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A systematic review of the energy and climate impacts of teleworking

Andrew Hook^{1,5}, Victor Court^{3,4}, Benjamin K Sovacool²  and Steve Sorrell²

¹ Department of Geography, School of Global Studies, University of Sussex, Falmer, BN1 9SL, East Sussex, United Kingdom

² Science Policy Research Unit (SPRU), University of Sussex Business School, University of Sussex, Jubilee Building, Falmer, East Sussex, BN1 9SL, United Kingdom

³ Energies Nouvelles, IFP School, 1 & 4 avenue de Bois Préau, 92852 Rueil-Malmaison cedex, France

⁴ Chair Energy & Prosperity, Institut Louis Bachelier, 28 place de la Bourse, 75002 Paris, France

⁵ Author to whom any correspondence should be addressed.

E-mail: a.hook@sussex.ac.uk

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Abstract

Information and communication technologies (ICTs) increasingly enable employees to work from home and other locations ('teleworking'). This study explores the extent to which teleworking reduces the need to travel to work and the consequent impacts on economy-wide energy consumption. The paper provides a systematic review of the current state of knowledge of the energy impacts of teleworking. This includes the energy savings from reduced commuter travel and the indirect impacts on energy consumption associated with changes in non-work travel and home energy consumption. The aim is to identify the conditions under which teleworking leads to a net reduction in economy-wide energy consumption, and the circumstances where benefits may be outweighed by unintended impacts. The paper synthesises the results of 39 empirical studies, identified through a comprehensive search of 9000 published articles. Twenty six of the 39 studies suggest that teleworking reduces energy use, and only eight studies suggest that teleworking increases, or has a neutral impact on energy use. However, differences in the methodology, scope and assumptions of the different studies make it difficult to estimate 'average' energy savings. The main source of savings is the reduced distance travelled for commuting, potentially with an additional contribution from lower office energy consumption. However, the more rigorous studies that include a wider range of impacts (e.g. non-work travel or home energy use) generally find smaller savings. Despite the generally positive verdict on teleworking as an energy-saving practice, there are numerous uncertainties and ambiguities about its actual or potential benefits. These relate to the extent to which teleworking may lead to unpredictable increases in non-work travel and home energy use that may outweigh the gains from reduced work travel. The available evidence suggests that economy-wide energy savings are typically modest, and in many circumstances could be negative or non-existent.

1. Introduction

Efforts to reduce greenhouse gas (GHG) emissions focus upon both technological innovation and behavioural change, while recognizing that these domains are interdependent (Bel and Joseph 2018, Creutzig *et al* 2018, Dubois *et al* 2019). One area that has received particular attention is encouraging technology-enabled changes in

working patterns to reduce commuter travel and office-related energy consumption (Hopkins and Mckay 2019). Since the transport sector in the United States (US), for example, accounts for around 33% of final energy use, a reduction in commuter travel could have a significant impact (Zhu and Mason 2014).

One trend that could reduce energy consumption and thus carbon emissions from travel is

teleworking,¹ where employees use information and communication technologies (ICTs) to work from home, in satellite telecentres or in other locations. Employees may telework part-time or, less commonly, full-time (Hynes 2016, Giovanis 2018). However, despite assumptions that teleworking would provide an important contribution to a 'lower energy future', evidence of its impacts is inconclusive (Brand *et al* 2019). Indeed, while some studies suggest that teleworking can reduce energy consumption (primarily through avoided commuting) by as much as 77% (e.g. Koenig *et al* 1996), others find much smaller gains, with some studies suggesting a paradoxical increase in energy consumption (e.g. Rietveld 2011).

This lack of consensus on the energy and environmental benefits of teleworking has arguably contributed to the lack of coordinated promotion of teleworking by business or government, even in countries where multiple studies have been conducted—such as the US (Allen *et al* 2015). Indeed, despite the promise of energy savings and other social benefits, teleworking has not grown as rapidly as predicted, even in sectors and regions that appear well-suited to it—such as growing cities in developing countries (Ansong and Boateng 2018). For example, (Zhu *et al* 2018) estimates that only around 9% of the US working population teleworks more than once a week.

This uncertainty about environmental benefits is compounded by persistent scepticism about the social implications of teleworking. Many believe, for example, that practices such as 'face to face' meetings' are essential for building confidence between colleagues and clients and cannot be substituted by 'virtual meetings' enabled by ICT (Baruch 2001). Other studies have suggested that concerns about emotional isolation or future career advancement may hinder people's willingness to adopt teleworking (Golden *et al* 2008, Schulte 2015). For firms, concerns over accountability and productivity persist, despite evidence to the contrary (Pérez *et al* 2005).

In this context, this paper provides a systematic review of the current state of knowledge about the energy impacts of teleworking. This includes the energy savings from reduced commuter travel and the indirect impacts on energy consumption associated with changes in: (a) non-work travel by both the teleworker and other household members; (b) the size and occupancy of work premises; and (c) the location and occupancy of employees' homes. The aim is to identify the conditions under which teleworking can lead to a net reduction in overall energy consumption, and the circumstances where the benefits from teleworking are outweighed by the unintended

impacts, such as greater private travel or increased non-work energy consumption. The latter are commonly referred to as 'rebound effects' (Berkout and Hertin 2004, Horner *et al* 2016).

Our interest is the impacts of teleworking on economy-wide energy consumption, taking into account the full range of mechanisms through which those impacts occur. But many studies have a narrower *scope*, in that they focus upon a more limited range of impacts, such as the changes in commuter travel alone. These studies may nevertheless provide useful evidence, as they frequently capture the most *important* impacts. Similarly, many studies use different *metrics* to measure those impacts, such as changes in vehicle distance travelled. Again, these studies may provide useful evidence, as there is frequently an approximately linear relationship between those metrics and energy consumption. However, it is important to recognise that studies with a narrower scope will omit many important categories of impact, and studies with a different metric will provide rather inaccurate measures of the impact on energy consumption.

The article is structured as follows. Section 2 summarises the academic and policy debates about the energy and environmental benefits of teleworking. Section 3 outlines the systematic review methodology, while section 4 presents the key results of the 39 identified studies. Section 5 discusses these results in more detail, including the magnitude of the identified impacts, the determinants of those impacts, and the source and scale of associated rebound effects. It also assesses the scope of the studies in terms of the types of impact that are included, as well as their methodological quality. Section 6 summarises the overall findings and reflects upon their implications for research and policy.

2. Teleworking and the impacts on energy use and emissions

'Teleworking' means working either full- or part-time from home, from a 'telecentre' located close to home, or from other locations. The practice has grown in popularity as technology has improved, but definitional ambiguities and data limitations make it difficult to estimate the precise number of teleworkers at any one time (Mokhtarian *et al* 2005). The concept of teleworking can be traced back to the 1960s when ICTs such as telephones and fax machines were first mooted as offering the possibility of liberating workers from commuting to work every day (Mokhtarian 1997). At this time, however, teleworking was largely promoted as a *social* policy that would enable workers to spend more time with their families and less time travelling (Johnson 2003).

The advent of the internet in the mid-1990s and innovations such as teleconferencing coincided with a focus on the broader benefits of teleworking and a

¹Within the literature on home- or office-based working as a travel or environmental policy, a number of different terms are used. 'Teleworking' and 'telecommuting' are the most popular, but a host of others are also used, such as 'remote working', and 'flexible working'. For the purposes of this study, 'teleworking' will be used.

Table 1. Classifying the mechanisms influencing the impact of ICTs on energy consumption.

| (Pohl et al 2019) aggregate categories | (Horner et al 2016) aggregate categories | Impact mechanism (+ or – impact on energy consumption) | Teleworking example |
|--|--|--|---|
| Direct impacts | Technology perspective | Embodied energy (+) Operational energy (+) Disposal energy (+) Efficiency/Optimisation (–) Substitution (+ or –) Direct rebound (+) | Energy used to manufacture the ICTs and associated infrastructure needed to support teleworking Energy used to operate the ICT equipment for teleworking, including cloud storage and video streaming Energy used to dispose of the ICT equipment for teleworking (Does not apply in this example) Energy saved by avoiding commuting to the office |
| Higher-order impacts | User perspective | Indirect: single-service | Energy consumed in longer commuting trips, owing to the availability of teleworking encouraging people to take jobs that are further away from home Energy used for heating (or cooling) the home during days in which the commuter is working from home Energy used and saved in multiple markets owing to economy-wide adjustments in prices and quantities (e.g. investments previously made in the car industry are now redirected towards ICTs). |
| | System perspective | Indirect: elementary services Indirect: economy-wide Indirect: society-wide | Energy used and saved because of far-reaching changes in the spatial structure of societies, including where people live and work |

Source: Adapted by authors from (Horner et al 2016) and (Pohl et al 2019).

Note: In the case of teleworking, the substitution effect is normally considered to be the most significant.

shifting rationale for its expansion (e.g. Marvin 1997, Allenby and Richards 1999). The increasing prominence of climate change within popular discourse led teleworking to be seen as an *environmental* or *energy* strategy that could reduce air pollution related to peak-time traffic congestion (Niles 1994), along with energy use and emissions from travel to work (Henderson *et al* 1996) and energy consumption within workplaces (Matthews and Williams 2005). The main source of these benefits was that working from home (or from satellite telecentres that were closer to the home than the workplace) should reduce the energy expended in both travelling to work (typically by private car) and in heating, cooling and lighting large office spaces (Marcus 1995, Williams 2003).

Appraising whether such changes in working practices have indeed had these benefits is difficult, however, since the enabling technology (ICTs) triggers a range of ‘direct’ and ‘higher-order’ effects that are very hard to measure. Frequently, these effects are both unexpected and unintended (Pohl *et al* 2019). ‘Direct’ effects relate to the energy used in the manufacture, operation and disposal of ICTs together with the associated network infrastructure, while ‘higher-order’ effects relate to the changes in energy consumption stimulated by ICTs, including changes in individual behaviour (e.g. commuting behaviour) and changes in prices, consumption, investment and other variables throughout the economy (Horner *et al* 2016). These higher-order effects take a number of forms that (both individually and collectively) may either increase or reduce energy consumption relative to a baseline scenario where those changes do not occur. Table 1 provides a classification of these different types of impact, and illustrates this with examples relevant to teleworking.

Whether the economic and behavioural changes stimulated by teleworking lead to an overall reduction in energy consumption therefore depends upon the sign and magnitude of these different categories of impact—the relative importance of which is likely to vary with context and change over time (De Graff 2004, Horner *et al* 2016). Since personal transport is significantly more energy intensive than ICT services, most studies of teleworking *ignore* the direct impacts altogether and focus solely upon the indirect impacts—and particularly those from reduced commuter travel (Horner *et al* 2016). However, factors such as the short lifetime and rapid replacement of ICTs, their increasingly complex supply chains (including dependence on a growing range of rare earth elements), and the advent of cloud storage and video streaming (which are relatively energy intensive) may be contributing to a growing energy footprint for ICTs. Hence, these direct impacts may become a more significant focus of teleworking studies in the future (Chapman 2007, Lachapelle *et al* 2018).

The focus of the majority of studies has been the nature and magnitude of the ‘higher-order’ impacts indicated in table 1 (Horner *et al* 2016, Pohl *et al* 2019). The most commonly cited benefit of teleworking is its ‘substitution’ effect, whereby commuter travel is substituted (or displaced) by less energy-intensive activities or behaviours that are enabled by ICTs (Salomon 1998). Historically, this has typically involved using ICTs to work from home or from a ‘telecentre’ located closer to the home than the workplace (Balepur *et al* 1998). More recently, there has been a rapid growth in mobile working from cafes, trains and other Wi-Fi-enabled locations, but the energy implications of these emerging practices have yet to be fully studied. Whether these substitution effects lead to a net reduction in energy consumption (at either the individual or societal level) depends, however, on the higher-order impacts (Mokhtarian 2009). Indeed, in some circumstances teleworking could encourage changes in behaviour that *increase* work and/or non-work travel, and thereby energy consumption (Pérez *et al* 2004, Williams 2011, Zhu 2012).

In the case of work-travel, for example, the ability of teleworkers to live further away from their place of work could mean that the longer trips they make on non-teleworking days (where, as is the norm, they are only *part-week* teleworkers) wholly or partly outweigh the travel and energy savings they make on days that they work from home (Bailey and Kurland 2002). These impacts will also depend on the mode of transport they use to commute to work: in countries where public transport is a common mode of commuting, teleworking practices will have less impact on energy use than in countries (such as the US) where the private car is the dominant mode (Mokhtarian 2009, Van Lier *et al* 2014). The energy impacts will further depend upon the energy efficiency and level of occupancy of the relevant mode (e.g. one person in a Sport Utility Vehicle (SUV) versus several hundred in a crowded train), and the carbon impacts will additionally depend upon the carbon intensity of the relevant energy carriers (e.g. gasoline versus electricity).

In the case of non-work travel, there is evidence that gaining more time at home as a result of teleworking may induce extra trips by teleworkers—for leisure and social purposes, for example—that would not have been made had the teleworker been commuting to work every day (Lyons *et al* 2008). It may also enable greater use of the household car by other household members on days that the commuter works from home. This latter trend has been observed in countries where households have fewer cars, such as South Korea, where the car is more of a ‘scarce’—and thus more desirable—commodity (Kim *et al* 2015). Such examples of additional, non-work travel enabled by teleworking may be considered expressions of ‘latent’ travel demand (Mokhtarian *et al* 1995).

Table 2. Summary of direct and indirect impacts of teleworking on energy use and emissions.

| Type of effect | Nature of impact on energy use and emissions | |
|---------------------|--|--|
| | <i>Reduce</i> | <i>Increase</i> |
| <i>Direct</i> | | <ul style="list-style-type: none"> • Energy consumed in manufacturing, using and disposing of ICT equipment |
| <i>Higher-order</i> | <ul style="list-style-type: none"> • Reduction in commuting travel and energy use • Reduction in office energy use | <ul style="list-style-type: none"> • Increase in weekly travel due to longer commute on non-teleworking days • Increase in non-work travel by teleworker • Increase in energy consumption at home for heating, cooling, lighting and other uses • Increase in travel by teleworking household due to increased availability of car |

Another induced travel effect could be where the feelings of isolation and sedentariness generated by teleworking stimulate a desire for movement and mobility (Gurstein 2002). This compensatory travel, which may involve habitual trips to libraries or cafes for work, may partly offset the travel and energy savings achieved by avoiding commuting (Rietveld 2011). Overall, these examples suggest that the travel demand displaced by teleworking may be partly offset by induced travel demand in other areas.

Home and office energy consumption is another area where the benefits of teleworking could potentially be offset (Pérez *et al* 2004). For example, teleworking may lead to more energy being used at home (e.g. for heating, cooking and lighting) without any compensating reductions in the energy used at work (e.g. offices may continue to be heated and lit as much as before). There could be an 'additive' impact of teleworking if businesses neither move to smaller offices (which have a smaller energy footprint) nor close their offices in response to increased teleworking. The net result could be an increase in building energy consumption, and possibly total energy consumption, as a result of greater teleworking (Kitou and Horvath 2008).

At the societal level, the aggregation of these and other trends may generate broader indirect and economy-wide rebound effects (Horner *et al* 2016). If households reduce car travel, they may spend the money they save on road fuel on other goods and services that also require energy and emissions to produce (Sorrell *et al* 2020). Alternatively, if teleworking boosts labour productivity and stimulates economic growth, it could encourage increased consumption, travel and energy use by both producers and consumers (Lachapelle *et al* 2018). (Berkhout and Hertin 2004) draw attention to the potentially small impact of teleworking on energy consumption relative to other driving forces such as population and income growth. A summary of the direct and higher-order

effects of teleworking at the individual and societal level is given in table 2.

The identification of these higher-order effects suggests that, to accurately estimate the net energy impacts of teleworking, a study must have as broad a scope as possible: a narrow scope may mean that important impacts are overlooked (Berković *et al* 2013). For example, a study may estimate the reduction in commuter travel from teleworking but ignore the increase in other forms of travel. Alternatively, a study may overestimate the energy savings from teleworking by assuming that all commuting is by car, thereby neglecting any commuting by public transport. Similarly, a study may estimate the energy savings from reduced commuting and reduced office use but ignore the increase in home energy use. A limited scope could therefore lead to either an over- or under-estimate of the energy savings from teleworking depending on the context-specific interactions between a range of variables (Mokhtarian 2009).

While the range of possible interactions among different variables suggests that studies should have a wide scope, there are considerable methodological challenges in designing studies that capture the full range of impacts from teleworking. As a result, most studies focus upon a narrower range of impacts, such as commuter travel alone, whose measurement is more feasible. As Horner *et al* (2016, p. 14) observe, this is a more general problem when studying the impact of ICT on energy use:

The inability to draw concrete conclusions reflects, in large part, uncertainty regarding the rebound effect for ICT and the inability to disentangle root causes of interrelated economic effects. The dynamics of these effects are hugely dependent upon human behavior, which is laden with uncertainty and confounds efforts to

achieve the full technical potential of ICT interventions.

3. Research design

3.1. Research questions and approach

Our primary research question is as follows:

- What are the determinants and magnitude of the impacts of teleworking on energy consumption or proxies for energy consumption such as distance travelled by car?

Our sub-questions were as follows:

- What are the full range of impacts identified in the literature?
- What are the key socio-technical determinants or drivers of those impacts?

To review the evidence on this topic, we employ the methodology of ‘systematic reviews’ (Petticrew and Roberts 2006). These offer a number of advantages over traditional literature reviews, including minimising unintentional bias (e.g. excessive self-citations, or citations of colleagues) and avoiding the exclusion of studies that are frequently overlooked (Haddaway *et al* 2015). For these and other reasons, many authors have called for greater use of systematic reviews in the area of energy and climate research (Sorrell 2007, Sovacool *et al* 2018, Pereira and Slade 2019).

The first stage of our systematic review involved choosing search terms that were relevant to the selected topic. These were combined to construct search queries that were used in the search engines of two scholarly databases. The process was iterative, since small changes in the search terms can have a large influence on the number of identified sources. As such, while reviewing the bibliographies of review articles in the area (e.g. Horner *et al* 2016), we repeatedly refined our search strings to ensure that they captured all of the identified studies.

The references generated by this search phase were then screened in order to remove irrelevant studies. This involved applying explicit inclusion and exclusion criteria to the title and abstract of the study, and if necessary, to the full text. Following this, information was extracted in a consistent way from each of the selected studies. Since the evidence was both quantitative and qualitative, as well as being highly variable and using a variety of metrics (e.g. energy use, distance travelled, carbon emissions), a narrative synthesis was considered most appropriate (Snijlsteveit *et al* 2012). To formulate our search and screening protocols, we followed the guidelines of the Collaboration for Environmental Evidence (Haddaway *et al* 2018) and used the free online platform CADIMA to perform the screening phase (Kohl *et al* 2018).

3.2. Sources and databases

The evidence base includes peer-reviewed academic journals, conference proceedings, books, working papers, doctoral theses, and technical reports. We gave priority to studies that provided quantitative estimates, but also examined qualitative evidence to obtain a deeper understanding of the relevant mechanisms and determinants. Given the pace of technical change in this area, we considered that older studies were unlikely to be of much value. Hence, we confined the review to studies published after 1995, approximately the start of the ‘internet age’ (Huws 2013). We also confined the review to English language studies, since this was the language of the research team. We applied our search protocol to *Scopus* and *Web of Science*, which are the most widely used scientific literature databases. We also searched for relevant grey literature (technical reports, doctoral theses, working papers) through a combination of internet searches and checking the profiles of key researchers in the field and the bibliographies of the identified studies.

3.3. Search terms and combinations

We combined three types of keywords in our search query, namely: a synonym for ‘teleworking’; a second for ‘energy’ (including various proxies for energy such as distance travelled); and a third that referred to the relationship or interaction between these two. We investigated exhaustive variations around these terms using the Boolean OR operator, and combinations of them using the Boolean AND operator, and made sure that studies identified by other authors (e.g. Horner *et al* 2016) were caught. This led to an extensive search string for each database (see supplementary material 1 (available online at stacks.iop.org/ERL/15/093003/mmedia)).

3.4. Inclusion and exclusion criteria

The search results were merged, and duplicates removed to obtain our initial sample. We then applied the inclusion/exclusion criteria in table 3 to select only those studies that appeared relevant to our research question. Analysis of this preliminary sample led to the exclusion of further studies in which results or data were duplicated or where, on closer inspection, relevant data were not present. Once the final set of studies had been defined, we extracted the data into an Excel file (see supplementary material 2). The key results are summarised in section 4.

4. Results: searching, screening and data extraction

4.1. Search and screening phases

As indicated in figure 1, the search phase generated an initial sample of 7041 references from *Scopus* and 4585 from *Web of Science*, making a total of 11 626 references. This is a very large number compared to

Table 3. Inclusion and exclusion criteria used to screen the identified studies.

| <i>Inclusion criteria (IC)</i> | |
|--------------------------------|--|
| IC1 | Refers to an analysis of ICT-enabled teleworking |
| IC2 | Refers specifically to an energy-related effect of teleworking |
| IC3 | Contains primary research results |
| <i>Exclusion criteria (EC)</i> | |
| EC1 | The main topic does not relate to teleworking or energy |
| EC2 | The study contains no quantitative analysis of the effects of teleworking on energy demand |
| EC3 | The study is not accessible at the time of review (e.g. due to it being unpublished or behind a paywall) |

other systematic reviews because we were exhaustive when designing our search query. Adopting such a ‘large nest’ approach minimises the risk of missing relevant studies but leads to the inclusion of a large number of irrelevant studies that need to be screened out. After removing 2165 duplicates, our initial sample comprised 9461 references. Screening the titles and abstracts led to the removal of 9042 irrelevant references, while full text screening led to the removal of an additional 63 studies. Our preliminary sample therefore consisted of only 56 studies, which was further reduced to 39 by removing studies with data that was duplicated in other studies or those which had no relevant primary data.

4.2. Data extraction

Table 4 summarises the extracted data from the 39 studies in our final sample, presenting the studies alphabetically (a more detailed table is provided in supplementary material 2). For each study, we include:

- the study’s number in the list;
- the main author’s name and the year of publication;
- the country location;
- the methodology (distinguishing between analysis of survey data, evaluation of pilot schemes, and scenario modelling)
- the most relevant metric (e.g. commuting distance travel);
- the scope of the study (i.e. coverage of: (i) commuter travel; (ii) non-commuter travel; (iii) home energy use; and/or (iv) office energy use);
- the estimated impact on the relevant metric (‘increase’, ‘neutral’, ‘reduce’, or ‘unclear’);
- the nature and scale of that impact, including quantitative estimates; and
- our appraisal² of the methodological robustness of the study (‘good’, ‘average’, or ‘poor’).

²A justification for the ‘grading’ assigned to each paper’s methodological robustness can be found in the right-hand column of the table in supplementary material 2.

5. Discussion: impacts and rebounds of teleworking

This section discusses the results of the systematic review that are presented in table 4 and in greater detail in supplementary material 2. It first provides an overview of the results, before discussing the sources and conditions of impacts on the relevant metrics, the potential rebound effects from teleworking, the scope of the studies and the methodological quality of the evidence base.

5.1. Overview of the studies

The 39 studies in the final sample examine a range of configurations and scales of teleworking in a variety of contexts. The studies examined two main *types* of teleworking, home-based (35 studies) and telecentre-based (four studies). As table 4 shows, most studies are from the US (19 studies) and Europe (11 studies), with only three from the Global South (Thailand, Malaysia, and Iran). The dominance of US studies may influence the overall findings, since most US commuters travel by private car rather than public transport, and vehicles and buildings in the US tend to be larger and less energy efficient than those in other OECD countries.

As figure 2 indicates, there is a fairly even distribution of studies across the time range (1995–2019). While this suggests there has been no slackening of interest in teleworking over this period, the character of teleworking has changed as ICTs have evolved. In particular, telecentre-based teleworking is now largely obsolete, and the three studies that involved the collection of data on telecentre pilot schemes were all published before 1998.

The studies employ a variety of methods that are described in detail in supplementary material 2. The studies also vary in methodological quality and include both *ex post* estimates and *ex ante* projections of impacts on a number of different metrics (e.g. commuting trips, commuting distance, energy consumption) which makes them challenging to compare. These methods can be grouped into three broad categories:

- *Scenario modelling*: using simulation models or other types of model to project future impacts from teleworking (often using rather sparse datasets) (e.g. Larson and Zhao 2017).
- *Quantitative analysis of survey data*: using publicly available datasets on transport and working behaviour, often from national surveys, to estimate the historical impacts of teleworking on energy use and other indicators (e.g. Chakrabarti 2018).
- *Evaluation of teleworking pilots*: using ‘travel diary’ data to establish travel patterns and energy use among teleworkers and non-teleworkers (e.g. Balepur *et al* 1998).

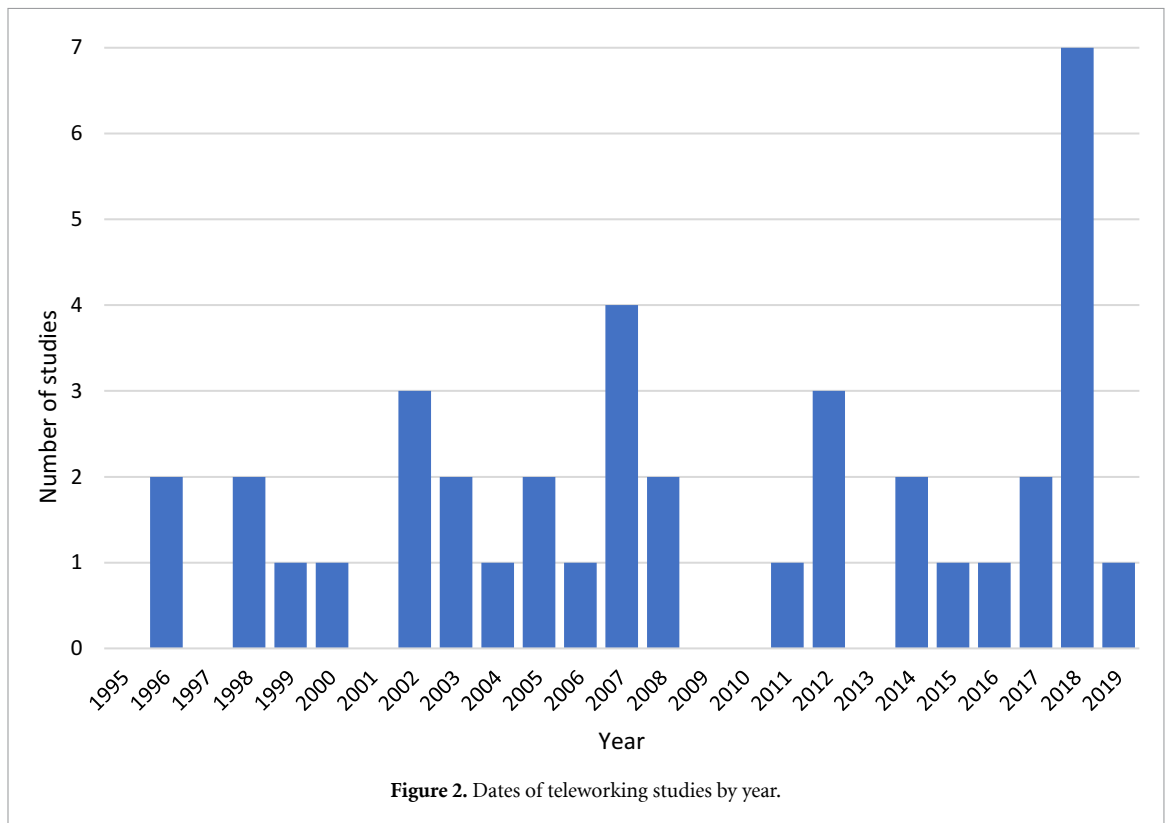
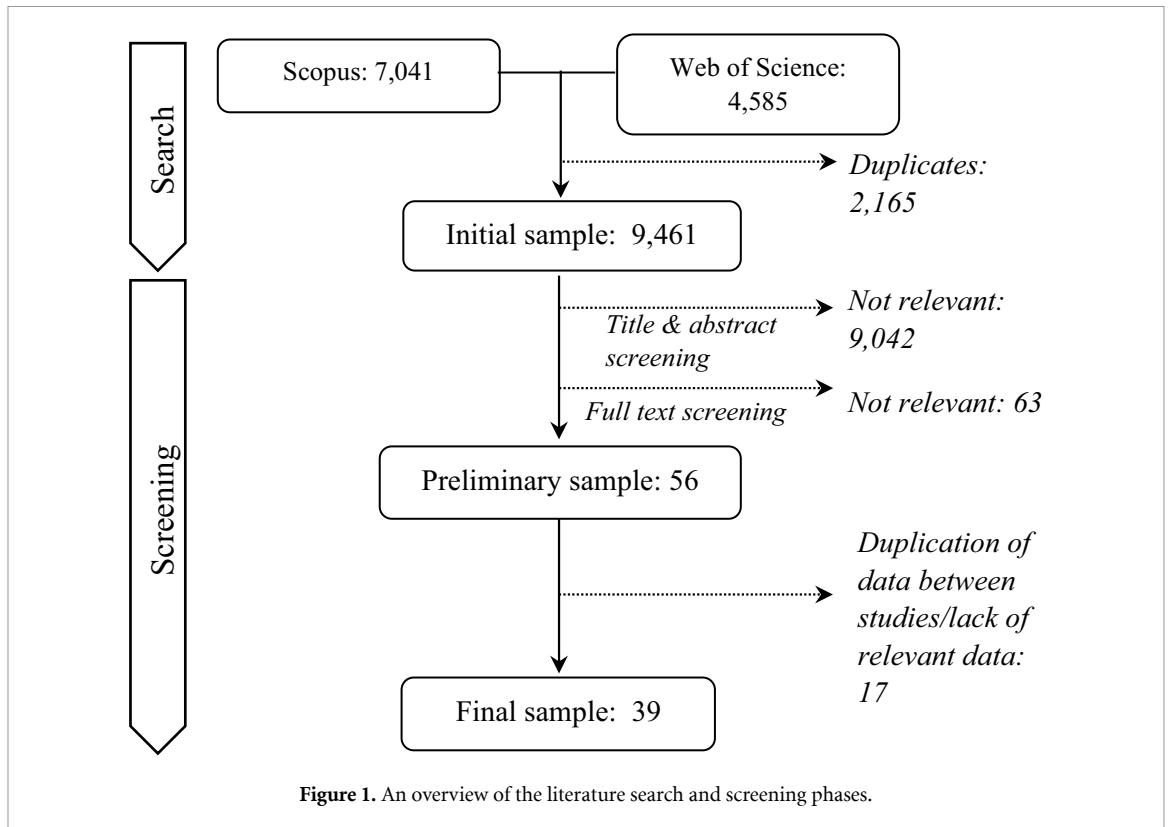


Table 4. Key results from final study sample on teleworking and environmental impacts.

| Study no. | Authors and date | Country | Methodology | Metrics | Whether flexible commutes (part-day teleworking) enable reduced congestion. Vehicle distance travelled avoided by working from home. | Scope (number of impact categories considered) | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|---------------------------|---------|----------------------------------|----------------------------------|--|--|-------------------|---|--|
| 1 | (Asgari and Jin 2018) | USA | Analysis of survey data | Analysis of survey data | Whether flexible commutes (part-day teleworking) enable reduced congestion. | 1 (commuting travel only) | Unclear | Teleworking during peak travel times could potentially reduce peak travel (and thus congestion) by 20%. | Poor |
| 2 | (Atkyns et al 2002) | USA | Analysis of survey data | Analysis of survey data | Vehicle distance travelled avoided by working from home. | 1 (commuting travel only) | Reduce | Having one fifth of AT&T employees working one day a week from home could reduce vehicle distance travelled by 110 000 miles, reduce gasoline use by 5.1 million gallons, and reduce carbon emissions by 48 450 tons. | Average |
| 3 | (Balepur et al 1998) | USA | Evaluation of teleworking pilots | Evaluation of teleworking pilots | Vehicle distance and person distance avoided in working at telecentre vs. travelling to work/home-based telework | 2 (commuting travel, non-commuting travel) | Reduce | A telecentre commuting frequency of one day a week led total weekly person travel to be reduced by 19% (17 miles) and weekly vehicle travel to be reduced by 19% (10 miles) compared with regular commuters who travel to the office every day. | Good |
| 4 | (Bussière and Lewis 2002) | Canada | Scenario modelling | Scenario modelling | Peak-time trips reduced through working from home. | 1 (commuting travel only) | Reduce | Over 20 years (1996–2016) and assuming teleworking rates of 3.3% of the workforce in Montreal and 3.6% in Quebec, the number of peak-time trips would be reduced by 2.3% in Montreal and by 2.5% in Quebec. | Poor |

Table 4. (Continueud)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope of impact categories considered | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|----------------------------------|----------|-------------------------|---|--|-------------------|--|--|
| 5 | (Chakrabarti, 2018) | USA | Analysis of survey data | Annual miles driven per person | 2 (commuting travel, non-commuting travel) | Increase | Frequent teleworkers travel 5.9% further by car each year than non-teleworkers and occasional teleworkers travel 8.0% further. This is because the longer commutes of teleworkers on days they work more than offset the savings made on teleworking days. | Good |
| 6 | (Choo et al 2005) | USA | Analysis of survey data | Vehicle distance travel avoided by working from home vs. traveling to work | 1 (commuting travel only) | Reduce | Teleworking by 12% of the workforce once a week has reduced total annual vehicle miles travelled (VMT) in the US (estimated as 2.4 trillion miles) by 0.8%. | Good |
| 7 | (De Abreu e Silva and Melo 2018) | UK | Analysis of survey data | Vehicle distance travel avoided by working from home vs. traveling to work for one and two-worker households | 2 (commuting travel, non-commuting travel) | Increase | For single-worker households where the person teleworks once a week, there is an average increase of 9.7 miles travelled by all modes (9.0 by car, or 3.9%, 0.5 by public transport, or 2.4%, and 0.2 by non-motorized modes, or 3.8%). For two-worker households one day a week teleworking increases miles travelled by car by 1.6 miles (or 0.4%). This is lower than above because workers share trips. | Good |
| 8 | (Dissanayake and Morikawa 2008) | Thailand | Scenario modeling | Vehicle distance travelled reduced and emissions avoided through the optimum placement of five satellite telecentres in the outer suburbs of Bangkok Metropolitan Region. | 1 (commuting travel only) | Reduce | The modelled scenario for satellite telecentres reduces private vehicle usage in the area by 18–20%. | Poor |

Table 4. (Continueud)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope (number of impact categories considered) | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|-------------------------------|-------------|----------------------------------|--|--|-------------------|--|--|
| 9 | (Eldér 2017) | Sweden | Analysis of survey data | Whether teleworking reduces total travel distance. | 2 (commuting travel, non-commuting travel) | Increase | Teleworkers travelled further than non-teleworkers on both teleworking and non-teleworking days. While non-teleworkers travelled an average of 46 km per day, teleworkers travelled 54 km on teleworking days and 64 km on non-teleworking days. | Good |
| 10 | (Fu <i>et al</i> 2012) | Ireland | Analysis of survey data | Energy used in commuting lifestyle vs home-working lifestyle | 2 (commuting travel, home energy use) | Reduce | If 5% of the Irish population teleworked full time, final energy consumption would fall by 0.14%. | Good |
| 11 | (Giovani 2018) | Switzerland | Analysis of survey data | Traffic volume and pollutants reduced | 1 (commuting travel only) | Reduce | Teleworking (by 8.43% of the population) is associated with a reduction in traffic volume on average by 1.9% and equivalent reductions in various pollutants. | Average |
| 12 | (Gubins <i>et al</i> 2019) | Netherlands | Analysis of survey data | Commuting distance reduced by ICT-enabled home-based working | 1 (commuting travel only) | Unclear | The existence of ICT has increased commuting distance by 13% for each worker between 1996 and 2010. | Average |
| 13 | (Helminen and Ristimäki 2007) | Finland | Analysis of survey data | Commuting distance reduced by teleworking | 1 (commuting travel only) | Reduce | Teleworkers in the survey commute 3.7 km further than non-teleworkers. But the use of teleworking (at least once a week) by 4.7% of the Finnish labour force reduces total commuting distance travelled in Finland by 0.7%. | Good |
| 14 | (Henderson <i>et al</i> 1996) | USA | Evaluation of teleworking pilots | Commuting distance and emissions reduced by cutting down on need for daily commutes. | 2 (commuting travel, non-commuting travel) | Reduce | On non-teleworking days, telecentre-based teleworkers have 91% higher VMT than non-teleworkers, while home-based teleworkers have 54% higher VMT—suggesting they live further from work than regular commuters. On teleworking days, home-based teleworkers have 67% less travel distance than commuters and telecentre workers have 54% less distance. | Average |

Table 4. (Continueud)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope of impact categories considered | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|-----------------------|-------------|-------------------------|--|--|-------------------|---|--|
| 15 | (Hjorthol and 2006) | Norway | Analysis of survey data | Commuting distance reduced by cutting down on need for daily commutes. | 1 (commuting travel only) | Reduce | Home-based teleworkers have 'work travel totals by car' that are 8% lower per month than non-teleworkers. | Poor |
| 16 | (Jaff and Hamsa 2018) | Malaysia | Scenario modeling | Commuting distance avoided by cutting down on need for daily commutes. | 1 (commuting travel only) | Reduce | Based on sample, if 2% of female workforce teleworked three times per week, peak-hour traffic could be reduced by 1.3–7.8%. If 2% of female workforce teleworked once per week, peak-hour traffic could be reduced by 0.6%–3.7% | Poor |
| 17 | (Kim et al 2015) | South Korea | Analysis of survey data | Distance travelled avoided by the head of house teleworking | 2 (commuting travel, non-commuting travel) | Increase | For dual- or multiple-earner households, the household has lower commute travel for the teleworking head (compared to households without a teleworking head), but greater amounts of the other four types of travel (teleworker's non-work travel and other household members' work and non-work travel). As a result, the vehicle miles reduced by the head of household teleworking (–7.8 km per day) is offset by the teleworkers' non-commute trips (+24.2 km), non-work trips (+11.7 km), as well as by other household members' non-work trips (+1.5 km). This is because the car (of which there are only 0.91 per household in South Korea compared to 1.79 in the USA) gets used more by other members for other purposes. | Good |

Table 4. (Continueud)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope (number of impact categories considered) | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|--------------------------|---------|----------------------------------|---|---|-------------------|--|--|
| 18 | (Kitou and Horvath 2003) | USA | Scenario modeling | Emissions reduced through telework. | 3 (commuting travel and office and home energy use) | Unclear. | Teleworking between one, three, and five times a week decreases CO ₂ emissions by between 2%–80% (rounded). | Good |
| 19 | (Koenig et al 1996) | USA | Evaluation of teleworking pilots | Commuting distance and emissions reduced by cutting down need for daily commutes. | 2 (commuting travel, non-commuting travel) | Reduce | Teleworkers had an overall daily travel of 10.2 miles on teleworking days compared with 32.7 miles for non-teleworkers. While non-commute trips increased by 1 per day for teleworkers, their non-commute travel on teleworking days reduced by 0.7 miles, from 34.6 miles per day to 33.9 miles per day. On non-teleworking days, travel distance for teleworkers was 36.9 miles per day, slightly higher than for non-teleworkers (around 32 miles per day), suggesting that teleworkers live further away from work than regular commuters. | Good |
| 20 | (Lachapelle et al 2018) | Canada | Analysis of survey data | Travel time reduced by working from home. | 1 (commuting travel only) | Neutral | Full time teleworking reduces daily travel time by 13 min. Morning peak trips were not avoided because of school runs. | Average |
| 21 | (Lari 2012) | USA | Analysis of survey data | Travel distance avoided through teleworking. | 1 (commuting travel only) | Reduce | Part-day teleworking has no effect on overall travel. On teleworking days, vehicle miles travelled per person was 27.96 miles lower than on a traditional commuting day. Overall, 7.46 million vehicle miles travelled per year were avoided by teleworking among 678 teleworkers. Assuming 1.10 lbs CO ₂ per mile travelled, eWork-Place participants saved 4070 tons of CO ₂ . | Poor |

Table 4. (Continued)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope (number of impact categories considered) | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|--------------------------------|-------------|-------------------|--|--|-------------------|--|--|
| 22 | (Larson and Zhao 2017) | USA | Scenario modeling | Commuting distance and emissions reduced by cutting down on need for daily commutes. | 2 (commuting travel and home energy use) | Unclear | If 20% of workers telework one day a week, commuting energy consumption would decrease by 20%, but home energy consumption would increase by 5.3%. Overall energy consumption from the household would increase by 0.4%. | Poor |
| 23 | (Mamdoohi and Arde-shiri 2011) | Iran | Scenario modeling | Peak hour commuting trips avoided through teleworking by 36% of government employees | 1 (commuting travel only) | Reduce | If 36% of the 148 551 government employees teleworked once a week, 53 898 peak hour trips could be avoided. | Poor |
| 24 | (Martens and Korver 2000) | Netherlands | Scenario modeling | Commuting trips avoided by teleworking. | 1 (commuting travel only) | Reduce | Between 71 000 and 529 000 daily commuting trips could be substituted in the Netherlands through teleworking assuming teleworking rates of 20% and 60%, respectively. This equals a maximum of 5% reduction in commuting travel, and 1% reduction in overall travel. | Poor |

Table 4. (Continueud)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope (number of impact categories considered) | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|--------------------------------|------------|----------------------------------|--|--|-------------------|---|--|
| 25 | (Matthews and Williams 2005) | USA, Japan | Scenario modeling | Net energy savings from teleworking (due to avoided transportation energy use and net building energy consumption) | 3 (commuting travel, home and office energy use) | Neutral | For current estimated teleworking populations and practices in the US (currently 0.4% of total worker days, once a week) and Japan (currently 2.5 m workers, once a week), there are national level energy savings of only 0.01–0.4% in the US and 0.03–0.36% in Japan. Where 50% of information workers telework 4 d per week, United States and Japan national energy savings are estimated at only about 1% in both cases. | Good |
| 26 | (Mitomo and Jit-suzumi 1999) | Japan | Scenario modeling | Reduction in peak time congestion | 1 (commuting travel only) | Reduce | If 9–14 million workers telework daily, the congestion rate during peak hours will be reduced by 18%–28%. | Poor |
| 27 | (Mokhtarian <i>et al</i> 2004) | USA | Evaluation of teleworking pilots | Commuting distance displaced by telecommuting. | 2 (commuting travel, non-commuting travel) | Reduce | Average quarterly per capita total commute distances are generally 15% lower for teleworkers than for non-teleworkers, indicating that they telework often enough to more than compensate for their longer one-way commutes (which tend to be on average 16 miles compared with 11 miles for non-teleworkers). | Good |

Table 4. (Continueud)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope (number of impact categories considered) | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|-----------------------------|---------|----------------------------------|--|--|-------------------|--|--|
| 28 | (Mokhtarian and Varma 1998) | USA | Evaluation of teleworking pilots | Commuting travel and travel-related emissions avoided through telecentre-based teleworking | 2 (commuting travel, non-commuting travel) | Reduce | On teleworking days, distance travelled by centre-based teleworkers decreased significantly compared with regular commuters, by 51 person-miles (58%) and 35 vehicle-miles (53%). There were no increases in non-work travel on teleworking days. When weighted by teleworking frequency (which was just over one time a week for the sample), there were average reductions in total person miles travelled (PMT) of 11.9% and in VMT of 11.5% over a week compared with non- teleworkers. | Good |
| 29 | (Nelson <i>et al</i> 2007) | USA | Evaluation of teleworking pilots | Emissions avoided through teleworking programme. | 1 (commuting travel only) | Unclear | Impossible to derive meaningful estimates. | Poor |
| 30 | (O'Keefe <i>et al</i> 2016) | Ireland | Analysis of survey data | The reduction in emissions through travel-savings via teleworking. | 2 (commuting travel, non-commuting travel) | Reduce | Based on patterns in the sample data (which showed that 44% of the population in the Greater Dublin Area teleworks once a month and which showed how certain segments travel to work), teleworking by between 20% and 50% of the population once a week would contribute to emissions reductions of between 31 000 tonnes and 78 000 tonnes of CO ₂ per year. | Good |

Table 4. (Continued)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope (number of impact categories considered) | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|--------------------------|---------|---|--|--|-------------------|---|--|
| 31 | (Pratt 2002) | USA | Analysis of survey data | Daily travel distance avoided through teleworking | 1 (commuting travel only) | Reduce | Individuals who part-time telework travel 3.6 miles (or 17%) less on teleworking days for work-related travel than employer-based workers. | Poor |
| 32 | (Röder and Nagel 2014) | Germany | Analysis of survey data | Potential reduction in energy demand through teleworking. | 4 (commuting travel, home and office energy use) | Neutral | Teleworking by 10% of the sample (unspecified frequency) within this model reduces commuter mileage and transport energy consumption by 10% but increases energy consumed at home by about the same amount. By contrast, office energy consumption is barely affected. | Average |
| 33 | (Roth <i>et al</i> 2008) | USA | Scenario modelling (based on assumptions drawn from (Henderson <i>et al</i> 1996) | Avoided energy consumption, emissions, and gasoline consumption through teleworking. | 4 (commuting travel and office energy use) | Reduce | Teleworking by 4 million US workers (3% of the total workforce) one or more days per week could reduce annual primary energy consumption by between 0.13% and 0.18% and CO ₂ emissions by between 0.16% to 0.23%. It could also decrease US light-duty vehicle gasoline consumption by 0.8%. | Average |

Table 4. (Continueud)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope (number of impact categories considered) | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|--------------------------------|---------|--------------------|--|--|-------------------|--|--|
| 34 | (Shabanpour <i>et al</i> 2018) | USA | Scenario modelling | Avoided commuting distance travelled and emissions from teleworking. | 2 (commuting travel, non-commuting travel) | Reduce | When 50% of workers have 'flexible working schedules'; total daily VMT and vehicle hours travelled (VHT) can be reduced by up to 0.69% and 2.09%, respectively. Considering the same comparison settings, this policy has the potential to reduce greenhouse gas emissions by up to 0.71%. | Average |
| 35 | (Shimoda <i>et al</i> 2007) | Japan | Scenario modelling | Reduced energy consumption from the reduction in commercial energy consumption overweighing increases in residential energy consumption. | 2 (home and office energy consumption) | Reduce | Provided the floor area of office buildings being utilized decreases as the rate of teleworking increases, 60% of the population could teleworking lead energy consumption to decrease by 0.6% of the total energy consumption of the residential and non-residential sectors in Osaka City. | Average |

Table 4. (Continued)

| Study no. | Authors and date | Country | Methodology | Metrics | Scope (number of impact categories considered) | Impact on metrics | Nature/scale of impact | Our appraisal of methodological robustness |
|-----------|-------------------------|-----------|-------------------------|---|---|-------------------|---|--|
| 36 | (Van Lier et al 2014) | Belgium | Analysis of survey data | Commuting distance displaced by teleworking. | 1 (commuting travel only) | Reduce | Difficult to say. All that is reported is that working from home reduces teleworkers' commute by 45 km per day on teleworking days and that working in a satellite centre reduces the commute for these workers by 38 km, from 60 km to 22 km per day. | Poor |
| 37 | Vu and Vandebona (2007) | Australia | Scenario modelling | Car distance travelled avoided by teleworking. | 1 (commuting travel only) | Reduce | Assuming a 60 km commute, a once-a-week teleworking frequency by 18% of all workers in New South Wales, and a rate of single-occupier driving of 70%, 3 million vehicle-km (4.2% of the total) could be avoided by 2001 and there could be a reduction of 15.5% of the total by 2021. | Average |
| 38 | (Williams 2003) | Japan | Scenario modelling | Overall energy reduced by teleworking, taking into account changes in travel behaviour and office and home energy consumption (heating and cooling) | 3 (commuting travel and office and home energy use) | Reduce | The adoption of 4-day per week teleworking by mobile sales and specialist/technical workforce (approx. 14% of the total workforce) could reduce national energy consumption by 1.0%. If clerical workers (and additional 23% of the workforce) also telework an additional 1.1% of savings become possible. | Poor |
| 39 | (Zhu 2012) | USA | Analysis of survey data | Whether teleworking reduces overall distance travelled (both work and non-work together) or whether teleworking is a complement to other forms of travel. | 2 (commuting travel, non-commuting travel) | Increase | In 2001, teleworkers' work trips were 34.2% longer in distance than non-teleworkers (39 km instead of 29 km); their non-work trips were 17.1% longer (39 km instead of 33 km). Teleworkers also take more non-work trips than non-teleworkers, 4.39 per day instead of 3.87 per day. In 2009, teleworkers' work trips were 43.3% longer in distance than non-teleworkers, 43 km instead of 30 km; their non-work trips were 15.7% longer, 36 km instead of 32 km. Teleworkers frequency of non-work trips had however fallen compared with non-teleworkers, 4.18 per day instead of 3.77 per day. Overall, if the rate of teleworking is 3%, the impact on the monthly round-trip commute distance is negligible. | Good |

Table 5 summarises the primary method used, with the specific studies referenced to the list in table 4.³

Table 6 classifies the studies by their *scope*, or the ‘number of impact categories’ included. We distinguish four categories of impact, namely the energy used in: (a) commuting; (b) non-work travel; (c) the home; and (d) the office. Most studies do not estimate energy consumption directly, but use other metrics such as distance travelled that serve as proxies for energy consumption. While there may be additional impact categories, such as economy-wide rebound effects, these are not included in any of the reviewed studies. The scope of a study depends in part upon the research questions employed: for example, if the primary interest is the impact of teleworking on congestion, a narrow scope is appropriate. Conversely, if the primary interest is the impact on energy consumption, a wide scope is appropriate. While our interest lies with the latter, studies with a narrow scope nevertheless provide useful evidence on the impacts on energy consumption within a particular area.

While approximately half the studies (19) only consider the impact of teleworking on commuter travel, the remainder estimate a wider range of impacts. For example: 12 studies also estimate the impact on non-commuting travel by either the commuter or other household members; five studies estimate the impacts on home and/or office energy use as well as commuting travel; and two studies estimate the impacts on commuting travel and home energy use (but not on non-work travel). An exception is (Shimoda *et al* 2007), who ignore the impact on travel altogether and only consider the impact on home and office energy consumption. It is notable, however, that *none* of these studies encompass all four of our impact categories.

Table 7 summarises our assessment of the methodological quality of each study. We ranked 14 of the studies as methodologically ‘good’, 11 as ‘average’ and 14 as ‘poor’. Some justification for these rankings can be found in supplementary material 2. Section 5.5 discusses the relevance of methodological quality to the estimated impacts on energy consumption.

5.2. A summary of the energy, climate and environmental impacts of teleworking

Table 8 shows that the majority of the studies (26 out of 39) suggest that teleworking (both from home and telecentres) leads to a net *reduction* in energy use and/or emissions, with only five studies finding a net increase. These benefits largely result from the elimination of the commute, reductions in congestion,

concomitant reductions in vehicle emissions, and reductions in office-based energy consumption.

While most studies compare the *net* energy/environmental impacts of a teleworking and non-teleworking mode of working, a few studies (e.g. Atkyns *et al* 2002) provide only *absolute* estimates of changes in key variables, such as gallons of gasoline saved. These studies are less useful than those providing relative figures expressed in terms of a percentage gain or loss. Only the latter are included in table 9, which displays the full range of estimates found in our sample of the net impact of teleworking on different metrics. As with scope, the diversity of metrics used by the different studies reflects their different research questions.

While all of the metrics in table 9 are relevant to the impact of teleworking on energy consumption (our research question), some are more useful than others. It is important to stress, furthermore, that the estimates in table 9 are a mix of relative and absolute figures, reflecting the diversity of the studies. So, while some studies estimate the impact of telecommuting versus not telecommuting for single journeys (a *relative* figure), other studies estimate the *total* impact of a specific proportion of the population telecommuting a certain number of times per week or month (an absolute figure). This makes it difficult to extract any normalized estimates of relative energy savings from across contexts.

Table 9 indicates that the most commonly used metric (used by 26 of the 39 studies) is vehicle distance travelled, which is a proxy for the energy consumed by motorized travel. Studies using this indicator give the widest range of estimates, ranging from a 20% reduction in distance travelled (Balepur *et al* 1998), to a 3.9% increase (De Abreu E Silva and Melo 2018). These studies either measure or assume different *proportions* of teleworkers and/or differing *frequencies* of telework, making comparison between them difficult. In addition, most of the studies do not disaggregate ‘avoided travel’ by mode and instead (implicitly) assume that it relates to travel by private car. In fact, (De Abreu E Silva and Melo 2018) is the only study to recognise that the (avoided) commuter travel may be by other modes such as public transport. This bias partly reflects the dominance of US studies, but the assumption that avoided travel *necessarily* take the form of avoided car travel may lead to an overestimate of energy and travel savings (see section 5.6).

Moreover, while many studies estimate the impacts of teleworking on weekly distance travelled, they typically confine attention to commuter travel and hence neglect non-work travel. As a result, they may overestimate the total reduction in travel distance. For example, (Hjorthol 2006), who only considers work travel by car, finds that vehicle travel distance is 8% lower per month for teleworkers than non-teleworkers; whereas (Zhu 2012), who *also* considers impacts on non-work travel, finds a negligible

³Note that some studies used more than one method. For example, some studies based primarily on survey data *also* utilize some secondary transport data to establish teleworking impacts.

Table 5. Classifying studies by method.

| Type of method employed | No. of studies using this method | Specific studies using this method |
|----------------------------------|----------------------------------|--|
| Scenario modelling | 14 | 4, 8, 16, 18, 22, 23, 24, 25, 26, 33, 34, 35, 37, 38 |
| Analysis of survey data | 19 | 1, 2, 5, 6, 7, 9, 10, 11, 12, 13, 15, 17, 20, 21, 30, 31, 32, 36, 39 |
| Evaluation of teleworking pilots | 6 | 3, 14, 19, 27, 28, 29 |

Table 6. Classifying studies by scope.

| Scope of studies (impact categories included) | | | | No. of studies with this scope | Studies with this scope |
|---|-----------------|-----------------|-------------------|--------------------------------|--|
| Commuting travel | Non-work travel | Home energy use | Office energy use | | |
| X | | | | 19 | 1, 2, 4, 6, 8, 11, 12, 13, 15, 16, 20, 21, 23, 24, 26, 29, 31, 36, 37, |
| X | X | | | 12 | 3, 5, 7, 9, 14, 17, 19, 27, 28, 30, 34, 39 |
| X | | X | | 2 | 10, 22 |
| | | X | X | 1 | 35 |
| X | | X | X | 4 | 18, 25, 32, 38 |
| X | X | X | X | 1 | 33 |

Table 7. Classifying studies by methodological quality.

| Methodological quality | No. of studies of this standard | Specific studies of this standard |
|------------------------|---------------------------------|---|
| Good | 15 | 3, 5, 6, 7, 9, 10, 13, 17, 18, 19, 25, 27, 28, 30, 39 |
| Average | 10 | 2, 11, 12, 14, 20, 32, 33, 34, 35, 37 |
| Poor | 14 | 1, 4, 8, 15, 16, 21, 22, 23, 24, 26, 29, 31, 36, 38 |

Table 8. A summary of the net impacts of teleworking on energy across the final sample of studies.

| Impact of teleworking | Reduce | Neutral | Increase | Unclear |
|-----------------------|--------|---------|----------|---------|
| No. of studies | 26 | 3 | 5 | 5 |

Table 9. The range of estimated impacts of teleworking on different metrics within the final sample of studies.

| Metric | Measures | No. of studies using this metric ^a | Range of net impacts ^b (%) |
|----------------------------|-------------------------|---|---------------------------------------|
| Vehicle distance travelled | Miles, km | 26 | −20 to +3.9 |
| Person distance travelled | Miles, km | 6 | −19 to −11.9 |
| Commuter trips | No. of trips | 7 | −30 to −2.3 |
| Congestion | Minutes in congestion | 3 | −28 to −1.9 |
| Overall energy use | MJ, kWh, litres of fuel | 7 | −15 to −0.01 |
| CO ₂ emissions | Grams, tonnes | 10 | −80 to −0.1 |

^aSome studies examine more than one indicator, so the total in this column sums to more than 39.

^bThese impacts are under very different conditions and are estimated using very different methodologies. For more detail, see supplementary material 3.

impact on total vehicle distance travelled. This pattern is visible across the studies, with studies with a wider scope (i.e. including more impact categories) tending to provide lower estimates of energy or travel savings. This point is discussed further in section 5.6.

Six of the studies measure the impact on ‘person distance travelled’, rather than vehicle distance travelled, and find that teleworking reduces the former by between 11.9% and 19%. This is less useful, however, since it does not tell us *how* the commuter was travelling (e.g. by car or public transport), or whether

they were sharing the vehicle with other occupants. For example, person distance travelled could increase owing to a longer commute, while vehicle distance travelled could fall owing to greater use of public transport—and the latter is more strongly correlated with energy consumption (Henderson *et al* 1996).

Seven studies measure impacts in terms of the *number* of commute trips and find reductions of between 2.3% and 30% per week. This metric tells us less about energy savings, however, as it does not

indicate the distance travelled. (Mitomo and Jitsuzumi 1999) measure impacts in terms of time savings from reduced traffic congestion and estimate that these range from 1.9% to 28%, with implications for energy use and emissions from stationary traffic.

Seven studies estimate the impact of teleworking on energy consumption and estimate reductions of between 0.01% and 14%. Several of these take into account the impacts on both commuting energy use and home or office energy. For example, (Matthews and Williams 2005) estimate that, if half of the 'information workers' in the US and Japan telework four days per week, this would reduce primary energy consumption by ~1%. Finally, ten studies suggest that teleworking could reduce carbon emissions by between 0.1% and 80%, with this higher estimate assuming a five-day teleworking routine by the whole population (Kitou and Horvath 2003).

5.3. Sources and estimates of environmental benefits from teleworking

The majority of the 39 studies suggest there are energy savings and other environmental benefits from teleworking. This section examines the main sources and estimates of these savings in more detail and contextualizes these results in terms of the broader literature.

5.3.1. Elimination or reduction of commutes

The main source of energy savings is the reduction in commuter travel to and from work. This is a substitution effect, whereby ICT facilitates remote working and removes the need to commute for at least part of the week. Overall, the studies suggest varying reductions in weekly, monthly or annual vehicle distance travelled, up to a maximum of 20%. They also suggest corresponding benefits, including reductions in the number of trips by up to 30%, time savings from reduced congestion of up to 28% (which in turn could lead to significant energy savings since slow-moving traffic is inefficient), and associated reductions in carbon emissions. It should be stressed, however, that the majority of the studies finding reductions in vehicle distance travelled neglect potential rebound effects—such as increased non-work travel (see section 5.4).

Studies of telecentre workers find significant reductions in commuting distance travelled. For example, (Balepur *et al* 1998) show how participants in the Puget Sound pilot who teleworked once a week reduced their total weekly commuting vehicle travel by 19% (10 miles). However, different studies make different estimates of, or assumptions for, the number of households that are teleworking and the frequency with which they are teleworking. They also estimate both *relative* and *absolute* figures, making it difficult to compare their estimates of travel/energy savings and to generalise their findings. For example, (Choo *et al* 2005) estimate that teleworking is practised by 12% of the US workforce once a week and estimate

a resulting 0.8% reduction in the total distance travelled by private cars. In contrast, (Martens and Korver 2000) assume a teleworking rate of 'between 20% and 60%' of the US working population and estimate a resulting 5% reduction in vehicle distance travelled. But (Martens and Korver 2000) do not state the assumed *frequency* of teleworking (i.e. how many times per week these 20%–60% of the population will telework). They moreover make arguably unrealistic assumptions about the potential future uptake of teleworking considering that the current proportion of teleworkers is only 9% in the US and 5% in the UK. Other studies (e.g. Röder and Nagel 2014) fail to state *either* the proportion of the population teleworking *or* their frequency of teleworking, making it impossible to extrapolate useful lessons from their results.

The studies also relate to very different geographical contexts, where differences in the patterns and modes of commuting differ have important implications for the potential energy savings from teleworking. For example, (Helminen and Ristimäki 2007) estimate that teleworking by 4.7% of the Finnish labour force once a week would reduce commuting distance travelled by 0.7%. (Larson and Zhao 2017) meanwhile estimate that if 20% of US workers telework once a week, commuting energy consumption would decrease by 20%. However, Finland and the US differ significantly in terms of the average distance between home and work, the modal mix for commuter travel and the relative energy efficiency of different modes; with the result that the energy savings from teleworking in Finland may be substantially lower than in the US. For example, while (Helminen and Ristimäki 2007) state that 70% of the Finnish population commute by car or motorbike, (Larson and Zhao 2017) assume that all US commuting is by car. This means that the energy savings from telecommuting will be higher in the US, where the forgone travel is in the form of avoided car trips, compared with Europe, where a large proportion of commuting is by other modes (Van Lier *et al* 2014).

For our purposes, however, the most fundamental problem with many of the studies is their limited *scope*. Indeed, whether teleworking reduces economy-wide energy consumption depends upon the impacts on commuting travel, non-work travel, home energy use and office energy use, together with the relative energy efficiency of transport modes, homes and office buildings. Most studies only provide a partial coverage of these different variables. While some studies examining both work and non-work travel find that increases in non-work travel as a result of teleworking do *not* lead to increases in overall travel (e.g. Mokhtarian and Varma 1998), others find evidence to the contrary (e.g. Zhu 2012). Capturing these nuances in order to appraise the impact of teleworking on *overall* energy use is difficult but essential—an issue that will be returned to in section 5.5.

5.3.2. Reductions in office energy consumption

Some of the literature on ICT and energy suggests that more remote working may lead to higher energy consumption at home (e.g. Chapman 2007). However, several studies show how, even allowing for increases in home energy consumption, teleworking could achieve overall energy savings since it enables reductions in per capita office space (e.g. through hot-desking) and potentially means that offices no longer need to be heated or cooled to the same level or for the same period of time. (Williams 2003), for example, estimates that the adoption of 4-day per week teleworking by the specialist/technical workforce in Japan (~14% of the total) could reduce national energy consumption by 1.0% by eliminating the need for office heating and cooling on non-working days. Similarly, (Matthews and Williams 2005) estimate that the potential energy savings from reducing office space are comparable to those from reduced commuting. In countries such as Japan, where there is a lower level of office space per worker, the energy savings from reduced office use may be smaller than in the USA, where offices tend to be larger (Matthews and Williams 2005). The gains may also be smaller in more temperate regions, since less energy is required to heat and cool office buildings (Kitou and Horvath 2003) and may also be partly offset by the embodied energy associated with duplicated equipment such as printers. The latter forms part of the direct impacts of ICT on energy consumption (table 1), but this is ignored in all of the reviewed studies.

As with gains from reduced commuting, these potential gains also depend upon a range of factors, including the extent to which firms downsize or close their offices as the number of teleworkers increase. (Shimoda *et al* 2007) estimate that, if utilised office space decreases in proportion to the rate of teleworking, full-time teleworking by 60% of workers in Osaka City (Japan) would reduce total energy consumption for residential and non-residential buildings by 0.6%. (Shimoda *et al* 2007) stress, however, that if teleworkers are only part-time, companies may not downsize their offices or reduce energy consumption since they will need to retain the same sized premises for the days that teleworkers join non-teleworkers in the office. Since part-time teleworking is more common than full time teleworking, the latter appears a more likely outcome. Thus, the potential gains in terms of reduced office energy consumption may not be realised.

More generally, (Shimoda *et al* 2007) demonstrate that, even assuming office energy use falls in proportion to the rate of teleworking, very high levels of teleworking may achieve only modest reductions in aggregate energy consumption. Similar conclusions are reached by (Matthews and Williams 2005), who estimate that if all US 'information workers' teleworked four days a week, US energy consumption

would fall by only ~2%. This is partly because teleworking is expected to be suitable for less than half of the US workforce. For comparison, (Matthews and Williams 2005) estimate that a 20% improvement in average car fuel efficiency in the US would reduce aggregate energy use by ~5.4%.⁴

Although (Shimoda *et al* 2007) provide some useful evidence about the potential impacts of teleworking on home and office energy consumption, their study provides no analysis of the impacts of teleworking on work or non-work travel. Hence, it still provides only a partial picture of the net impacts of teleworking on energy consumption.

5.4. Rebound effects from teleworking

While teleworking is framed by some studies as a promising way to reduce energy consumption, particularly from commuting travel, other studies draw attention to potential unintended impacts that could increase energy consumption and negatively affect various environmental indicators. They also highlight the uncertainty about the impacts of teleworking, owing to the complexity of impact pathways and the unpredictability of human behaviour.

5.4.1. Dispersion of residential location and longer commutes

Although 70% of the studies in our review suggest that teleworking reduces energy use, five studies—which we also consider to be methodologically rigorous—suggest that the gains from eliminating commutes on teleworking days may partly or wholly offset by longer commutes on non-teleworking days (Balepur *et al* 1998, Chakrabarti 2018). For example, (Helminen and Ristimäki 2007) find that Finnish teleworkers have a 3.7 km longer commute than non-teleworkers. This concurs with (De Abreu e Silva and Melo's 2017) finding that, controlling for a wide range of sociodemographic variables, UK teleworkers (in one-worker households) have a 10.7 mile longer commute than non-teleworkers. Several studies moreover find that some teleworkers also travel further than regular commuters on days that they are *not* teleworking. For example, (Henderson *et al* 1996) find that home-based teleworkers in the US travel 67% less than regular commuters on teleworking days, but 54% *more* on non-teleworking days. Thus, over the course of a week—and given a part-week teleworking lifestyle—teleworkers may potentially travel further than regular commuters.

However, such studies do not establish the direction of causality, i.e. do people telework to avoid a long (and/or a slow or difficult) commute, or

⁴The proportional reduction in emissions contributing to poor air quality may be larger, since these are particularly concentrated in the road transport sector.

do they *choose* to live further away from the workplace because their job *enables* them to telework? One approach to identifying whether teleworking has a causal influence on commuting distance is to use instrumental variables. In his analysis of US national household survey data, (Zhu 2012) used the frequency of internet use as an instrument for teleworking since this should be correlated with the latter while not affecting commuting distance. (Zhu 2012) finds that teleworking has a positive influence on commuting distance that has increased over time. In 2009, US teleworkers' work trips were 43% longer in distance than those of non-teleworkers—compared to 34% in 2001.

An alternative approach to addressing endogeneity is to use panel data, since this allows the changes in teleworking and commuting distance over time to be identified whilst controlling for time-invariant fixed effects. Using this approach, (de Vos *et al* 2018) estimate that Dutch teleworkers have 5% longer commuting times on average, with every additional day of home working being associated with a 3.5% longer duration commute. In a more recent study using a different data set, (de Vos *et al* 2019) obtain larger estimates of 12% and 16% respectively. Both studies use commuting duration rather than commuting distance as the dependent variable, but these two variables should be correlated—and (Zhu's 2012) results suggests that the impact of teleworking on distance travelled could be larger than the impact on commuting duration.

Overall, evidence from both the US and Europe suggests that the adoption of teleworking may induce long-term changes in residential location that offset some of the environmental benefits. The size of this effect may be expected to vary with contextual factors, such as the differential in property prices between urban and peri-urban regions and the financial and temporal cost of the commuting journey. However, it seems clear that, in some circumstances, the increased adoption of part-time teleworking could *increase* weekly, monthly, or annual commuter travel. More generally, the environmental benefits of teleworking will depend upon both the frequency of teleworking and how far teleworkers live from their workplace (Lachapelle *et al* 2018).

5.4.2. Non-work travel

Another potential unintended effect of teleworking is that it may encourage more non-work travel. In this case, the travel avoided by the daily commute is partly or wholly offset by additional travel by the teleworker for other reasons. This is sometimes termed a 'complementary' effect of teleworking (Mokhtarian 2002, 2009). Several studies find such effects, though it is important to underline that they only do so because their wider scope enables the interactions between teleworking behaviour and non-work travel to be explored.

For example, (Eldér 2017) finds that teleworkers travel further than non-teleworkers on *both* teleworking *and* non-teleworking days. While non-teleworkers travelled an average of 46 km per day, teleworkers travelled 54 km on teleworking days and 64 km on non-teleworking days. Similarly, (Zhu 2012) find that, according to US National Household Travel Surveys (NHTS), teleworkers took 10.8% more non-work trips per day than non-teleworkers (4.18 versus 3.77) and that these were, on average, 15.7% longer (36 km versus 32 km). Again, using instrumental variables, (Zhu 2012) finds that teleworking has a significant impact on non-work travel.

The reasons for greater non-work travel on teleworking days are complex and are not explored by most of the studies in the sample. Of the studies that did attempt to explain causality, (Zhu 2012) suggests that non-commuting workers are less able to 'daisy chain' (or 'link') trips together in an efficient way, and thus have to make specific trips for non-work activities. This effect may be particularly pronounced where there is one household member who works: with that member no longer commuting, other household members may have to make separate trips out to carry out specific non-work duties (Kim *et al* 2015, De Abreu E Silva and Melo 2018). The distance travelled for non-work activities will also vary with geographical context, including the proximity of the home to schools, retail outlets and other destinations—which again suggests that the results from US studies may not necessarily apply to other contexts.

Teleworking could also increase daily/weekly travel among those who telework by creating a displacement effect, whereby commuting trips are replaced with other forms of non-work travel, such as leisure trips (Lachapelle *et al* 2018). These trips could be due to boredom or could merely be opportunistic where teleworkers take advantage of their free time to travel more or to engage in more social activities (Rietveld 2011). This type of induced travel is consistent with the broader evidence on the stability of daily travel time in widely different contexts—at slightly over one hour a day (Schäfer and Victor 1997, Stopher *et al* 2017).

The evidence for a definitive, non-work travel rebound is, however, inconclusive. For example, (Mokhtarian and Varma 1998), in their analysis of travel diary data in a teleworking pilot in California, find no evidence of increased non-work travel on teleworking days. However, this lack of evidence is partly because most studies neglect non-work travel altogether, and therefore fail to detect these effects. For example, although only 15 of the 39 studies in our sample examine non-work travel, five of these find complementary travel effects. As most studies focus more narrowly upon commuter travel and ignore interactions between teleworking practices and non-work travel, it seems likely that they overestimate the energy savings from teleworking.

5.4.3. Intra-household dynamics and non-work travel

The potential rebound effects discussed above may be further amplified by intra-household travel dynamics. Indeed, two studies examined the ways in which the travel behaviour of all household members is affected by one or more members' teleworking. (De Abreu E Silva and Melo 2018), for example, find that the travel effects of teleworking by one household member were different when there were two household members working. Using UK National Travel Survey data, they find that higher teleworking frequencies in one-worker households were associated with more travel by all modes, particularly by car. But in two-worker households, the estimated increase in travel was much smaller and not statistically significant. They claim that this lower increase in travel in two-worker households is due to a greater degree of sharing of household-related travel tasks between workers.

In South Korea, an additional effect was discovered, whereby home-based working by the 'head of household' led the level of household vehicle usage to increase. Using cross-sectional data for Seoul, South Korea, (Kim *et al* 2015) find that teleworkers' non-work trips as well as his/her household members' non-work trips were greater than those of non-teleworkers and their household members. While the daily distance travelled by the teleworking head of household fell by 7.8 km per day, this was offset by increases in the teleworker's non-commute travel (+24.2 km per day), as well as by increased non-work travel by other household members' (+1.5 km per day). But these differences were only significant in households with less than one vehicle per employed member. Car ownership is lower in South Korea than the USA (0.91 per household compared to 1.79), so the car is more of a scarce commodity. More generally, the focus of the teleworking literature on the US (where per capita car ownership is exceptionally high) may have led researchers to pay insufficient attention to the induced impact on travel by other household members.

5.5. Reflections on the types of teleworking and teleworkers

The studies examined two types of teleworking: home-based and telecentre-based. It is however difficult to assess the merits of one type over the other due to the highly specific conditions examined by different studies.

In terms of *types* of teleworkers, most studies examined office-based and computer-dependent workers, recognizing that these professions have the greatest potential for teleworking. For example, Matthews and Williams (2005) estimated that approximately 40% of jobs in the US and Japan would be suitable for teleworking. Within this group, studies emphasise that, above all, it is the frequency of teleworking over the course of a week that is

the crucial factor in determining impacts—especially among those who live far from their place of work. Thus, from this perspective, it is full-time (or near full-time) telework that has the greatest potential for energy savings. Many of the studies examine schemes within larger companies (e.g. Atkyns *et al* 2002) and suggest that mass teleworking may be more realistic within large firms that can still retain a few office-based workers. In contrast, small firms whose workers take on multiple roles may be less able to encourage teleworking (Aguilera *et al* 2016).

While most studies investigate the impacts of a single teleworker, others examine the impacts of intra-household travel dynamics where more than one household member works, suggesting that teleworking impacts may be conditional on households being able to *reconfigure* non-work duties (e.g. De Abreu E Silva and Melo 2018). This would depend on economic and social capacity, as daily commuting may be an important part of households' economic strategy, with commuting travel being combined with other non-work duties, such as childcare and shopping.

Beyond the fairly unsophisticated analysis of the differing temporal frequencies of teleworking and certain intra-household work and travel dynamics, there is relatively little exploration of social differentiation among teleworkers and its impact on energy, suggesting that further research would be useful in this area. For example, none of the studies examine the gender dimensions of teleworking, although some studies in the *preliminary* sample of studies (e.g. Jaff and Hamsa 2018) consider such dynamics. Nor do any of the final studies examine other demographic dimensions of teleworking, such as ethnicity or political affiliation. However, many studies note the importance of household income, and observe that wealthier households may have longer commute distances on non-teleworking days (e.g. Fu *et al* 2012, Kim *et al* 2015).

5.6. Methodological assessment: a question of robustness and scope

As noted, the studies vary widely in both methodological quality and scope—raising the question of whether there is any correlation between these variables and the estimated impacts of teleworking. Table 10 maps our assessment of methodological quality against the sign of the estimated impact. This suggests that the more methodologically rigorous studies are *less likely* to estimate energy savings from teleworking. Specifically, 19 out of the 27 studies judged to be methodologically 'poor' or 'average' found reductions in energy use, while all six of the studies that found that teleworking led to negligible reductions or an increase in energy use were judged to be methodologically 'good'.

In terms of methods, table 11 shows that the strongest studies tended to be those analysing survey

Table 10. Methodological quality of studies mapped against the impacts of teleworking.

| Methodological quality of study | Study assessment of impact of teleworking impact on energy | | | | Total |
|---------------------------------|--|---------|----------|---------|-------|
| | Reduction | Neutral | Increase | Unclear | |
| Good | 7 | 1 | 5 | 1 | 14 |
| Average | 8 | 2 | - | 1 | 11 |
| Poor | 11 | - | - | 3 | 14 |
| Total | 26 | 3 | 5 | 5 | 39 |

Table 11. Classifying studies by methodological type and methodological quality (number of studies).

| Methodological quality | Scenario modelling | Analysis of survey data | Evaluation of teleworking pilots | Total |
|------------------------|--------------------|-------------------------|----------------------------------|-------|
| Good | 2 | 9 | 4 | 15 |
| Average | 4 | 5 | 1 | 10 |
| Poor | 8 | 5 | 1 | 14 |
| Total | 14 | 19 | 6 | 39 |

Table 12. Mapping the scope of studies against the impacts of teleworking.

| Study scope | Study assessment of teleworking impact on energy consumption | | | | Total |
|--|--|---------|----------|---------|-------|
| | Reduction | Neutral | Increase | Unclear | |
| Only the impact on commuting travel | 15 | 1 | - | 3 | 19 |
| The impact on commuting travel <i>and</i> one other variable | 8 | - | 5 | 1 | 14 |
| The impact on <i>only</i> home and office energy demand (and not travel) | 1 | - | - | - | 1 |
| The impact on commuting travel <i>and</i> two other variables | 2 | 2 | - | 1 | 5 |
| Total | 26 | 3 | 5 | 5 | 39 |

data, especially those using large-scale national transport surveys and using panel and time-series data on work and travel behaviour (e.g. Kim *et al* 2015, Chakrabarti 2018). Although based on much smaller data sets, the studies examining specific teleworking pilot schemes—either within firms or within bounded regions (e.g. Henderson *et al* 1996)—also contain rich data on travel behaviour in response to teleworking. The weaker studies meanwhile projected future impacts from teleworking using scenario modelling rather than estimating historical impacts. These studies frequently relied upon limited datasets and/or unrealistic assumptions (e.g. Dissanayake and Morikawa 2008, Mamdoohi and Ardeshiri 2011). More fundamentally, as they are projecting impacts rather than measuring them, the estimated impacts rely upon modelling assumptions rather than empirical data. They are therefore a much weaker form of evidence.

Table 12 maps the scope of the studies against the sign of the estimated impacts. This suggests that studies with a wider scope are also more likely to find that teleworking leads to an *increase* in energy use, or else has a negligible impact on energy use.

Indeed, table 11 shows that *all* five of the studies finding that teleworking lead to an increase in energy use examined at least two variables—typically the impact on commuting travel *and* non-commuting travel. By contrast, 15 of the 27 studies finding that teleworking causes a reduction in energy use examined the impact on commuting travel alone.

Finally, table 13 shows the relationship between methodological quality and scope, with the studies having a wider scope (considering impact variables beyond just commuter travel) tending to be judged of higher methodological quality. Conversely, most of the studies with a narrower scope (considering the impact on commuter travel alone) are judged of lower methodological quality. Specifically, we can see that 17 out of the 19 studies with a narrow scope were rated methodologically poor or average, while 13 out of the 20 studies with a wide scope were rated methodologically good.

Overall, this analysis suggests that researchers should be wary of drawing conclusions from methodologically weaker studies that also have a narrow scope.

Table 13. Mapping the methodological quality and scope of studies against the impacts of teleworking.

| | Narrow scope (commuter travel alone) | Wide scope (commuter travel and additional variables) |
|----------------------------------|--------------------------------------|---|
| Methodologically average or poor | 17 | 7 |
| Methodologically good | 2 | 13 |

6. Conclusion and implications

This article has conducted a systematic review of the evidence on the impacts of teleworking on energy consumption. It reduced an initial sample of over 9000 academic articles to a final sample of 39 relevant studies by using specific inclusion and exclusion criteria. The final sample contained studies which investigated teleworking in a variety of contexts and which employed a range of different research methods—including scenario analysis and the quantitative analyses of survey data. The studies were predominantly focused on the US, with fewer from the EU and only three from the Global South. The studies mainly examined home-based teleworking, with three older studies examining experience with telecentres.

Overall, 26 out of 39 studies found that teleworking reduced energy use via a substitution effect, with only eight studies finding that teleworking led to higher—or else had a negligible impact on—energy use. This suggests that teleworking has some potential to reduce energy consumption and associated emissions—both through reducing commuter travel and displacing office-related energy consumption. However, a major difficulty in establishing whether teleworking does lead to a consistent relative reduction in energy use is the fact that every study provides estimates of energy savings based on a different set of conditions. Indeed, while some studies estimate the energy savings from telecommuting versus not telecommuting for single journeys (a *relative* figure), other studies present estimations of the total energy savings based on a specific proportion of the population telecommuting a certain number of times per week or month (an *absolute* figure). Some studies fail to specify either the frequency of teleworking or the proportion of teleworkers within the population that their estimates are based on. This makes it difficult to extract any normalized estimates of relative energy savings from across contexts based on identical (or similar) proportions and frequencies of teleworking. It also demands that researchers examine closely the specific configurations of conditions within particular studies that have led to particular estimates to be made for specific time periods.

While most studies conclude that teleworking can contribute energy savings, the more rigorous studies and/or those with a broader scope present more ambiguous findings. Indeed, where studies include additional impacts, such as non-work travel or office

and home energy use, the potential energy savings appear more limited—with some studies suggesting that, in the context of growing distances between the workplace and home, part-week teleworking could lead to a net *increase* in energy consumption. In short: it is likely that many studies in the sample may have concluded that teleworking reduces energy use because their scope was too narrow—a problem identified by (Mokhtarian 2009, p. 43):

Although direct, short-term studies focusing on a single application (such as teleworking) have often found substitution effects, such studies are likely to miss the more subtle, indirect, and longer-term complementarity effects that are typically observed in more comprehensive analyses.

These uncertainties and complexities suggest that, despite the positive evidence for energy savings that was found across the sample of studies, we should be cautious in drawing conclusions about the scale and consistency of energy savings from teleworking. Context matters, and in many circumstances the savings could be negative or non-existent. Moreover, the associated carbon savings will depend upon additional factors such as the carbon intensity of the energy used for transport (e.g. conventional versus electric vehicles), as well as that used for heating and cooling buildings (Moradi and Vagnoni 2018) (Giovanis 2018). Both of these are undergoing rapid change.

Furthermore, while ‘teleworking’ or ‘telecommuting’, as terms, predate the internet itself, they also arguably refer to practices that do not reflect the dynamic new realities of working practices. Indeed, the technological basis of the working environment has changed dramatically since the 1990s, driven by the panoply of new innovations, such as ‘cloud’ storage, ubiquitous high-bandwidth Wi-Fi, video streaming, and ‘5 G’ mobile services (Appio *et al* 2018). So too has the range of social forms of work, with stable, single-location jobs yielding to ‘zero hours’ contracts and flexi-time arrangements (Akbari and Hopkins 2019). In short, modern modes of flexible or mobile work have become so non-linear and fluid (but also increasingly energy intensive in places) that it has become increasingly difficult to track their energy footprint, or to compare it with a dissolving notion of ‘regular’ work (Hopkins and McKay 2019).

Studies interested in appraising the potential of more flexible, ICT-enabled work practices should therefore aim to combine a range of methods capable of capturing the dynamic new configurations of working conditions. As well as accounting for change in commuting travel, non-commuting travel, distance between home and office, and home and office energy consumption, these studies must also consider other factors, such as the mode of commuting transport in the region being studied and the ways that people choose to use their time when they no longer have to commute to and from work. As many of these realities can only be established through qualitative methods, modellers must work together with other social scientists in order to build a better picture of the changing patterns of work and the energy saving potential of new working practices (e.g. Hampton 2017).

Finally, as 'flexible work' has become increasingly dependent on new energy-intensive forms of digital technologies (not to mention the reliance on rare earth metals and minerals (e.g. Sovacool et al 2019)), researchers should examine critically whether indeed new, flexible ways of working are indeed 'sustainable', in the broadest sense (Mattila et al 2014, Priest et al 2016). Future studies in this area should therefore aim to combine a range of methods, types of work, and work arrangements in order to attempt to capture the dynamic configurations of conditions that could potentially support teleworking as a socially, economically, and environmentally constructive practice for the future.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

ORCID iD

Benjamin K Sovacool  <https://orcid.org/0000-0002-4794-9403>

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