 87% reduction in the primary energy footprint of the three business applications**. The main driver of this reduction stems from the decrease in operational energy use when moving from local data centres to the cloud, which is expected considering “the cloud is expected to use far fewer serves in far more efficient data centres compared to present-day local data centres”. However, these findings are reliant on publicly

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99 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1022646/Superfast_Broadband_evaluation_sythesis_report.pdf

available data. This gives rise to significant uncertainty, particularly considering that such data was gathered from various studies and sources, published in differing years and scopes of analysis.

These findings are supported, however, in one of the most substantial studies produced by the one of the Big Five technology companies. Google applied **assumptions-led predictive analysis** to estimate that **switching from physical servers to cloud based servers can improve energy consumption by 68-87%.** An additional factor to consider is that Google powers its computing infrastructure through renewable energy and also commits to net zero sustainability targets. Therefore, businesses switching to cloud computing could reduce their CO_2 emissions by 68-87% or where cloud providers use renewable energy, this could be up to 100%.

To calculate low and high range estimates for carbon reductions, Google considered the following assumptions:

Client devices

- **For the 'Low' estimate:** Google assumed 1 laptop and 0.2 desktops per user, with an annual energy consumption of 60kWh and 160kWh, respectively.
- **For the 'High' estimate:** Google assumed 1 laptop and 0.8 desktops per user, with an annual energy consumption of 160kWh for the laptop and 400kWh for the desktop.
- Google states that these energy consumption figures are appropriate for a typical higher end 60 Watt laptop and a 150 watt desktop that are on for 2,600 hours per year. However, this does not align with other studies in the academic literature which equate to 2,080 hours.[100]

For server energy consumption after implementing Google Apps

- **For the 'Low' estimate:** Google assumed a 90% reduction in number of servers in the low estimate. This large reduction was to reflect the fact that the work in the "data-light" (office) business is heavily weighted towards the basic office applications that Google Apps can replace.
- **For the 'High' estimate:** Google assumed a 70% reduction in number of servers for the data intensive business, reflecting the fact that this workplace has many power users who rely on custom applications that still need on-site server support after the Apps migration. As above, it is assumed a PUE of 2.0 for the data-light business and a PUE of 1.5 for the data-intensive business.

In terms of its representativeness to energy usage as a whole, it is worth noting that a Business Insider article[101] stated that in 2020 there were 200 million users of Microsoft's Office 365 compared to only 5 million Google's G-Suite (now, Google Workspace). Therefore, using Google's own apps in this report does not give an accurate reflection of energy savings as assumptions of basic office applications being replaced by Google ones are quite a stretch.

[100] Murtagh et al. (2013) find a typical 40h week energy consumption value of 2.02KWh, equating to 105kWh in a year. Far lower than Google's estimate. A typical 40 hour week would also equate to 2,080 hours, less than the 2,600 hours per year Google uses. These would imply that Google's figures are actually higher than those found in other studies, which may be driven by a commercial imperative to maximise the reported carbon benefits of cloud computing. https://www.sciencedirect.com/science/article/pii/S0301421513007337

[101] https://www.businessinsider.com/google-g-suite-gmail-2-billion-vs-microsoft-office-2020-3?r=US&IR=T

For estimated savings in client devices referenced on page 3

- **For the 'Low' estimate:** Google assumed that 80% of the laptops and 80% of the desktops in the data-light business could be replaced by Chromebooks, reflecting the relatively routine use of computing resources that make up employees' work in this kind of company.

- **For the 'High' estimate:** It was assumed that only 25% of the data-intensive laptops and 5% of the data-intensive desktops could be replaced by Chromebooks. This was to reflect an underlying assumption that proprietary, non-enterprise software plays a large role in the work of employees at the data-intensive company.

- It is further assumed that Chromebook consumption is based on 11-watt consumption when awake, 0.5 watt consumption when asleep, and 20% fewer "on hours" per year than the desktop or laptop it replaces. This assumes that because Chromebook start-up and shut-down times are very fast, this would encourage users to turn off their devices more frequently, resulting in fewer "on hours", but discounts the fact that people will often leave their computers on with documents and applications open for convenience.

- Google's argument also based energy usage on their apps running on their own Chromebook devices. Again, it's an unlikely scenario to assume an 80% adoption of Chromebooks by data-light businesses. Although Chromebooks are seeing record sales, their adoption is highly skewed towards educational users, not firms[102]. Therefore, arguments leveraging Chromebooks superior start-up and shut-down times are not realistic.

As demonstrated by the above Google report and discussed in the Lawrence Berkely National Laboratory's (2013) study, the greater efficiency in cloud servers is often championed by the providers of such services and referenced in studies associated with these companies. Three of the Big Five technology firms - Amazon Web Services, Microsoft Azure, and Google Cloud Platform – have produced studies in this area. While it is worth noting that these companies have a commercial interest in making this claim, there does seem to be an industry shift towards cloud computing and the use of cloud servers (Cisco, 2018).

It is also worth noting that big cloud providers use carbon offsetting initiatives to reduce the carbon footprint of their servers. Therefore, not all of the carbon reductions are attributable to the technology itself, or they are at least made to appear more environmentally beneficial from these initiatives[103,104,105]. For example, Microsoft published a study in 2020[106] in partnership with WSP. Using **primary data from Microsoft datacentres and equipment and secondary data to calculate industry averages**, the report estimated that **Microsoft Cloud is between 22 and 93 percent more energy efficient than traditional corporate datacentres**. However, these estimations improve markedly once Microsoft's renewable energy purchases are considered, to between 72 and 98 percent increased carbon efficiency. The study also does not fully quantify carbon savings, with only relative percentages being used to illustrate environmental benefits of the cloud.

[102] https://www.canalys.com/newsroom/tablets-chromebooks-q4-2020
[103] https://sustainability.aboutamazon.com/environment/the-cloud?energyType=true
[104] https://cloud.google.com/sustainability
[105] https://azure.microsoft.com/en-gb/global-infrastructure/sustainability/#overview
[106] https://www.microsoft.com/en-us/download/confirmation.aspx?id=56950

Summary

There has been, and continues to be, a shift towards cloud computing evidenced by trends in cloud computing uptake in the Cisco (2018) report. While the efficiency of cloud computing is somewhat backed up by the literature, this remains a nascent topic of academic study, and there are few sources from which to draw confident conclusions on the energy, cost, and environmental savings that may be borne from greater cloud computing adoption. The loudest proponents of cloud computing are the benefactors of its use, and environmental benefits are often clouded by carbon offsetting pledges, shifting the focus away from the energy demands of cloud computing itself. Nonetheless, the findings illustrated in the Lawrence Berkely National Laboratory (2013) cannot be overlooked; their analysis provided convincing evidence on the energy savings that can be realised from cloud computing adoption, and one can expect significant economies of scale savings to be realised if cloud computing is adopted on a large scale.

The table below summarises the literature evidencing the efficiency connected with a shift towards cloud data centres:

Table A2: Enabled technology literature review: key findings

Title	Citation	Link	Methodology	Values / Results
Enabling Sustainable Clouds: The Case for Virtualizing the Energy System	Bashir, N., Guo, T., Hajiesmaili, M., Irwin, D., Shenoy, P., Sitaraman, R., Souza, A. and Wierman, A., 2021. Enabling Sustainable Clouds: The Case for Virtualizing the Energy System. arXiv preprint arXiv:2106.08872.	https://arxiv.org/pdf/2106.08872.pdf	Literature review based	Cloud platforms have long had a strong financial incentive to optimize energy-efficiency to lower their operating expenses, which are massive for hyper-scale cloud data centres. These optimizations have been quite successful: despite the end of Dennard scaling, the cloud's energy demand grew much more slowly than expected over the past decade. The success was largely due to industry's intense focus on reducing data centres' power usage effectiveness (PUE) to near 1 by aggressively optimizing energy-efficiency en masse across hardware, software, and cooling systems."
The Carbon Reduction Opportunity of Moving to Amazon Web Services Amazon – Sustainability in the Cloud	Bizo, D., 2019. The Carbon Reduction Opportunity of Moving to Amazon Web Services.	https://sustainability.aboutamazon.com/carbon_reduction_aws.pdf	Survey data analysis and assumptions based modelling.	"AWS's infrastructure is 3.6 times more energy efficient than the median of the surveyed US enterprise data centres. More than two-thirds of this advantage is attributable to the combination of a more energy efficient server population and much higher server utilization. AWS data centres are also more energy efficient than enterprise sites due to comprehensive efficiency programs that touch every facet of the facility" "Even when compared to the top 10% most efficient organizations surveyed, moving to AWS would deliver a 72% reduction in carbon footprint on average. The results suggest that moving to the cloud would reduce workload carbon footprint for virtually any US enterprise in this cohort of companies with revenues between $10m and $1bn."
Cisco Global Cloud Index: Forecast and methodology, 2016–2021 white paper	Cisco, "Cisco Global Cloud Index: Forecast and methodology, 2016–2021 white paper" (Cisco, document 1513879861264127, 2018).	https://virtualization.network/Resources/Whitepapers/0b75cf2e-0c53-4891-918e-b542a5d364c5_white-paper-c11-738085.pdf	Assumptions based	"Cloud adoption enables faster delivery of services and data, increased application performance, and improved operational efficiencies."
Energy efficiency in cloud computing data center: a survey on hardware technologies	Katal, A., Dahiya, S. and Choudhury, T., 2021. Energy efficiency in cloud computing data center: a survey on hardware technologies. Cluster Computing, pp.1-31.	https://link.springer.com/article/10.1007/s10586-021-03431-z	Assumptions based	"Data organizations foresee a decrease in the quantity of data centres, as more businesses close their little data centres and move towards cloud computing. All things

				considered, the move by clients towards cloud, will increase the general energy utilization significantly, exceeding any energy productivity increase; which has recorded for over 70% of data centre development in 2018.”
The energy efficiency potential of cloud-based software: a US case study	Masanet, E., 2013. The energy efficiency potential of cloud-based software: a US case study.	https://escholarship.org/content/qt68b51379/qt68b51379.pdf	Predictive analysis using publicly available secondary data.	“Cloud computing holds great potential to reduce data centre energy demand moving forward, due to both large reductions in total servers through consolidation and large increases in facility efficiencies compared to traditional local data centres.” “Our results suggest that the potential for energy savings is substantial: if all U.S. business users shifted their email, software, and CRM software to the cloud, the primary energy footprint of these software applications might be reduced by as much as 87% or 326 Petajoules. That’s enough primary energy to generate the electricity used by the City of Los Angeles each year (23 billion kilowattWhours).” “The primary driver of energy savings, namely, a substantial reduction in required data centre energy use when shifting from many inefficient local data centres to fewer and more efficient cloud data centres.
Recalibrating global data center energy-use estimates	Masanet, E., Shehabi, A., Lei, N., Smith, S. and Koomey, J., 2020. Recalibrating global data center energy-use estimates. Science, 367(6481), pp.984-986.	https://datacenters.lbl.gov/sites/default/files/Masanet_et_al_Science_2020.full_.pdf	Assumptions based	New data suggests that a large decrease in the energy use of data centre infrastructure systems (i.e., cooling and power provisioning), is enough to mostly offset the growth in total IT device energy use. “This decrease is explainable by ongoing shifts in servers away from smaller traditional data centres (79% of compute instances in 2010) and toward larger and more energy efficient cloud (including hyperscale) data centres (89% of compute instances in 2018) which have much lower reported PUE values owing to cutting-edge cooling-system and power-supply efficiencies.”

Video Conferencing

In light of the COVID-19 pandemic, video conferencing has become increasingly viable as more institutions and employees move their activities online. The assumption in the DSIT scoping report is that superfast broadband enables more people to engage through videoconferencing, reducing the need for physical travel.

O'Brien and Aliabadi's (2020) paper **provides a meta-analysis of the current quantitative literature exploring the effect of teleworking on four specific domains**: transportation, office buildings, homes, and information and communication technology (ICT). The paper highlights the murky state of this research area; while the topic has been around for many decades now, the authors state that their analysis shows the relationship is complex and current datasets and methods are, on the whole, inadequate to fully answer the research question. In spite of this, the study acknowledges that while the quantitative literature on the energy and GHG emission impact of telework for multiple domains remains relatively sparse, the **majority indicates that telework is beneficial (i.e., negative net energy/emissions**). In specific relation to car travel, the paper highlights that the "primary benefit to the teleworker and environment alike is the reduction in distance travelled (often by single occupancy vehicles)". Van Lier, De Witte, and Macharis' (2014) paper is referenced to illustrate this point. They explored the external environmental costs that would arise in three scenarios of various working from home options and found that a **combination of two days working at home and three days at the employer's headquarter office (scenario 2) would lead to external environmental cost savings (including air pollution and noise) of 39%,** compared to if the employee worked five days at their employer's head office (scenario 0). This paper lacked granular detail on specific emissions savings, nonetheless it illustrates the reduction in commutes that arise from working remotely.

As stated by O'Brien and Aliabadi (2020), Ong, Moors, and Sivaraman (2014) highlighted how, while it may seem obvious to assume videoconferencing has lower energy, carbon, and time costs than an in-person meeting, there exists little literature testing these claims. However, their 2014 paper, provided a holistic and – at the time – novel analysis focussing on the energy and carbon cost savings that may be derived from a substitution of in-person to videoconference meetings. Drawing predominantly on previous studies, **predictive assumptions** were made to calculate variables, such as the energy consumption of a typical laptop and separate display unit. These reasoned measures were then applied to a case study involving a 5-hour meeting with four separate participants travelling by various modes and distances. The study found that **video conferencing takes at most 7% of the energy and carbon emission cost of an in-person meeting**. However, this calculation neglects the inclusion of time costs. The authors argue that due to the lower task efficacy of videoconferencing, meetings become unnecessarily long, translating into higher costs for participants. The inclusion of time costs – both in terms of meeting length and the commute to an in-person meeting – would need to be considered to fully understand the extent to which videoconferencing can be considered an attractive meeting mode. It should also be noted that this study explored the use of video conferencing in Australia – further work would be required to understand how representative of the UK this is.

A Centre for Economics and Business Research (CEBR, 2019) report for Openreach provided a rare quantification of environmental benefits associated with increased levels of working from home, specific to the UK. Based on assumptions such as an average CO_2 emission level of 121.3g per kilometre, and average commutes of 15.9 kilometres (63.7% of which would be by car), the report estimated that with over a million people in the UK mainly working from home, each year there would be:

- 300 million fewer commuting trips, of which nearly 200 million are by car;
- 3 billion kms fewer travelled by car; and,
- 360,000 tonnes fewer of CO_2 emitted.

Acknowledging that the environmental benefits of remote working are heavily dependent on other factors such as teleworker (travel) behaviour and transportation patterns, Kharvari et al. (2021) applied **predictive assumptions-led analysis** to explore the impacts of teleworking in Canada on energy consumption and GHG in four scenarios: during the COVID-19 pandemic and a best, worst, and moderate-case scenario. The study does not provide analysis on the effect of video-conferencing on car travel but assumes this and incorporates it into a series of scenario analyses. As alluded to before, the paper argues that "a primary source of GHG emissions is transportation. Although its corresponding GHG emissions decreased during the pandemic due to stay-at-home orders and travel bans, there is evidence suggesting that teleworking increases GHG emissions for the transportation sector because individuals are more willing to live in suburban areas or locations away from downtown core". The study calculated key variables such as the average gas consumption by commercial and residential sectors, by taking averages from Statistics Canada and making reasoned assumptions from previous studies. This was applied to generate data for all scenario analyses and is therefore highly assumptions based. Nonetheless, **in the COVID-19 scenario, the paper argued that total transportation associated GHG emissions would reduce from 7.16 $MtCO_2e$ in the baseline, to 6.14 $MtCO_2e$**. Additionally, the study references an 'Insights from Markets' report which "shows **that sales of motor gasoline and diesel fuel decreased from 1.12E+11 to 9.56E+10 litres [yielding] a decrease of 14.25%" and is in accordance with the percentage of teleworkers.** However, it should be noted that there may be differences between the outcomes achieved in Canada and what would be expected in the UK, due to geographical differences between the countries.

A broad **meta-review** of existing literature was conducted by Mouratidis, Peters and Bert van Wee (2021). Their paper involved a qualitative interpretation of existing evidence from approximately 200 studies on how teleactivities, the sharing economy, and emerging transportation technologies may influence travel behaviour and the built environment. Teleactivities in this context encompassed telecommuting and teleconferencing, as well as online shopping among others. The authors argued that telecommuting may reduce work-related travel compared to a typical commute, with the potential to reduce overall travel demand, transport emissions, and air pollution. Helminen and Ristimaki's (2005) **quantitative analysis based on observable data** from Finland was referenced to support this; using **aggregate national data on commuting distances and a survey of 19,000 employed respondents**, their results indicated **that telework reduced 0.7% of the total kilometres travelled in Finland.**

On ways to decarbonise conference travel, Klower et al. (2020) argue for a rise in virtual attendance. Using the American Geophysical Union (the world's largest Earth and space-science conference) in San Francisco as a case study, the authors applied **assumptions-led analysis to predict** that emissions-minimised location decisions, virtual attendance and biennial meetings could result in a 90% reduction in travel-related carbon emissions. This finding was assumptions based; for example, of those that attended the conference in 2019 "around 92% travelled more than 400 kilometres and were assumed to have flown", and emissions figures were assumed to be **200, 250, and 300 $gCO_2e/km/person$** on a short-, long-, and super long-haul flight, respectively.

Hernandez et al. (2021) explored the effect of virtual working as a result of COVID-19. Their paper drew insights from **observable primary data collected through behavioural surveys administered to employees at the World Resources Institute (WRI) conducted both before (August 2019) and during**

(July 2020) the COVID-19 pandemic. Findings showed that the shift to virtual meetings mandated by travel restrictions had a huge effect on behavioural travel patterns which had follow-on benefits to the environment and expected future travel behaviour. Specifically, **moving to virtual meetings resulted in around 2,200 fewer business-related flights in 10 months amounting to a 92 percent reduction compared to the same period in 2019, before the pandemic. This translated to an avoidance of 3,000 MtCO$_2$e being emitted and cost savings of US$2.6 million in ticket expenses, and 11,000 hours of flight time for employees**. Results from the surveys also found that half of WRI's 1,400 staff had made a commitment to reduce business travel post-COVID following their experiences of virtual substituted ways of working. The study was specific to the organisation studied and no extrapolations were made to provide relevant insights on an aggregate national level. Additionally, unlike other studies, no considerations of virtual working-related carbon emissions, nor rebound effects were incorporated in this study. Nonetheless, the paper underlines the huge emissions savings that may be brought about if such working practices were adopted on a wider scale.

Summary

There is thin evidence in the academic literature highlighting the environmental benefits of videoconferencing and teleworking. Research using more rigorous methodologies highlight marginal environmental benefits to videoconferencing (Helimen and Ristimaki, 2005), and the more optimistic research findings often omit rebound effects, such as a teleworker travel behaviour. More research considering these effects are needed to fully address the effect of videoconferencing on the environment, however, when considering the emissions savings stemming from heavily-emitting business air travel, corroborating the reduced air transport mandated by the COVID-19 pandemic with Hernandez et al.'s (2021) findings, showcases the significant positive environmental benefits that may arise from a wide uptake in videoconferencing technology.

Table A3: Videoconferencing literature review: Key findings

Title	Citation	Link	Methodology	Values / Results
A platform for growth - A Cebr report for Openreach	Cebr. Full fibre broadband: A platform for growth - A Cebr report for Openreach - October 2019: The Environmental impact focuses on the reduction in commuting trips brought about by increased work from home can be expected to deliver environmental benefits as there will be fewer cars on the roads	https://www.openreach.com/content/dam/openreach/openreach-dam-files/images/hidden-pages/full-fibre-impact/CebrReport_online.pdf	Assumptions based	With over one million people in the UK mainly working from home, each year there would be: 300 million fewer commuting trips, of which nearly 200 million are by car; 3 billion kms fewer travelled by car; and 360,000 tonnes fewer of CO_2 emitted.
Relationships between commuting distance, frequency and telework in Finland	Helminen, V. and Ristimäki, M., 2007. Relationships between commuting distance, frequency and telework in Finland. *Journal of Transport Geography*, *15*(5), pp.331-342.	https://www.academia.edu/download/48116487/j.jtrangeo.2006.12.00420160817-5514-nx45ns.pdf	Survey data analysis	Telework reduced 0.7% of the total commuting related kilometres travelled in Finland.
Business Air Travel and Climate: Changing Behaviors Before, During, and Beyond the COVID-19 Pandemic	Hernandez, M., Xu, S., Toh, L. and ATTWOOD, D.S., 2021. Business Air Travel and Climate: Changing Behaviors Before, During, and Beyond the COVID-19 Pandemic.	https://web.archive.org/web/20211012123009id_/https://files.wri.org/d8/s3fs-public/2021-10/business-air-travel-climate-pre-post-covid.pdf?VersionId=HkF1KbWNP60SgAYeM5SfZ7xwU6AcCjvl	Survey data analysis	During the COVID-19 pandemic, WRI staff moving to virtual meetings resulted in around 2,200 fewer business related flights in 10 months amounting to a 92 percent reduction compared to the same period in 2019, before the pandemic. This translated to an avoidance of 3,000 $MtCO_2e$ being emitted and cost savings of US$2.6 million in ticket expenses, and 11,000 hours of flight time for employees.
A preliminary scenario analysis of the impacts of teleworking on energy consumption and greenhouse gas (GHG) emissions.	Kharvari et al. (2021) A preliminary scenario analysis of the impacts of teleworking on energy consumption and greenhouse gas (GHG) emissions. J. Phys.: Conf. Ser. 2069 012077	https://iopscience.iop.org/article/10.1088/1742-6596/2069/1/012077/meta	Assumptions based	In the COVID-19 scenario model, remote working results in total transportation associated GHG emissions reductions from 7.16 $MtCO_2e$ in the baseline, to 6.14 $MtCO_2e$.
An analysis of ways to decarbonize conference travel after COVID-19.	Klöwer, M., Hopkins, D., Allen, M. and Higham, J., 2020. An analysis of ways to decarbonize conference travel after COVID-19.	https://www.ecolsoc.org.au/wp-content/uploads/Klower-2020.pdf	Assumptions based	Specific to the case study referenced in the paper, emissions-minimised location decisions, virtual attendance and biennial meetings could result in a 90% reduction in travel-related carbon emissions
Transportation technologies, sharing economy, and teleactivities: Implications for built environment and travel.	Mouratidis, K., Peters, S. and van Wee, B., 2021. Transportation technologies, sharing economy, and teleactivities: Implications for built environment and travel. Transportation Research Part D: Transport and Environment, 92, p.102716.	https://www.sciencedirect.com/science/article/pii/S1361920921000225	Literature review	Telecommuting may reduce work-related travel compared to a typical commute, with the potential to reduce overall travel demand, transport emissions, and air pollution.
Does telecommuting save energy? A critical review of quantitative studies and their research methods.	O'Brien & Aliabadi (2020) Does telecommuting save energy? A critical review of quantitative studies and	https://www.sciencedirect.com/science/article/pii/S0378778820317710	Literature review	Majority of academic papers argue that telework is beneficial exhibiting negative net energy emissions.

	their research methods. Energy and Buildings Vol 225			
Comparison of the energy, carbon and time costs of videoconferencing and in-person meetings	Ong, D., Moors, T. and Sivaraman, V., 2014. Comparison of the energy, carbon and time costs of videoconferencing and in-person meetings. Computer Communications, 50, pp.86-94.	http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.677.9075&rep=rep1&type=pdf	Assumptions based	Using a case study of a 5-hour meeting with four separate participants travelling by various modes and distances, videoconferencing takes at most 7% of the energy and carbon emission cost of an in-person meeting
How worthwhile is teleworking from a sustainable mobility perspective? The case of Brussels Capital region	Van Lier, T., De Witte, A. and Macharis, C., 2014. How worthwhile is teleworking from a sustainable mobility perspective? The case of Brussels Capital region. European Journal of Transport and Infrastructure Research, 14(3).	https://journals.open.tudelft.nl/ejtir/article/view/3033/3222	Survey data analysis	A combination of an employee working from home for two days and working at their employers' head office would lead to external environmental cost savings of 39.1%

Copper vs Fibre networks

There is evidence that full-fibre networks have a lower impact on the environment compared to technologies using copper i.e. Fibre To The Cabinet (FTTC) and cable. It is anticipated that to achieve UK wide gigabit coverage, a large proportion will be through full-fibre networks. The following provides evidence of environmental benefits from reduced extraction of copper and lower operating energy to run the network:

Resource extraction:

According to the University of West Virginia[107],"the environmental consequences of the [copper] mining process are substantial and have both acute and chronic effects on the geography, water, vegetation and biological life in the surrounding areas."

As one of the world's largest economies, and accounting for around 35% of global refined copper production, Dong et al. (2020) analysed the environmental effects of different copper extraction methods using a Life Cycle Sustainability Analysis in China. Drawing **data from** previous **literature and national databases, they argue that primary – pyrometallurgical and hydrometallurgical – production methods are highly energy intensive, with pyrometallurgical production contributing most to acidification, photochemical oxidation (summer smog) and the depletion of abiotic resources-elements**. Hydrometallurgical production contributes more to cumulative energy demand and toxicity, with both production methods producing sulfuric acid, sulphur dioxide, and large quantities of toxic chemicals. Considering the expected growth in copper demand due to population growth, developed infrastructure, and the application of copper-intensive technologies, the study extrapolated environmental effects to 2050. Findings predicted that environmental impacts from pyrometallurgical production would "increase more than twofold" in this timeframe and would also remain the largest contributor to copper production's environmental footprint.

This sentiment is echoed in an OECD (2019) report collating the existing evidence from literature examining the health risks associated with the copper, rare earth, and cobalt industries. Referencing data from a paper by Nuss and Eckelman (2014), **copper production has the lowest carbon intensity of all other elements studied, producing 3.1 tCO_2/t metal in 2008**. By comparison, cobalt production emitted 8.3 tCO_2eq/t metal in 2008, however the sheer volume of copper production means it has the **highest contribution to global warming, where over 54 million tonnes CO_2eq was emitted globally because of it in 2008.**

Additionally, based on analysis by Calvo et al. (2016), the OECD (2019) paper outlined that the quality of metal ores has reduced. Subsequently, the **energy needed to extract smaller quantities of copper has increased**, where "**total energy consumption at copper mines has increased by 46% whilst production has gone up by a smaller amount, 30%."** This highlights that increasing environmental damage is being produced at the expense of lower marginal gains in terms of the quantity of copper extracted.

Optical networks are less energy intensive:

All-fibre networks require less power to operate, helping reduce growing demand for electricity and the associated generation of carbon dioxide from power plants. Fraunhaufer, a European research organization,

[107] https://faculty.virginia.edu/metals/cases/dudgeon3.html

points out in a 2012 paper[108], "Data transmission using light consumes only a fraction of the energy that conventional methods need."

A TalkTalk and Carnstone (2021) report quantified the energy expenditure required to boost signals through copper wires exchanges over short distances. TalkTalk operates 3,035 exchanges offering Local Loop Unbundling services which enable other network providers to share infrastructure with Openreach. Using UK government guidance and emission factors, **predictive analysis** suggests that these **exchanges consume over 85,000 kWh of energy each year, equating to around 20,000 tonnes of CO_2e**. With the adoption of optical fibres and the longer distances they allow without signal boosts, **only around 1,000 exchanges** are expected to be needed, which proposes a potential **20-fold saving in carbon emissions**.

The report also highlights that the **technology used to operate a Full Fibre network is much more energy efficient than copper** networks, requiring less power to operate and less cooling. Adoption of Full Fibre would necessitate the replacement of existing Multi-Service Access Node technology located within Openreach exchanges with smaller, more efficient switch technology. Using on-site measurements engineers estimated this **new technology to be around 10-15 percent more energy-efficient**, and as fibre has a smaller physical footprint producing less heat than copper, engineers further estimated that **10 percent less energy would be needed for cooling purposes.**

Babani et al. (2014) provided a wide-ranging evaluation comparing the advantages and disadvantages of fibre optic and copper cables. The study considered aspects such as bandwidth, cost, signal loss, and information capacity. In relation to efficiency, they argued that the **low signal attenuation performance and superior signal integrity in fibre optic cable allows much longer runs for signal transmission than metal-based systems**. In copper, "when high speed electrical signals propagate along metal wires or circuit traces…they dissipate energy by radiating the signal away into space." As the data rate increases, so too do these losses, requiring more complex signal processing in the transceiver. In contrast, "optical pulses traveling through fibre suffer very little attenuation because the fibre absorbs light only weakly. An optical signal still retains 50% of its signal strength after traveling 12 km over a single mode fibre, independent of the data rate". This low loss characteristic makes fibre optics preferable for long distances such as inter-state communication links.

Similar findings were highlighted in an older 2007 study by Unger and Gough. They highlight how over relatively short intervals (100m – 2km), copper cable signals need to be repeated or amplified to compensate for the loss of power and noise interference that commonly come about. Fibre optics, on the other hand, are able to cover much longer distances in absence of a loss in signal strength. As a consequence, **fibre optics require much less frequent regeneration of its signal, where repeaterless distances of 200 km are common.**

Finally, Ogudo, Mthwthwa and Nestor (2019) highlight some environmental benefits that may be brought about from wider fibre optic adoption. As mentioned by the above studies, they highlight fibre's immunity to electromagnetic interference. In addition to this, they flag that – as the telecommunication of fibre optics does not use electricity – there is **no danger of electrical fires as seen with copper wires**. Importantly though, in a data centre environment where thousands of ports are being operated, "a fibre-based architecture could save hundreds or thousands of kWh per year compared to the equivalent copper-based network just in port power consumption."

[108] https://www.fraunhofer.de/en/press/research-news/2012/november/visible-light-communications.html

Lower maintenance:

The literature has wide agreement that fibre technology is more likely to be future proofed in terms of providing the capacity required for future capacity demands. It is also more reliable[109] and will therefore result in fewer resources being used to maintain the network.

The 2021 TalkTalk and Carnerstone report referenced above also highlights the superior reliability of fibre optic over copper wire cables. **Copper wire cables are "highly vulnerable to water ingress", whereas pure fibre does not suffer from this**. Additionally, given that fibre connections are connected to premises directly, the likelihood of physical damage in shared broadband cabinets seen with copper connections is significantly reduced. The report flags this as a particular advantage of fibre over copper**; faults are one of the largest drivers of customer dissatisfaction and amount to high levels of field engineer visits. The report estimated the total distance of these journeys to be 740,000 miles a year.** With less faults, exchanges and street cabinets, the frequency of engineer visits is expected to fall dramatically, and even is this reduced by a third, the report estimated that "hundreds of tonnes of GHG [emissions] would be saved as fewer journeys would be made."

Babani et al. (2014) largely mirror TalkTalk's (2021) report. They mention that optical fibres are smaller in size, and much lighter compared to copper-based wires. Additionally, optical fibres are more flexible than copper, making it "attractive for installations containing many turns along the transmission path due to the materials used in manufacturing". Furthermore, optical fibres are more heat resistant than copper wires, meaning "that even when the outside jacket surrounding the optical fibre has melted, an optical fibre system can still perform well."

Finally, the installation of optical fibres is also less costly; Unger and Gough (2007) mention how "the dimensions - diameter and consequently weight - required for optic fibre cable are notably smaller, thus facilitating installation, and resulting in lower costs for installation."

Summary

The copper extraction landscape accounts for a significant portion of worldwide metal extraction. Although it emits lower levels of environmental damage than the extraction of other metals (e.g., cobalt), the sheer volume of copper demand and levels of production results in significant amounts of health and environmental damage. Copper demand is expected to rise significantly in the future driven by factors such as population growth, and the quality of metal ores has reduced, requiring more energy and subsequent environmental damage to produce less quantities of copper. The widespread adoption of optical fibre networks would offset some of this reliance on copper extraction and the academic literature provides convincing evidence of the benefits that would arise from a shift to fibre. They are not only more efficient in transferring data than copper, but also require less energy to maintain, and are much more physically reliable.

[109] https://www.cablinginstall.com/cable/fiber/article/16465844/how-fiber-can-help-make-your-network-greener

Table A4: Copper vs Fibre networks literature review: Key findings

Title	Citation	Link	Methodology	Values / Results
Comparative study between fiber optic and copper in communication link	Babani, S., Bature, A.A., Faruk, M.I. and Dankadai, N.K., 2014. Comparative study between fiber optic and copper in communication link. Int. J. Tech. Res. Appl., 2(2), pp.59-63.	https://d1wqtxts1xzle7.cloudfront.net/34322554/comparative-study-between-fiber-optic-and-copper-in-communication-link-with-cover-page-v2.pdf?Expires=1643974486&Signature=Urpfg1ildQo3e1XIRyg6eOpVX3coJmgHHoG02xt-aeipHuzFWb5CsHI7N2YtIu3rxtbB4ZQx85YPAeEwNW1dhxbXciVICr64hXyaUcsZWvYa1kVaYu8oqU1ivCsNXoSQXSIp7iZSpvBIya0UZcVKh4ELFYkZxJ3OYC~POzMuug8IduewdoFGL2sY~1Z0LqIO6qrgQILNIVSORpuPyBKM0N7yeyg1uHRTJORFxEjyj~ZI0G7kemY4IZ43Pf07HwHMdtV2fRrGy2eQHa8AUHOpZQ4Smp6LW8PdN3XiceELxkuZjh5MihA7mfiyXL~Ud7qbvOBzh9yiE~35kTyz89KkMw__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA	Assumptions based	Low signal attenuation performance and superior signal integrity in fibre optic cable allows much longer runs for signal transmission than metal-based systems Optical fibre networks are lighter, more flexible, and more heat resistant than copper wires.
Assessing the future environmental impacts of copper production in China: implications of the energy transition	Dong, D., van Oers, L., Tukker, A. and van der Voet, E., 2020. Assessing the future environmental impacts of copper production in China: implications of the energy transition. Journal of Cleaner Production, 274, p.122825.	https://reader.elsevier.com/reader/sd/pii/S0959652620328705?token=22D4DF2F259A39410AA09CF96532861428B18A500DA7A0C42C29ECAC08D63294CD076E5F656A11DE553DF647AF125D8B&originRegion=eu-west-1&originCreation=20220204101144	Life cycle sustainability analysis using data from national databases and previous literature	Primary – pyrometallurgical and hydrometallurgical – copper production methods are highly energy intensive, with pyrometallurgical production contributing most to acidification, photochemical oxidation (summer smog) and the depletion of abiotic resources-elements Environmental impacts from pyrometallurgical production would “increase more than twofold” into 2050 and would also remain the largest contributor to copper production’s environmental footprint
Reducing the health risks of the copper, rare earth and cobalt industries The transition to a low-carbon economy	Holland, M., 2019. Reducing the health risks of the copper, rare earth and cobalt industries: Transition to a low-carbon economy.	https://www.oecd.org/greengrowth/Reducing%20the%20health%20risks%20of%20the%20copper,%20rare%20earth%20and%20cobalt%20industries.pdf	Literature review	Copper production has the lowest carbon intensity of all other elements studied, producing 3.1 tCO_2/t metal in 2008. The sheer volume of copper production means it has the highest contribution to global warming, where over 54 million tonnes CO_2eq was emitted globally because of it in 2008. Total energy consumption at copper mines has increased by 46% whilst production has gone up by a smaller amount, 30%.
Comparative Analysis of Fibre Optic and Copper Cables for High-Speed Communication: South African Context	Ogudo, Kingsley A., Mbongiseni H Mthethwa, and Dahj Muwawa Jean Nestor. 2019. ‘Comparative Analysis of Fibre Optic and Copper Cables for	https://ieeexplore.ieee.org/abstract/document/8851021	Primary measured data	As the telecommunication of fibre optics does not use electricity – there is no danger of electrical fires as seen with copper wires

	High-Speed Communication: South African Context'. In 2019 International Conference on Advances in Big Data, Computing and Data Communication Systems (IcABCD), , 1–8.			"A fibre-based architecture could save hundreds or thousands of kWh per year compared to the equivalent copper-based network just in port power consumption."
Making the 'climate case' for Full Fibre	TalkTalk and Carnerstone. 2021. Making the 'climate case' for Full Fibre	https://www.talktalkgroup.com/dam/jcr:4de10c1d-1b46-4d9a-91d9-198acceded6f/TalkTalk%20-%20Making%20the%20climate%20case%20for%20Full%20Fibre%20Report.pdf	Assumptions based	"a shift to Full Fibre could yield, GHG emissions reductions and energy efficiency improvements of up to an 80% compared to copper-based infrastructure. This is owing to: Rationalisation of infrastructure required to deliver services; Utilisation of more energy efficient technology; Better reliability of fibre optic networks." Exchanges consume over 85,000 kWh of energy each year, equating to around 20,000 tonnes of CO_2e. With the adoption of optical fibres and the longer distances they allow without signal boosts, only around 1,000 exchanges are expected to be needed, which proposes a potential 20-fold saving in carbon emissions. The technology used to operate a Full Fibre network is much more energy efficient than copper networks, requiring less power to operate and less cooling. This new technology is around 10-15 percent more energy-efficient, and as fibre has a smaller physical footprint producing less heat than copper, engineers further estimated that 10 percent less energy would be needed for cooling purposes. Copper wires are "highly vulnerable to water ingress", whereas pure fibre does not suffer from this. With less faults, exchanges and street cabinets, the frequency of engineer visits is expected to fall dramatically, and even is this reduced by a third, the report estimated that "hundreds of tonnes of GHG [emissions] would be saved as fewer journeys would be made."
Life Cycle Considerations about Optic Fibre Cable and Copper Cable Systems: A Case Study'	Unger, Nicole, and Oliver Gough. 2008. 'Life Cycle Considerations about Optic Fibre Cable and Copper Cable Systems: A Case Study'. Journal of Cleaner Production 16(14): 1517–25.	https://www.sciencedirect.com/science/article/abs/pii/S0959652607001904	Life cycle assessment using data from databases, previous literature, and primary measurements of cable composition.	Fibre optics require much less frequent regeneration of its signal, where repeaterless distances of 200 km are common. Optical fibre has lower installation costs than copper wires.

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