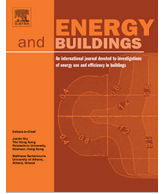




Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.



# Does telecommuting save energy? A critical review of quantitative studies and their research methods



William O'Brien<sup>a,\*</sup>, Fereshteh Yazdani Aliabadi<sup>b</sup>

<sup>a</sup> Architectural Conservation and Sustainability Engineering, Department of Civil and Environmental Engineering, Carleton University, Canal Building, 432 Mackenzie, 1125 Colonel By Drive, Ottawa K1S 5B6, Canada

<sup>b</sup> Department of Civil and Environmental Engineering, Carleton University, Canal Building, 5208, 3432 Mackenzie, 1125 Colonel By Drive, Ottawa K1S 5B6, Canada

## ARTICLE INFO

### Article history:

Received 29 May 2020

Accepted 7 July 2020

Available online 20 July 2020

### Keywords:

Telework  
Telecommuting  
Transportation  
Buildings  
Internet  
Research methods

## ABSTRACT

Teleworking has been widely perceived as a more sustainable mode of working for knowledge workers compared to the status quo of commuting to centralized offices because of its reduced dependency on transportation and centralized office space. However, the situation is far more complex than would appear on the surface, when the scope is expanded to include home office energy use, the Internet, long-term consumer choices, and other so-called rebound effects. Few studies have quantified home, office, transportation, and communications energy or GHG emissions implications of telecommuting simultaneously. To make progress in answering the question of whether telecommuting results in less energy use and greenhouse gas emissions than conventional centralized office working, this paper reviews results and research methods of primarily quantitative studies of any and all four domains that consider operating energy and/or greenhouse gas emissions. The results ultimately show that this problem is complex, and that current datasets and methods are generally inadequate for fully answering the research question. While most studies indicate some benefit, several suggest teleworking increases energy use – even for the domain that is thought to benefit most: transportation.

© 2020 Published by Elsevier B.V.

## Contents

1.	Introduction	2
1.1.	Advantages and disadvantages of teleworking	3
1.2.	Spatial and temporal study boundaries	3
2.	Literature review	4
2.1.	Transportation and urban form	4
2.1.1.	Potential	5
2.1.2.	Rebound effects	7
2.1.3.	Research methods and limitations	7
2.2.	Offices	8
2.2.1.	Potential	8
2.2.2.	Rebound effects	8
2.2.3.	Research methods and limitations	9
2.3.	Homes	9
2.3.1.	Potential	9
2.3.2.	Rebound effects	9
2.3.3.	Research methods and limitations	10
2.4.	Information and communication technology	10
2.4.1.	Potential	11
2.4.2.	Rebound effects	11
2.4.3.	Research methods and limitations	11

\* Corresponding author.

E-mail addresses: [Liam.obrien@carleton.ca](mailto:Liam.obrien@carleton.ca) (W. O'Brien), [Fereshteh.YazdaniAliabadi@carleton.ca](mailto:Fereshteh.YazdaniAliabadi@carleton.ca) (F. Yazdani Aliabadi).

3. The verdict . . . . . 11  
 4. Research needs and methods . . . . . 11  
 5. Conclusion . . . . . 13  
 Declaration of Competing Interest . . . . . 13  
 Acknowledgement . . . . . 13  
 Appendix A. Supplementary data . . . . . 13  
 References . . . . . 13

**1. Introduction**

For nearly the past five decades, teleworking has been touted as a movement that is beneficial for employee and employer alike and one that can reduce commuting time, traffic, and energy use [87,97]. Since then, technology and the corresponding shift towards knowledge-based jobs has enabled significant growth in teleworking [2,23,35], while the pandemic of 2020 has accelerated this growth. However, under normal circumstances, full predicted extent has not been realized [111]. And whereas telecommunication technology was once speculative [89,114] or a major obstacle [7], it is now ubiquitous with video-based communication being possible for anyone with a computer or smartphone and a broadband Internet connection [2].

In principle, a full-time teleworker could eliminate transportation to work and the need for a central office, both of which carry a significant environmental and economic cost. However, the literature (extensively cited throughout this paper) indicates that there numerous so-called *rebound effects* that erode or eliminate the potential energy savings from telework [58,85]. On telework, Moos, Andrey et al. [83] stated that “Since lifestyle alterations are rarely linear combinations of decisions that can cause unexpected and offsetting results are likely to occur. Without assessing the complete spectrum of environmental consequences, the net effects will remain uncertain.”

Fig. 1 shows the conceptual balance between zero impact of teleworking (i.e., no net energy benefit of teleworking) and the maximum theoretical potential. In fact, there is no reason that the net impact cannot be negative, as this paper exposes.

Quantifying the net energy and GHG emissions impacts of teleworking –the topic of the current review paper– is a nontrivial exercise. Consider the following illustrative example where all rebound effects are underlined.

*Bob gets a new job in engineering consulting and brings his family to a new city as a result. Bob's new boss allows him to work up to three days a week at home; this was used as a perk to recruit him from a different company. Because Bob's wife plans to get a job a local school, wherever they end up living, Bob and his wife opt to live in the suburbs, about 30 km from the central business district where his office is located. He figures that this is a bit far to commute, but if he only must do it twice per week, then his average commute (normalized by five days per week) is merely 12 km each way. That's better than the 15 km he used to drive each way to work every day. And now they can afford a much bigger house to accommodate their three teenaged children. Moreover, Bob's company gave him funding to furnish the*

*home office of his dreams. He's got a powerful desktop computer with four LED monitors, a laser printer, and a heavily used high-speed Internet connection so he can videoconference with his colleagues and clients and use cloud computing. The office is on the second floor of the house and has big windows. As a result, the furnace (in the heating season) and central air-conditioning (in the cooling season) are often running on full to keep Bob's office comfortable, even though the family is away and the rest of the house is unoccupied. At work, Bob has a dedicated cubicle. Because he is free to choose which days he works from home and the company is relatively small, it is not worth risking letting someone else use Bob's cubicle in case he needs to come into the office. Afterall, Bob's salary is still an order of magnitude higher than the employer's cost to lease his cubicle. The open-plan office where Bob's cubicle is located has overhead lighting that is controlled by a schedule for the entire space even when he's working from home. Bob leaves his computer on most of the time because he may need to access his files from home. Back at home, now that Bob's car is in the driveway three days a week, his teenaged children drive to school (even though it's within walking distance) and they each drive to an after-school sporting activity that would not have been possible if Bob drove the car to work. The kids recommend that the family buy a bigger car next time; Bob figures they can justify a less fuel-efficient car since he's commuting so much less now so the gas bill won't be too expensive. While Bob used to pick up some groceries for dinner on the way home from work, he or his wife now drive 7 km to the nearest suburban big-box grocery store.*

The above example illustrates the complexity of the problem at hand. Much of the theoretical savings of teleworking are reduced or eliminated. And many purchasing or everyday behaviors are affected or enabled by teleworking. Moreover, the effects are wide-ranging and far beyond the teleworker him/herself, to include the whole household.

Before proceeding, teleworking and telecommuting need to be properly defined. Teleworking is an umbrella term that covers numerous working arrangements. Consider the following definitions that are used throughout this paper.

- **Teleworking** is an inclusive term meaning partially or fully working outside of a central workplace in a remote location (e.g. home, library, café) using information and communications technology (ICT) and either during normal business hours or otherwise [31].

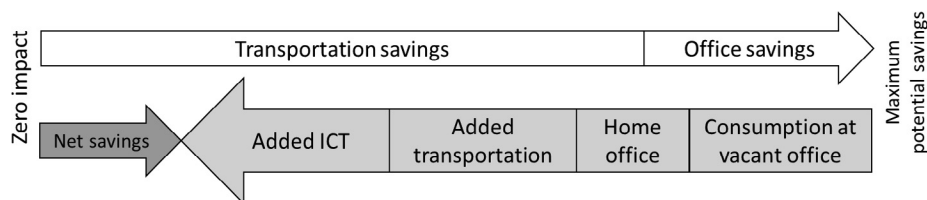


Fig. 1. Conceptual illustration of primary potential for net energy savings from telecommuting and rebound effects.

- **Telecommuting** is a subset of teleworking, with the condition that there is a formal arrangement (e.g. policy or contract) between the employee and employer allowing or encouraging remote work at home [2].
- **Hoteling/hot-desking:** An office space management approach whereby individual employees are not permanently assigned to a desk or office, such that the number of workplaces can be less than the number of employees [75].

Great care must be taken when researching the current topic, due to the broad spectrum of teleworkers and associated definitions [98,80,2]. For example, childcare workers, plumbers, door-to-door salespeople, homemakers, and moonlighters could all be considered teleworkers – and may skew results because travel is a major part of their job [99]. However, this paper is focused on workers who would normally work at a central office (e.g. administration, design, banking, legal services, etc.), but instead are spending one or more days per month working from home (i.e. telecommuters). This distinction is not only important for the scope of this review, but also for research methods. Broader definitions for telework in studies may dilute the environmental impact of teleworking.

### 1.1. Advantages and disadvantages of teleworking

The advantages and disadvantages of telecommuting are summarized in Table 1. *Primary effects* on energy are those which are immediate and direct, whereas *secondary effects* are those which may be unanticipated and/or indirect. Non-energy impacts of teleworking are also summarized, as they are an important part of policymaking, though not part of the comprehensive review.

### 1.2. Spatial and temporal study boundaries

To answer the title question (*does teleworking save energy?*) or more generally quantify the environmental impacts of humans, one must carefully define the study scope and boundaries [109]. While secondary and tertiary effects and beyond are known to occur, a balance using judgment and existing knowledge must be made to define the appropriate study scope that is comprehensive enough to answer the question, yet not so onerous as to prevent the question from being answered in a reasonable timeframe and cost.

On the basis of the literature review that was performed in preparation of this paper, in addition to the authors' experience,

**Table 1**  
Energy and non-energy advantages and disadvantages of teleworking (with sample references).

	Advantages	Disadvantages
Primary effects	<ul style="list-style-type: none"> <li>• Reduced commuting time and distance [36,94,41,61]</li> <li>• Reduced traffic faced by teleworker due to flexibility of timing [36]</li> <li>• Reduced office space and associated operating costs/energy [88,11]</li> </ul>	<ul style="list-style-type: none"> <li>• Increased energy use at home for lighting, HVAC (heating, ventilation, air conditioning), and office equipment [85]</li> <li>• Increased HVAC energy because it may condition entire homes during telework days because of centrally controlled HVAC [70,83]</li> <li>• Increased reliance on ICT for work-related communications and associated energy use/infrastructure</li> <li>• More home office space required, which may mean larger homes and higher energy use [87,116]</li> </ul>
Secondary effects	<ul style="list-style-type: none"> <li>• Outward movement of teleworkers to suburbs allows non-teleworkers to live closer to work on average (e.g., through relaxed housing prices in urban cores) [65]</li> <li>• Reduced traffic congestion resulting from fewer commuters means more efficient travel [86,65]</li> <li>• Improved energy efficiency behaviors at home because telecommuters pay for energy use at home (and not at work)</li> </ul>	<ul style="list-style-type: none"> <li>• Increased transportation energy because teleworkers opt to live further from their workplace and thus potentially further from amenities and in less transit-accessible neighborhoods [78,84]</li> <li>• Increased commute time and distance because teleworkers tend to live further from their workplace [103]</li> <li>• Increased non-commuting trips for errands, etc. because teleworkers cannot integrate those into commutes [121,105]</li> <li>• Larger homes that are more affordable away from teleworkers' central office and thus more energy for HVAC and lighting [65]</li> <li>• Larger car given the (perceived) reduced cost of driving (due to less frequent commutes)</li> <li>• Increased non-commute trips because household members have access to car(s) on days when the worker(s) work(s) from home [55]</li> <li>• Teleworkers may obtain a second apartment [40]</li> <li>• Need for redundant office equipment (e.g. personal computer, printer), which likely has phantom loads</li> </ul>
Non-energy	<ul style="list-style-type: none"> <li>• Reduced commuting costs</li> <li>• Improved employee recruitment potential (e.g., from further away or those who value flexibility) [7,69,44]</li> <li>• Increased employee productivity (e.g., fewer disruptions, flexible hours, work during normal commuting time, work during peak productivity hours rather than normal work schedules) [118–120]</li> <li>• Improved employee satisfaction means reduced turnover and absenteeism [88,7,69]</li> <li>• Improved employee morale and sense of being trusted [7,69]</li> <li>• Less exposure to illness at work [29]</li> <li>• Increased flexibility to avoid poor weather for commuting</li> <li>• Increased personal time because of avoided commute [7]</li> <li>• Reduced stress means lower health care costs [69]</li> <li>• Improved family life [20,46]</li> <li>• Improved opportunities for child/elder care [19]</li> <li>• Fewer barriers for employees with disabilities [42]</li> <li>• Decreased formal clothing [43]</li> <li>• Improved diet because teleworkers can make their own food at home during work [2]</li> <li>• Decreased transportation infrastructure and parking cost [88]</li> <li>• Reduced number of cars per household because of flexibility afforded [5]</li> </ul>	<ul style="list-style-type: none"> <li>• Reduced physical activity (e.g., shorter distances to walk)</li> <li>• Increased employee perception of isolation, loneliness and lost camaraderie [7]</li> <li>• Reduced access to resources/equipment [7]</li> <li>• Downloaded office operating costs (e.g. electricity, Internet service, furniture) to the employee</li> <li>• Increased difficulty to manage employees [100]</li> <li>• Increased data security risks [107]</li> <li>• Reduced reliability of network connection [35]</li> <li>• Worsened social problems associated with urban sprawl [83,65]</li> <li>• Reduced visibility for employee [7]</li> <li>• Reduced psychological benefits of commutes (e.g., adventure, independence, control, mental therapy, work-life separation) [76]</li> </ul>

this review's scope is limited to transportation, office buildings, residential building, and information and communications technology (ICT), as illustrated in Fig. 2. We must also include the impacts of teleworking over time, as some of its impacts evolve over decades [95,84]. Some obvious omissions to this review include embodied energy/carbon of buildings, vehicles, transportation infrastructure and ICT equipment, and food and clothing.

While this paper is focused on energy, GHG emissions cannot be neglected, as they are arguably more indicative of environmental impact. Teleworking's effect on GHG emissions may be quite different than energy because of different levels of GHG emission intensity for different energy sources – to the extent that the impact of teleworking could increase energy and decrease emissions or vice versa [65]. Emission factors, but local infrastructure, construction

types, climate, and availability of transit all cause studies to be somewhat locally specific [47].

The objective of this paper is to synthesize the existing knowledge on the energy/GHG emission impact of teleworking and then identify gaps in knowledge and research methods. The remainder of paper is structured as follows. The next section is the core of the paper and covers all four domains. For each domain, the potential energy savings, rebound effects, and research methods are reviewed as per the literature. Following the core literature review section, the overall verdict of the studies is summarized to provide some meta-evidence towards the title question: does teleworking save energy? Finally, the paper provides a forward-looking overview of research method and some closing thoughts.

## 2. Literature review

This literature review provides an overview of the existing quantitative studies that attempted to quantify the energy and/or GHG emission impacts of one or more of the four main domains of teleworking. First Table 2 summarizes the studied papers. It is structured to reveal the studies' scope and methods because the inconsistency of scopes and assumptions makes it difficult to form generalized conclusions [59].

### 2.1. Transportation and urban form

The potential for teleworking to save on transportation is the predominant and oldest motivator [89] for teleworking in the reviewed literature on its environmental impacts, as per Table 2.

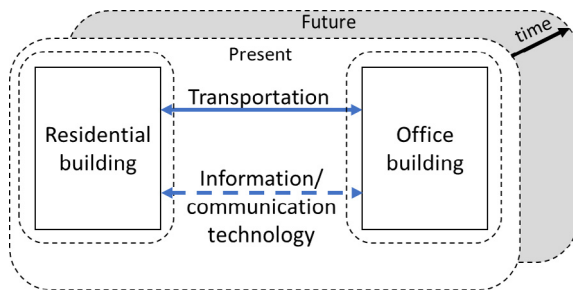


Fig. 2. Framework for studying the energy and GHG emissions resulting from teleworking versus traditional office working models.

Table 2

Original research papers that attempt to quantify one or more environmental effects of teleworking. Note papers that quantify transportation distance were included.

Study	Scope of energy/GHG emission quantification				Metrics of main results	Primary research Method(s)		
	Transportation	Offices	Homes	ICT		Modeling/simulation	Survey/interview/focus group	Secondary/existing data analysis
[3]	X				E, GHG	X		
[7]	X				E, GHG		X	
[8]	X				-		X	
[17]	X				GHG	X		
[22]	X				-			X
[26]	X		X		E			
[30]	X				GHG			X
[31]	X				GHG		X	
[32]	X				-			X
[46]	X		X		E		X	
[49]	X		X		E		X	
[54]	X				-			X
[57] [58,59]	X	X	X		GHG	X		
[61]	X				GHG		X	
[64]	X				GHG		X	
[65]	X		X		E, GHG	X		
[70]	X	X	X		E	X		
[72,14,15,16]	X				-			X
[82]	X				GHG		X	
[78]	X				-		X	
[85]		X	X		E		X	
[88]	X		X		E		X	
[95]	X				GHG			X
[99]	X							X
[102]	X	X	X		E	X		
[103]	X	X	X	X	E, GHG	X		
[105]	X				GHG	X		
[106]		X	X		E	X		
[110]	X <sup>1</sup>				GHG		X	
[112]	X				-	X		
[113]	X				GHG		X	
[114]	X	X	X		E	X		
[117]	X				GHG			X
Total (33)	31	7	12	1		10	13	8

**Table 3**  
Typical transportation scenarios.

Worst	Moderate	Best
Teleworking allows household to move to more rural, sparsely populated area that is heavily car-dependent for errands and traveling to work. Household incorrectly assumes reduced travel and purchases larger and/or more personal vehicles.	Teleworker does not change long-term home/vehicle purchasing decisions, but still drives significant distances for errands that were previously chained as part of commuting to a central office.	Teleworker eliminates travel to work and lives in neighborhood that supports cycling, walking, transit, etc. Their flexibility in location reduces demand for real estate near employers (e.g., CBD) so that other commuters can live closer to work.

While some of the reviewed papers only focus on vehicle-distance travelled, the assumption here is that a reduction in distance travelled has a positive environmental impact, if all else is equal.

We must consider spatial scale; an avoided commute has broader implications than the commuter, including reduced congestion and in turn, more efficient and enticing travel for others [57,76,65]. Accordingly, this section also reviews the wider perspective of telework's impact on travel and its short and long-term impacts. Table 3 provides a range of possible scenarios regarding the environmental impact of transportation from telework.

Electric self-driving vehicles are virtually void from the teleworking literature, in part because they were only a fantasy during the time of much of the research (much like videoconferencing was in the 1970s). On the one hand, electric vehicles are likely to reduce energy use and GHG emissions (though not with certainty [51]; on the other hand, self-driving cars may promote urban sprawl [73].

### 2.1.1. Potential

The primary benefit to the teleworker and environment alike is the reduction in distance travelled (often by single-occupancy vehicles) [36,94,41,61,110]. In principle, teleworkers can reduce their travel to zero on teleworking days. However, the literature is quite consistent on the fact that teleworkers typically only telework part of the time (e.g., once per week) [8,7,14], which immediately reduces the potential.

Flexible hours for days worked in a central office, which may be associated with employers who permit or promote teleworking, have the advantage that employees can commute during non-peak traffic hours and/or integrate errands [88,3,62]. Flexible commuting times benefits teleworkers and overall traffic congestion alike, which in turn can reduce energy use and emissions of vehicles.

The potential of teleworking for reducing transportation energy use and GHG emissions also depends on the form of transportation it is replacing [110]. In regions with a high proportion of walking, cycling, and public transportation, the benefit of teleworking is significantly less than in sprawling cities where commuters primarily rely on personal automobiles and with bad congestion. Tang, Mokhtarian et al. [108] found that individuals with positive views towards public transit and cycling and negative views about driving were more likely to telework. Conversely, teleworkers may have greater tolerance for public transportation if they only must make a few roundtrips per week, thus further reducing the environmental impact of commuting.

Among the 30 reviewed papers that quantified the impact of travel from teleworking, the estimated magnitudes of the effect are as diverse as the units used to express them. The results are

not only difficult to compare to each other, but also highly context dependent. Some papers focused on individuals, others increased the spatial scope to the household level, while others used city or nation boundaries as their analysis scope. The benefit of teleworking ranges from negative (e.g., [117] to very significant (e.g., [46], with many papers reporting modest improvements (e.g., [105]). As shown in Table 4, only four of the reviewed papers predicted an increase in travel distance, energy use, and/or emissions. Given the vast variety of contexts, this paper does not attempt to directly compare the reported impacts to each other. However, we briefly assess the context and methods for the four papers that predict negative impacts here.

Alonso, Monzón et al. [3] project a 10% decrease in the number of trips to work by 2031 in the Madrid Region. They further predict telework to reduce traffic at peak hours, which would improve vehicle efficiency. However, their city-wide model predicts that teleworkers commute more during non-peak times and take more or longer non-work trips, such that energy and GHG emissions. Additional information is not provided in the paper.

The remaining three papers that suggest teleworking increases transportation use are based on large surveys. Zhu and Mason [117] analyzed the US-based National Household Travel Surveys (NHTS) in 2001 and 2009 to attempt to estimate the vehicle distance traveled for telecommuters and non-telecommuters. From their Tobit-based analysis, they concluded teleworkers drive significantly more on average, than their counterparts. However, there were several fundamental challenges with the dataset. First, the survey is based on a randomly selected single-day self-reported travel log and thus it might be completed by a teleworker who happens not to be teleworking that day. Moreover, the data is separated by those who did not travel on the survey day and those who did. When the participants who did not travel on the surveyed day were included, and not accounting for income and related variables, the teleworkers commuted by car marginally farther (approximately 10%) than their counterparts. For the same comparison, non-work trips were about 25% higher for teleworkers. Due to the coarseness of the dataset, it is possible that telecommuters include salespeople and other telecommuting jobs that are known to be associated with significant travel. The NHTS asked "How many times in the last month did you work at home for an entire workday instead of traveling to your usual workplace?". The NHTS data also assume –by the nature of the data collection—that each day is independent, whereas for example, teleworkers may add weekly errands to their commuting trips rather than leaving home on teleworking days. Like Moos and Skaburskis [84] and [15], Zhu and Mason [117] note that teleworkers may also drive further because they opt to live far from work or they may be more likely to telework because they live far from work. Thus, if the randomly selected day in the NHTS happened to be a commuting day, they would be disproportionately penalized even if they have a shorter annual net travel distance. Despite the data limitations, Zhu and Mason [117] were thorough in attempting to remove biases and their finding suggest that potentially teleworking leads to greater distance travelled should be considered a real possibility.

Similarly, de Abreu e Silva and Melo [14,15] used the results of the Great Britain's National Travel Survey (NTS) from 2005 to 2012. That dataset includes seven days of self-reported travel logs, thus addressing part of the limitation of the American data used by Zhu and Mason [117]. Following previous work [14], the paper divided the data into single and double-worker households, having found significantly different travel behaviors between the groups. Namely, single-worker households with more frequent teleworking positively correlates with both number of trips and distance travelled, whereas double-worker households with higher teleworking frequency is only positively related with number of car

**Table 4**  
Comparison of papers that sought to estimate the impact of teleworking on travel impacts.

Paper	Energy impact	GHG emission/air pollution impact	Distance/ mode/ cost impact	Assumptions/ scope
[3]	Increase of 3% in energy use	Increase of 2% for GHG emissions		Linear projection to 2031 in Madrid
[7]	–	Decrease of 0.65 tonnes CO <sub>2</sub> /employee/year		Survey of 1238 AT&T managers
[8]			Decrease of 27 VKT per week for teleworkers	Three-day diary of 24 workers
[14]			Increase of 93 VKT per week for single-worker households and 16 VKT for double-worker households whose worker teleworks three or more days per week	Great Britain's National Travel Survey – 17,000 seven-day trip diaries
[17]		Decrease of 18 – 26% for overall air pollutant emissions from transportation	Decrease of 18 – 20% overall	Modeling of Bangkok and five hypothetical teleworking centres
[22]			Increase of 33% in daily travel distance from 46 to 61 km	Analysis of 2300 participants of the Swedish National Travel Survey for the Gothenburg, Sweden area
[26]	Decrease of 61 MJ/day			Bottom-up approach assuming three days per week working from home in Ireland
[30]		Decrease of NO <sub>2</sub> , CO, PM <sub>10</sub> by 3.3–3.7%; O <sub>3</sub> by 2.3%; SO <sub>2</sub> by 2.1%		Survey of 5000 Swiss households
[31]		Decrease of 9%		Survey of 72 workers in Mexico City
[32]			Insignificant impact	74,000 participants of Dutch Labor Force Survey in 1996 and 2010
[46]			Decrease of 98 and 407 km/week, depending on survey	Survey of 199 employees of British companies who adopted telework
[49]			91% of participants disagreed that teleworking increased travel distance	Survey of 53 teleworkers
[54]			Non-commuting travel doubles to 4 PKT/day/household if household head telecommutes	Survey of 15,458 Korean households where the household head is a professional
[57]	[5859]		Decrease of 17, 52, and 89% over no telework case for 1, 3, and 5-day per week teleworking	
	Bottom-up model with setting in United States			
[61]		Decrease of 48–78% depending on emission type	Decrease of 77% VKT on teleworking days (15% of which is non-commuting travel)	Travel diary of 40 telecommuters and 58 non-telecommuters
[65]	Decrease of 23% for one teleworking day per week			Numerical model, considering teleworking, urban density, and wages
[64]			Decrease of 45 VKT per teleworked day	Longitudinal survey of eWorkPlace participants
[70]	Decrease of 42 and 14.4 GJ/teleworker in the US and Japan			Bottom-up model based on national averages
[82]		Decrease for teleworking days: 15% organic gases, 21.5% CO, 34.9% NO <sub>x</sub> , 51.5% PM	Decrease of 11.5% for teleworkers per five-day workweek	Combination of interviews and surveys for 72 center-based telecommuters in California
[78]			Decrease of 15% for overall commuting distance	Survey of 221 workers – one-third of which are teleworkers
[88]	Decrease of 22 GJ/year/telecommuter			Survey of 329 telecommuters and 231 controls
[99]			Decrease of 5.8 km travelled to work	Analysis of several surveys in the USA
[102]	Decrease of approximately 10%			Simulation and analytical models
[103]	Decrease of 0.13–0.18% of total US primary energy or 9 MJ/year for 5-day/week telecommuters	Decrease of 0.16–0.23% of total US CO <sub>2e</sub>		Simplified model of 4-million teleworkers in US
[105]		Decrease of 0.71–1.14% of GHG and PM emissions	Decrease of 0.69%	Model if 50% of workers have flexible working time (up from the current 12%)
[110]			Decrease in external transportation costs of approximately 19.9% per teleworked day per week	Survey of 1247 Belgian office workers
[112]			Decrease of 15.5 VKT by 2021	Simplified model applied to New South Wales, Australia
[113]		Decrease of 54 g of VOCs and 48 g NO <sub>x</sub> per telecommuted day		Based on travel log of 535 workers in five US cities
[114]	Decrease of between 13 and 40 petajoules/year for each telecommuted day per week			Japan-wide transportation energy savings using national statistics
[117]			Increase of 61 (2001 dataset) to 72 (2009 dataset) extra VKT for telecommuters	42,000 and 63,000 day-long travel diaries from National Household Travel Survey in 2001 and 2009

trips but not distance driven. The paper is thorough and controls for demographics (where were shown to profoundly affect results). However, it is likely subject to the same potential errors associated with coarseness, definitions, and self-reporting. This NTS wording for the telework question is: "How often, if at all, do you...work from home instead of going to your (usual) place of work?" Like Zhu and Mason [117], the difference in travel patterns were found to be both statistically different and significantly larger –93 VKT/week for single-worker households and 16 VKT/week for double-worker households– between teleworkers and non-teleworkers. However, the paper's predecessor [14] noted the anomaly that very frequent teleworkers do not drive further than the non-teleworker counterparts – and in fact the use active modes (e.g., cycling) more often.

Similarly, Elldér [22] analyzed the Swedish National Travel Survey. The survey is based on a single day of travel diaries, which has the limitations. However, it separates the participants into regular teleworkers and non-teleworkers, as well as whether the survey day was a teleworking day for the former group. On average the teleworkers who commuted on the survey travel about 20% farther than those working from home. However, regardless, teleworkers travelled about 33% further than their non-teleworker counterparts. The data indicate that teleworkers are: more likely to have access to a car, much more educated, more likely to have knowledge based jobs, more likely to have children, and older – all of which may lead to farther travel distances. The study controlled for these variables.

### 2.1.2. Rebound effects

Despite the 26 of the 30 reviewed papers indicate reduced travel from teleworking, numerous rebound effects with varying degrees of impact have been established (many of which are implicitly incorporated into the results of Table 4). The most optimistic studies acknowledge but do not consider these rebound effects [114,70,103,26]; whereas four studies concluded that the rebound effects overtake the primary benefits (as noted above). This section reviews the literature according to short-term and long-term rebound effects of telework. Short-term effects are those which are generally made by decision making on a daily or weekly basis, whereas long-term effects involve major purchasing decisions (i.e., homes and vehicles) and the corresponding societal effects.

**2.1.2.1. Short-term effects.** A predominant rebound effect cited by much of the literature is the increase frequency and/or distance of non-work trips [117,55]. It seems that many commuters incorporate errands into their commute, thus achieving some efficiencies. Hopkinson and James [46] found about 20% of telecommuting survey respondents did shopping errands that would have otherwise been part of commuting; and about 10% said transporting children. They found non-work trips increased by the equivalent of about 25% of the distance saved from teleworking. Kim, Choo et al. [55] reported that non-commuting trips can add slightly more VKT than a one-way trip to work. However, several older studies [88,61,77] refuted this rebound effect.

Because teleworkers can generally avoid rush hour, they may be inclined to drive farther – in part because driving can be enjoyable [76]. Teleworking results in more travel during off-peak hours [3]. de Abreu e Silva and Melo [14,15] concluded that teleworkers may take more non-work trips and that teleworkers' tendency to live further from amenities means that those trips are more likely to be taken by personal car, rather than more sustainable means. Balepur, Varma et al. [8] reported that teleworkers tend to drive alone rather than take transit on non-telecommuting days. Finally, the time saved from lack of commuting may also spur more non-work travel [117].

Furthermore, teleworking behavior may have a major impact on family members and their own travel behavior due to division of non-work tasks and availability of vehicles on telecommuting days [55,14]. On the one hand, multi-person households can optimize trip planning to minimize travel time and distance [14]; on the other hand, telecommuting makes vehicles more available to other household members to use [46]. Nilles [88] confirmed this finding, though noted that the trips by family members are still shorter than most commutes and a fifth of study participants reported a decrease in non-commuting car use.

**2.1.2.2. Long-term effects.** The major long-term transportation impacts include purchasing of more and/or larger household vehicles, moving further from the office and possibly other amenities, and reducing traffic such that others are more inclined to drive [57]. Regardless of these effects, a reduction in commuting costs (e.g., multiple household cars) frees up funds for other potentially energy-intensive purchases (e.g., larger house, international vacations) [65].

Frequent teleworkers may opt to live further from their office because the cost (time and energy) to travel to work is not as high if they do not make five roundtrip journeys per week. With flexibility afforded by telecommuting, the benefit to live close to work is reduced; employers and employees alike may opt to locate where land is less expensive [76]. On average, teleworkers tend to live further from centers of employment [78,84]. While this is a common research finding across the literature, results from Kim [54] indicate that telecommuters live 7 km closer (40% less distance) to their workplaces – possibly due to the study group being low income and more likely to live near their workplaces. Car ownership is positively correlated to commuting distance; thus, if teleworkers tend to live further, they may also be more likely to own one or more cars and drive for trips. Though little research was found on the topic [47], one may expect that teleworkers also opt for larger vehicles for the same reasons as above.

There is ongoing debate about which comes first: teleworker or moving further from workplaces. It is generally understood that both occur [93,84]. The question becomes: which causal direction is predominant? Ory and Mokhtarian [93] found that people who move after having telecommuted move closer to work on average, whereas those who move then begin telecommuting move much farther – an average of 30 km – from work. This finding may suggest inexperienced telecommuters may have the illusion that they will not have to commute often, whereas experienced telecommuters know better. Beyond the individual, teleworking may have some impact on sprawl, which may in turn affect transportation distances, modes, and congestion for the teleworker and commuters alike [116,65].

### 2.1.3. Research methods and limitations

As for the other domains in this paper, the research methods used for studying transportation include surveys, diaries, modelling, and analysis of existing regional statistics. Some studies (e.g., [88,59]) combined methods (e.g., survey combined with some simple assumptions about fuel efficiency).

Sample sizes for surveys and other participant-based studies ranged from six [5] to tens of thousands [117,30], with a general negative relationship between sample size and depth. Meanwhile modeling ranged from bottom-up Monte Carlo analyses for individual workers or households to city wide. Others, modeled households but then scaled results to estimate national impacts of teleworking, thus potentially missing interactions between households (e.g., impact on traffic and traffic's impact on commuter decision making) [70,49].

None of the reviewed studies directly measured individuals' travel behavior more directly than relying on self-reporting and



thus may include errors and bias [7]. For example, the participants may positively report on telework because they want to ensure such programs are maintained; others fear legal restrictions [39]. Mokhtarian and Varma [82] observed that teleworking program studies may involve dropouts who benefit least from teleworking because they live close to work, thus biasing the sample.

A notable limitation of many of the survey studies is the accurate characterization of real fuel consumption. Studies typically assume national fleet fuel consumption averages [88,7,117], which may neglect the fact that teleworkers avoid traffic and can drive faster and that teleworkers may own larger vehicles. Carpooling (e.g., with colleagues or family members) is also generally not well characterized [70].

A recurring discussion in the literature is the importance of definitions of teleworking terms and the way study participants understand them [99,81]. Pratt [98] recommended that instead of asking questions like “How many days a week do you telecommute?”, more precise phrasing is “How many days last week did you work at home instead of going to your usual work location?”. As mentioned above, the issue of definitions may be a major limitation for the census-based studies. National and municipal travel surveys may be subject to this limitation, as noted above. Moreover, it may be difficult to control for other variables. For example, teleworkers are more likely to be knowledge workers, which means they are, on average, wealthier and more likely to own vehicles [22].

The profound long-term impacts of teleworking (e.g., choice of vehicle and home) demonstrates the critical importance of capturing more than a snapshot of workers' behavior [39]. Ory [93] argues that even several years is insufficient to properly capture home-buying decisions and the causal effects. However, Rhee [101] observed that empirical studies are particularly challenging for studying the evolution of land use and city size. This is an argument for using modelling studies for such explorations (e.g., [3,65]. With the exception of Giovanis [30], the regional and national travel surveys were not longitudinal (i.e., tracking the same participants between years). On spatial scale, the results of the review above indicate that future studies should include entire households, due to the complexities of household-level decision-making [22,14].

## 2.2. Offices

Offices in the current context refers to centralized workplaces managed by the employer. After transportation, the second-most touted means for energy and cost savings in the teleworking literature is reduced office area and associated energy use reductions. Table 5 provides a range of possible scenarios regarding the environmental impact of central offices.

### 2.2.1. Potential

In principle, office space could be reduced to exactly provide a workspace for each present employee (i.e., those who are not working remotely) on a given day. Thus, theoretically, the potential reduction in office space is equal to the mean fraction of time when workers telework. In the most extreme cases, entire office buildings could be vacated by employers that opt for 100% teleworking – thus delaying the need for new construction or allowing buildings to be decommissioned. However, recent papers indicate that typical teleworkers only work remotely at most 20 to 60% of weekdays [25,111,115]. Nilles [88] projected that companies with telework programs would eventually be able to reduce office space by 30%.

Unless a teleworker works permanently remotely, to achieve significant space savings, a shared workspace (e.g., hoteling) approach must be applied whereby employees are not assigned

**Table 5**  
Typical office configurations and impact on office energy.

Worst	Moderate	Best
Open plan office with scheduled occupancy-independent, scheduled heating, cooling, ventilation and lighting; printers, computers, and other plug loads remain powered on most of the time, regardless of occupancy.	Open-plan office or private office with assigned seating and high-resolution occupancy sensing and small control zones	Open-plan offices with hoteling and near-full capacity every day; lighting, HVAC, and office equipment are controlled at a high spatial and temporal resolution based on occupancy

to specific and permanent workstations [75,24,53]. Flexible workspaces and transitioning from private cellular offices to open-place spaces can not only increase occupant density, but also yield the necessary flexibility to exploit teleworking [28]. However, hoteling/hot-desking is needed to create flexibility whereby an occupant does not have a dedicated workspace [24,53]. While employers may aim to have sufficient workspace capacity for peak occupancy, a more deliberate scheduling scheme is used, space utilization efficiency could be much higher [74]– and approach the theoretical upper limit.

As noted by several other researchers [70,102,85], the real impact on office energy use is highly dependent on the details of implementing teleworking and office space management. If a space is not occupied to capacity (e.g., because of long lease periods and expansion/contraction in workforce), technologies still exist to minimize energy use in vacant spaces. These include occupancy-based lighting control, demand-controlled ventilation, and occupancy-based heating and cooling [91]. Radiant heating and cooling have the potential to increase the resolution of delivering comfort because they only serve occupants near them, whereas air-based systems usually promote mixing of air throughout large spaces. So-called smart plugs and occupant feedback can be used to reduce plug loads when equipment is not in use [66,10]. Moreover, use of the same laptop in the office and at home means that teleworking necessarily reduces plug loads in the office. And virtualizing computers (i.e. removing the major power-consuming equipment from occupied spaces) can reduce cooling loads [27].

### 2.2.2. Rebound effects

Despite the theoretical potential to reduce energy use in offices, if a conventional office environment implements teleworking and employees have dedicated workspaces (i.e. not hoteling), the energy savings may be marginal [79,114]– particularly if few employees telework [85]. Williams [114] suggested teleworking “once or twice per week may not lead to any change in energy use at all” because it is perceived as not worthwhile to implement workspace sharing for occasionally vacant spaces. It should be noted that workstations only comprise of a small fraction of office building space [114,60]; thus, the potential total office building space savings from teleworking would be less than the fraction of absent employees. Moreover, buildings have base (unoccupied) energy loads that can be half or more of the fully-occupied load [56].

Typically, buildings are not designed to efficiency adapt to variable occupancy – in part due to lack of incentive and building codes [91]. For instance, overhead lighting in open-plan offices represents the majority of the lighting energy end use and would not be affected by the presence of a single occupant [33]. Similarly, office buildings have relatively coarsely controlled HVAC and light-

ing systems (e.g., at the floor, wing, or quadrant level), meaning that the building systems must provide comfortable temperatures and ventilation regardless of whether an individual occupant is present – and in anticipation of occupancy [33].

Office equipment often has some standby power and moreover and much of it is left on – intentionally or unintentionally – during absences. Gunay, O'Brien et al. [34] reported that 40 to 50% of surveyed people leave their computers on for the purpose of remote desktop use or updating cloud servers while they are absent. This greatly contrasts older assumptions in the telework literature about how teleworkers would not simultaneously have computers on at work and home [88]. In a study of 10 private offices, O'Brien, Gaetani et al. [90] reported that 75% of plug load energy use occurred during unoccupied periods. Gunay, O'Brien et al. [34] showed that occupants are more likely to turn off equipment for multi-day absences, but the situation is far from optimal.

### 2.2.3. Research methods and limitations

The majority of research on the potential impact of office energy use in offices from teleworking has been achieved using modelling and simulation, thus facing uncertainty of building operations, occupant behavior, and occupancy patterns. In the reviewed literature, the assumptions made in the simulation studies are quite simplistic relative to more recent measurement-based studies. To mitigate uncertainty, many studies presented results as possible scenarios whose accuracy depend on the exact implementation of telework.

For estimating the impact on office floorspace from teleworking, in lieu of detailed data, a number of studies opted to consider several possible scenarios, such as no impact and perfect space utilization [114,103]. Matthews and Williams [70] relied on a single-company study that found that four-day-per-week teleworker reduced office space by 25% (much less than the theoretical potential of 80%). They similarly assumed energy use to be reduced by the same amount. Kitou and Horvath [59] considered scenarios of no telework, and one, three, and five days-per-week telework; they assumed two employees share single offices in the last two cases, effectively reducing office space for such frequent teleworkers in half.

On HVAC energy, researchers have typically made simple assumptions about how the reduction of internal gains from lighting, equipment, and occupants themselves, affects heating and cooling energy (e.g., [103]). However, such simplified approaches tend not to be climate-dependent (considering internal gains may be useful or adverse depending on whether heating or cooling is needed). Röder and Nagel [102] relied on empirical data from one building to estimate the relationship between occupancy and office building energy use. Nakanishi [85] took the approach of dividing HVAC and office equipment into two categories: those which are elastic to occupancy (desk lamp and personal computers) and those which are inelastic (and area lighting). However, he assumed very specific equipment and used rated power. Moreover, he did not consider climate impacts of air-conditioning and lighting use. Kitou and Horvath [59] assumed lighting and HVAC savings were only possible if teleworking reduced office space and that the lighting and HVAC energy were approximately proportional to number of workspaces (occupied or not). Kitou and Horvath [59] assumed office equipment was approximately proportional to number of days per week teleworked, but that five-day-per-week teleworkers do not have office equipment that consumes energy.

In general, the previous methods to quantify office energy impacts of teleworking are simplistic, often optimistic, and lack the rigor necessary to quantify impacts of real HVAC and lighting systems and office equipment use.

## 2.3. Homes

The energy impact of teleworking on home offices has been recognized by some researchers (e.g. [49,85]) as a downside of teleworking and is the second-most studied domain, as per Table 2. Table 6 provides a range of possible scenarios regarding the environmental impact of homes.

### 2.3.1. Potential

In general, telecommuting has at best a null effect on household energy, with office equipment energy merely being transferred from the office to home. Thus, there is no direct potential to save energy at home via teleworking. The possible exception is that teleworkers may be incentivized to save energy because they pay for it at home, but not in the central office. Teleworkers may also have more flexible hours, thus allowing them to avoid peak electricity pricing (for regions with time-of-use pricing) and therefore possibly GHG emission-intensive electricity.

### 2.3.2. Rebound effects

As for transportation, the rebound effects are separated between short-term/day-to-day impacts, vs. longer-term and large-scale (months and beyond).

**2.3.2.1. Short-term effects.** Short-term impacts of teleworking on home energy use primarily include usage behavior of office equipment (computers, printers, etc.), lighting, and HVAC. Energy-consuming devices are highly dependent on both the nature of the systems and on behavior. Moreover, teleworkers may engage in other adaptive behaviors (e.g., open windows and blinds) that affect household energy use [104]. Regardless, their presence and all electrical equipment affect HVAC energy use affect internal heat gains, which in turn, affects HVAC energy.

Nakanishi [85] tabulated the assumptions or measurements of nine studies spanning from 1976 to 2014 and reported that daily net increase in total home energy from teleworking and found they ranged by a factor of 205, from 0.1 kWh to 20.5 kWh/day. Typical estimates for the daily energy consumption of home office equipment, using bottom-up approaches, are 0.4 to 1.6 kWh [57,103,85]. In general, the office equipment assumptions tend to be quite outdated, given that most research is over 10 years old and there have been significant advances since (e.g., laptop computers are much more common than desktops and there is a trend towards paperlessness).

Lighting energy in home offices is unlikely to be significant and it has predominantly been estimated using simple bottom-up methods [57,70,103,85]. The range of lighting power –60 to 200 Watts– generally appears to be based on older technology (e.g., incandescent bulbs) and thus overestimated. It is unclear from the literature whether occupants keep non-workspace lights on more because of being at home on teleworked days. Since work-days coincide with daylight hours, daylight is expected to reduce

**Table 6**  
Typical home office configurations and impact on household energy.

Worst	Moderate	Best
Teleworker purchases larger house to accommodate home office, house has central HVAC system without zoning, and office has energy-intensive office equipment	Teleworker has home office, but can control lighting and HVAC separately for that room and has efficient office equipment and lighting	House has zoned HVAC system and multiple teleworkers who efficiently use existing space for work (e.g., kitchen table); office equipment and lighting are energy-efficient

lighting electricity use, though residential building daylight research is not mature [18].

The energy increase from HVAC was considered by several papers, though similarly coarsely to other aspects. The impact on GHG emissions greatly depends on HVAC technology and energy source(s). In a comparative study on teleworking between Japan and the USA, Matthews and Williams [70] observed that HVAC configurations are significantly different between the countries. In North American homes, HVAC tends to be centralized with little ability to adjust temperature in individual rooms. Thus, a teleworker needing only small portion of the home to be comfortable, may inevitably condition the whole house at comfortable (and energy-intensive) conditions. However, presence of multiple teleworkers or family members in one home somewhat reduces this energy wastage [58]. Nakanishi [85] found that only one-third of teleworkers are alone at home when they work, thus offsetting potential wastefulness of HVAC.

In contrast, in Asia and Europe, room-by-room HVAC controls are more common. Thus, teleworking in North American is predicted to increase home energy use more than elsewhere [70]. Estimated energy for HVAC ranges greatly in the literature due in part to the wide variety of methodologies. Room-level systems have been estimated to use 300 to 600 W [70,85], while central HVAC systems are typically expressed as the relative increase over a non-telecommuting household. Such reported values vary greatly: a total increase of 5 to 15% for teleworkers [70], an 8.2 and 9.5% increase in heating and cooling energy on teleworked days (versus non-teleworked days), and 10% increase in total HVAC energy per teleworking day per week [57].

Roth, Rhodes et al. [103] and Matthews and Williams [70] used the elegant approach of reversing the energy-saving potential of programmable thermostats: 5 to 15%. The value of programmable thermostats has since been debunked because of occupants' tendency to not program them optimally – or at all [71]. That is, there may be little HVAC energy savings achieved if an occupant does not work from home if the household uses a constant setpoint. On the contrary, smart thermostats with occupancy-based control may be reversing that notion [48].

Nilles [88] observed that occupants in homes can tolerate wider ranges of temperatures at home than in the office, thus potentially reducing overall HVAC energy use (considering both homes and offices). This finding has been since confirmed in the thermal comfort literature (e.g., [50]).

Anecdotal evidence [49] suggests and some authors [57] assume home workers also use kitchen appliances (e.g., coffeemakers) and lighting in other rooms when they are working from home. It is unclear whether these activities would otherwise happen outside of working hours or at the workplace (eat lunch in the case of heating lunch, making coffee, etc.). Hopkinson and James [46] reported that most surveyed teleworkers reported that teleworking leaves more time for domestic tasks (e.g., cooking, laundry), though again it is not clear whether these tasks would still occur. Assuming they do, one implication on energy is that shifting high-energy activities to daytime may be adverse for electricity costs and associated emissions. On a lighter note, teleworking could reduce laundry loads due to the reduced constraints of work clothes for teleworkers not visibly interacting with others during the day [97].

**2.3.2.2. Long-term effects.** Long-term effects are focused on change of home location, size of home and home office, and other major purchasing decisions [88,83,84]. In the most extreme case, a teleworker may opt for a second apartment close to the workplace (and ultimately maintain two homes) [40].

The long-term decision to purchase a larger home because of teleworking is particularly impactful for homes that have centrally controlled HVAC systems. In general, a larger home will be an

energy liability for all hours – not just those during teleworking. Nilles [88] found that surveyed telecommuters 6.5 m<sup>2</sup> (or 4% more than the non-telecommuters) is used exclusively and 12.5 m<sup>2</sup> generally for home offices. Kitou and Horvath [57] reported that 45% of teleworkers have a dedicated office, whereas the remainder use shared space within their home.

While teleworking and larger homes are associated with each other [52,84], we are primarily concerned with the causal relationship that teleworking led to a larger home. Most reviewed studies capture a point in time and cannot easily distinguish between these two possibilities: 1) an individual with a large suburban home is more likely to telework due to their distance from their central office and the associated cost of commuting daily or, 2) an individual justified buying a large suburban home because they have the ability to telework and the need for greater space (e.g., a home office). Moos and Skaburskis [84] suggest both are partially true on the basis of a small survey in Moos, Andrey et al. [83].

### 2.3.3. Research methods and limitations

Home energy use has been estimated using both bottom-up (accounting for each appliance and end use) and top-down approaches (e.g., statistical methods based on monthly electricity bills). The lower estimates mostly use bottom-up methods and only consider equipment that was immediately necessary for teleworking (e.g., computer) and lighting in the immediate vicinity of the workspace. Typically, simple assumptions are made about each piece of equipment and hours of use based on statistics or other studies. Such bottom-up approaches are likely to miss phantom loads resulting from the equipment used for teleworking because they tend to focus on the duration that the equipment is in active use.

Mokhtarian, Handy et al. [79] used a survey to collect information about hours of use of equipment, which was then converted to energy using typical power ratings. Only Shimoda, Yamaguchi et al. [106] used simulation combined with the Japanese national time use survey to quantify the impact of home energy from teleworking, though the exact occupant behavior models are not clear. Atkyns, Blazek et al. [7] noted challenges in asking survey participants to make “physical/spatial” estimates (e.g., home office size).

Nilles [88] compared self-reported monthly energy bills between telecommuting and non-telecommuting households. The result was not statistically significant and did not account for other factors, such as home size. No papers were found that used detailed power metering to measure energy use.

As reviewed above, methods to estimate the impact on home HVAC energy have been similarly simple and have generally neglected the role of behavior and climate. No papers were found on the impact of teleworking on thermostat setpoints, though this is expected to be a rich data source due to emerging data [48].

## 2.4. Information and communication technology

Among the four domains studied in this paper, the environmental impacts of ICT are the least tangible to end users and relatively void from the telework literature. However, as the enabler of teleworking, it should be considered.

While the Internet was first envisioned as a means for videoconferencing and other forms of communication to support teleworking [87], it now also plays a critical role in file transfer, sharing, and backup, and collaborative work (e.g., via cloud computing) [67]. Overall, Internet communication and devices are estimated to consume 10% of global electricity – and this proportion is estimated to double by 2030 [4]. However, apportioning this to teleworking is non-trivial task because there are numerous uses for the Internet that are not related to work. In the current paper, ICT is limited to the equipment and processes that occur between

office equipment (e.g., servers, data centers, hubs, switches, etc.), as office equipment (e.g., laptops, printers) is placed within the office and household categories above. A range of possible ICT use scenarios are laid out in Table 7.

#### 2.4.1. Potential

Teleworking, at best, has a neutral effect on ICT-related energy use and GHG emissions because direct technology-less communication (e.g., face-to-face in conventional offices) that occurs in traditional office environments has zero direct environmental impact.

#### 2.4.2. Rebound effects

While numerous life-cycle analysis studies have quantified the environmental impact of ICT, the majority were focused on e-materialization (e.g. video streaming in place of DVDs) and e-commerce; whereas few have focused on telework [96]. Borggren, Moberg et al. [9] estimated the electricity use for data transmission in the context of teleconferencing as an alternative to long-distance travel to meetings and conferences. Similarly, Ong, Moors et al. [92] performed such a comparative study and found teleconferencing is associated with an order of magnitude less energy consumption and GHG emissions than in-person conferences. While showing a clear benefit of teleconferencing, these studies use a baseline that includes international flights, which greatly skews the results compared to routine telework.

Several studies have attempted to quantify the environmental impacts of Internet use, independent of the application. Coroama and Hilty [12] reported that the literature since 2000 yielded data transmission energy intensity with a range that spans four orders of magnitude – from 0.0064 to 136 kWh/GB. The age of studies is quite relevant, as energy per unit of data transmitted has approximately halved every two years since 2000 (though concurrent to growth of data transmitted) [6].

#### 2.4.3. Research methods and limitations

As noted above, few papers have quantitatively evaluated the impact of ICT from teleworking. There has been significant work on the environmental impact of Internet traffic such that rigorous estimates of the impacts of data transmission have been made [12,6]. Coroama and Hilty [12] noted that aside from improvements with time, the biggest discrepancy of estimates is inclusion of end devices (e.g., computers). In this paper, such devices were put in the building categories (households and offices). Another challenge is that the kWh/GB rates are not constant, but rather a function of time of day/week and data transfer rate [38,6]. Regardless, the top-down kWh/GB figure is likely most suitable for answering the research question at-hand because it would be near-impossible to accurately obtain data on the network devices involved in teleworking and for each end use (which typically range in number from 12 to 24 [6]. Coroama, Hilty et al. [13] illustrated the immense challenge in calculating the energy used for a single path for a teleconference from Switzerland to Japan.

However, the main gap lies in quantifying the amount of data transmitted from teleworking. This is a nontrivial exercise; Inter-

net use at homes is likely to be a combination of personal and work-related (the same is likely true for offices). Time of day cannot necessarily be used to distinguish personal from work-related Internet use – particularly as the line between teleworking and after-hours work blurs [21]. Since, home network equipment uses a similar level of power regardless of data traffic [38], the net effect of teleworking on such equipment may be minor. Moreover, many of the work-related Internet uses (e.g., videoconferencing, cloud storage) are likely to occur in traditional offices, regardless of teleworking. Borggren [9] assumed a certain number of hours of videoconferencing and a certain technology configuration. However, such bottom-up approaches are prone to errors due to lack of available data.

### 3. The verdict

Half of the papers reviewed in Table 4 studied the energy or emissions impact of teleworking considered multiple domains among transportation, office buildings, homes, and ICT. This section briefly summarizes their verdict on whether teleworking ultimately saves energy and/or reduces GHG emissions.

The results are summarized in Fig. 3, which is a further reduction from the above subset for those which used consistent units across domains. The authors caution against direct absolute comparisons between studies, as the assumptions and contexts vary greatly. Moreover, many of the papers examined multiple scenarios, whereas we attempted to select those which were most similar (i.e., approximately 20% of the population teleworks every day or the population teleworks 20% of weekdays, though these are not equivalent [65].

There appears to be a trend over time, whereby the studies' net energy use prediction seems to increase. This may be a result of the increasing study scope and/or emerging knowledge about rebound effects. In their recent review, Hook, Sovacool et al. [45] discovered a related relationship: methodologies that they deemed to be poor tend more frequently predict a reduction of energy vs. those that they considered good or average.

Two studies focused on or reported air pollutants, as summarized in Table 8. Both results are for one day per week. Both studies indicate net negative (i.e. beneficial) impacts of teleworking.

While the literature that quantifies the energy/GHG emission impact of telework for multiple domains remains relatively sparse, the majority indicates that telework is beneficial (i.e., negative net energy/emissions).

### 4. Research needs and methods

The results of this review indicate major limitations of the research methods – particularly for the buildings for which the assumptions are very simplistic. Moreover, ICT is virtually void from the telework research. While it is expected to be the least significant of the domains, it may be growing as data intensity of work increases.

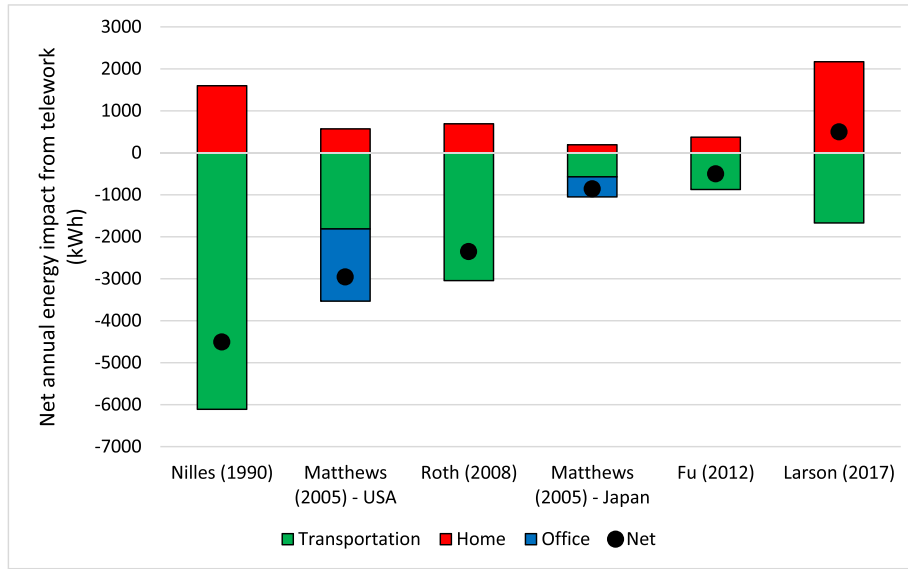
As evidenced by the review studies, some outstanding questions include:

- Do teleworkers move further or do people who live far away telecommute more? And assuming there is some combination of factors, how do they compare in prominence?
- How does teleworking affect long-term decision-making, such as vehicle and home purchases?
- To what extent do errands and trips of family members affect overall travel mode, distance, and timing?
- Do teleworkers use a different mode of transportation than non-teleworkers?

**Table 7**

Typical ICT use patterns for teleworking.

Worst	Moderate	Best
Teleworker extensively uses data-intensive videoconferencing, filesharing, and other data-heavy services	Teleworker uses a moderate level of data-intensive communication services and many of those would have been used regardless of teleworking	Teleworker does not change Internet use when teleworking



**Fig. 3.** Estimated impact of one-day-per-week teleworking vs. no teleworking on annual energy, where positive net energy indicates that teleworking uses more energy than non-teleworking.

**Table 8**

Estimated impact of one-day-per-week teleworking vs. no teleworking on annual CO2 emissions (kg).

Study	Transportation	Office	Home	Net
Kitou and Horvath [57]	-400	-10	150	-260
Larson and Zhao y[65]	-890	-	810	-80

- What is the role of electric and/or self-driving vehicles and how will they affect telework patterns, environmental impacts of transportation, and urban form?
- How much energy is saved in office buildings because of absent occupants – particularly when building managers do not actively account for telework in operations and space planning?
- To what extend to telecommuters use more energy at home? What underlying behaviors affect it and by how much?
- What is the magnitude of ICT-related energy use and associated GHG emissions?

The above review also indicates the importance of carefully considering spatial and temporal scope. Recurring recommendations from authors that have performed previous studies include the importance of considering long-term (e.g. on the order of dec-

ades) impacts to properly account for long-term decision making of teleworkers and their employers. On a similar note, it is important to study telework’s impact on both teleworking and non-teleworking days [39], because of the spill-over between day types (e.g., weekly errands are trip-chained on commuting days). Moreover, numerous studies above have emphasized the importance of adequate spatial scale. Some studies –particularly those using urban models or city-scale data—have suggested that metropolitan areas are the appropriate spatial boundary [39]. Another recurring recommendation is that entire households be studied rather than individuals, because of the complex energy-related behaviors caused by teleworkers, such as availability of vehicles and task-sharing.

Table 9 summarizes some of the strengths and weaknesses of common research methods in the context of teleworking research.

**Table 9**

Strengths and weaknesses of research methods for teleworking.

	Surveys/interviews/diaries	Modelling/simulation	Secondary data analysis	Field study
Strengths	<ul style="list-style-type: none"> <li>• Can be used to measure attitudes, behaviors, and beliefs</li> <li>• Can be used to understand causal directionality and rationales</li> <li>• Can be used to understand household relationships</li> </ul>	<ul style="list-style-type: none"> <li>• Possible to explore many scenarios at multi-scale - temporal and spatial – with fast results</li> <li>• Low-cost and no participant recruitment challenges</li> </ul>	<ul style="list-style-type: none"> <li>• Large sample</li> <li>• Low/no-cost to researcher</li> </ul>	<ul style="list-style-type: none"> <li>• Detailed and direct measurements</li> </ul>
Weaknesses	<ul style="list-style-type: none"> <li>• Subject to self-reporting error and bias</li> <li>• Focused on the individual teleworker</li> <li>• May be difficult to study longitudinal effects.</li> </ul>	<ul style="list-style-type: none"> <li>• Difficult to capture complex decision-making processes</li> <li>• Limited to the quality and accuracy of the underlying models</li> <li>• May lack credibility because of the above</li> </ul>	<ul style="list-style-type: none"> <li>• Limited study scope (i.e., researcher does not design research)</li> <li>• Definition of telework may be problematic/vague</li> <li>• May be subject to self-reporting error and bias (as for surveys)</li> </ul>	<ul style="list-style-type: none"> <li>• Potentially costly and labor-intensive for participant recruitment and equipment.</li> </ul>

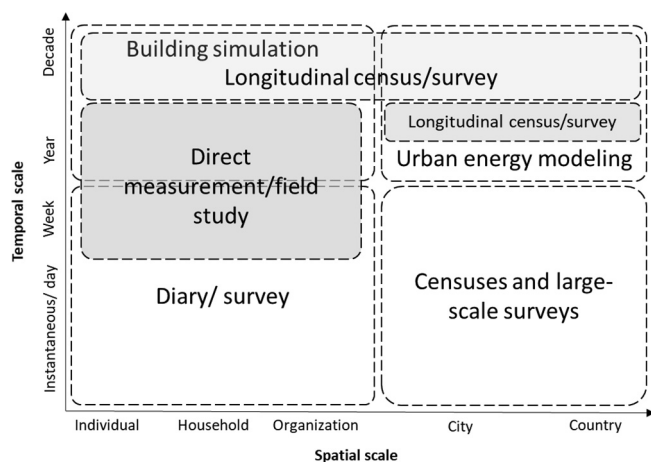


Fig. 4. Recommend research methods organized by study spatial and temporal scale.

While the first three methods listed are common [45], field studies are less so. By field study, we mean in-situ studies where researchers are in the field and taking assorted spot or long-term measurements (e.g., energy use, temperature, etc.). Field studies are commonplace in the buildings field (i.e., as post-occupancy evaluations) [68], but the technique does not appear to have entered the telework literature. Mixed methods research—despite its relative absence in the telework literature—also holds significant promise to take advantage of each method's strengths. Fig. 4 proposed the most suitable research methods as a function of spatial and temporal scope.

We note that there now exists a major opportunity to use existing and emerging data beyond traditional census-like surveys to study telework. For example, Google can provide location and trip data, smart meters can provide high resolution electricity and water data for homes and offices, and ecobee provides thermostat-related behavior and performance. These data sources have been used in research [48,37], but not in the context of telework.

Another opportunity for telework research is to exploit the emerging urban energy simulation tools, which could capture at least the building and transportation domains in a single model [1]. However, a challenge is to ensure that models properly reflect the impact of individuals' presence or absence at home or in the central office; occupancy is normally represented by a simple schedule rather than as agents [63].

## 5. Conclusion

This paper sought to critically assess the existing quantitative literature that attempts to answer the question: does teleworking save energy and reduce GHG emissions? By examining four domains – transportation, office buildings, homes, and ICT—the paper systematically reviewed the literature regarding the reported potential, rebound effects, and research methods for each domain.

Despite the age of the topic, the literature is relatively thin and sparse. It is widely acknowledged that re-bounce effects are plentiful, and the problem is complex. While the majority of studies indicate energy and/or GHG emission reductions from teleworking, this finding is not universal – nor is the estimated magnitude of savings. Moreover, there appears to be a loose trend whereby newer studies and those with more domains considered tend to indicate a lower benefit to teleworking.

The literature shows that study spatial and temporal scope are critical and can profoundly affect results. Short-term studies overlook the long-term home/vehicle purchasing decisions and the evolution of urban form. A wide variety of methods including one or more of surveys/interviews/diaries, modelling and simulation, and secondary data analysis have been used. Mixed methods approaches, which build upon all their strengths, are promising for future research. A major gap in the literature is the use of emerging data sources (e.g., smart meters, building automation systems, smart thermostats, smart phone location, etc.).

Regardless of the inconsistency in research methods, quality, and results, more studies are needed considering evolving technologies and economies, expected geographical and climatic differences, and to build more evidence towards answering the title question. The answers have many stakeholders including public policymakers and employers and employees seeking to reduce their environmental footprint. Given telework's shift of burden and environmental impacts from the employer to employee, some interesting questions arise about environmental accounting. For example, should government or companies incentivize telework? Perhaps companies should be entitled to take credit for telework in corporate social responsibility reporting.

Particularly considering the recent COVID-19 pandemic, but also with the shift towards a knowledge-based economy in the realm of climate change, teleworking is expected to become more important and prominent than ever. More long-term and comprehensive studies are needed for various contexts (countries, climates, cultures, industries) to yield better evidence to answer the title question. There are important policy and technology implications for these findings. Understandably, due to the age of the literature, discussion of electric and self-driving vehicles is virtually absent, despite the major ramifications for transportation and urban form. Meanwhile, it is important that building codes and technologies evolve such that buildings better adapt to varying levels of occupancy and use.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgement

The first author acknowledges support from NSERC via his Discovery Grant and Discovery Accelerator Supplement.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enbuild.2020.110298>.

## References

- [1] N. Abbasabadi, M. Ashayeri, Urban energy use modeling methods and tools; a review and an outlook for future tools, *Build. Environ.* (2019) 106270.
- [2] T.D. Allen, T.D. Golden, K.M. Shockley, How effective is telecommuting? Assessing the status of our scientific findings, *Psychol. Sci. Public Interest* 16 (2) (2015) 40–68.
- [3] A. Alonso, A. Monzón, Y. Wang, Modelling land use and transport policies to measure their contribution to urban challenges: the case of Madrid, *Sustainability* 9 (3) (2017) 378.
- [4] A. Andrae, T. Edler, On global electricity usage of communication technology: trends to 2030, *Challenges* 6 (1) (2015) 117–157.
- [5] J.C. Andrey, K.R. Burns, S.T. Doherty, Toward sustainable transportation: exploring transportation decision making in teleworking households in a mid-sized Canadian city, *Can. J. Urban Res.* (2004) 257–277.
- [6] J. Aslan, K. Mayers, J.G. Koomey, C. France, Electricity intensity of Internet data transmission: untangling the estimates, *J. Ind. Ecol.* 22 (4) (2018) 785–798.

- [7] R. Atkyns, M. Blazek, J. Roitz, Measurement of environmental impacts of telework adoption amidst change in complex organizations: AT&T survey methodology and results, *Resour. Conserv. Recycl.* 36 (3) (2002) 267–285.
- [8] P.N. Balepur, K.V. Varma, P.L. Mokhtarian, Transportation impacts of center-based telecommuting: interim findings from the Neighborhood Telecenters Project, *Transportation* 25 (3) (1998) 287–306.
- [9] C. Borggren, Å. Moberg, M. Räsänen, G. Finnveden, Business meetings at a distance—decreasing greenhouse gas emissions and cumulative energy demand?, *J. Cleaner Prod.* 41 (2013) 126–139.
- [10] M. Choi, W. Park, I. Lee, Smart office energy-saving service using bluetooth low energy beacons and smart plugs, 2015 IEEE International Conference on Data Science and Data Intensive Systems, 2015.
- [11] J. Cornford, R. Richardson, A. Gillespie (1997). In Search of the Electronic Cottage? The Geography of Professional Workers Working at Home, Centre for Urban and Regional Development Studies, University of Newcastle.
- [12] V.C. Coroama, L.M. Hilty, Assessing Internet energy intensity: a review of methods and results, *Environ. Impact Assess. Rev.* 45 (2014) 63–68.
- [13] V.C. Coroama, L.M. Hilty, E. Heiri, F.M. Horn, The direct energy demand of internet data flows, *J. Ind. Ecol.* 17 (5) (2013) 680–688.
- [14] J. de Abreu e Silva, P. C. Melo (2018). “Does home-based telework reduce household total travel? A path analysis using single and two worker British households.” *Journal of Transport Geography* 73: 148–162.
- [15] J. de Abreu e Silva, P. C. Melo. “Home telework, travel behavior, and land-use patterns.” *Journal of Transport and Land Use* (2018) 11(1): 419–441.
- [16] J. de Abreu e Silva, P. C. Melo. Intra-Household Travel Behaviour Effects of Home-Telework in Great Britain (2019).
- [17] D. Dissanayake, T. Morikawa, Impact assessment of satellite centre-based telecommuting on travel and air quality in developing countries by exploring the link between travel behaviour and urban form, *Transp. Res. Part A: Policy Practice* 42 (6) (2008) 883–894.
- [18] T. Dogan, Y.C. Park, A critical review of daylighting metrics for residential architecture and a new metric for cold and temperate climates, *Light. Res. Technol.* 51 (2) (2019) 206–230.
- [19] A.J. DuBrin, J.C. Barnard. What telecommuters like and dislike about their jobs. *Business Forum*, California State University, Los Angeles, School of Business and Economics (1993).
- [20] L. Duxbury, C. Higgins. “Between Work and Family: Is Telework Part of the Problem.” *The virtual workplace*: 218 (1998).
- [21] L. Duxbury, R. Smart. The “Myth of Separate Worlds”: An Exploration of How Mobile Technology has Redefined Work-Life Balance. *Creating Balance? International Perspectives on the Work-Life Integration of Professionals*. S. Kaiser, M. J. Ringlsetter, D. R. Eikhof and M. Pina e Cunha. Berlin, Heidelberg, Springer Berlin Heidelberg: (2011) 269–284.
- [22] E. Eldér, Does telework weaken urban structure–travel relationships?, *J. Transport Land Use* 10 (1) (2017) 187–210.
- [23] E. Eldér, Who is eligible for telework? Exploring the fast-growing acceptance of and ability to telework in Sweden, 2005–2006 to 2011–2014, *Social Sci.* 8 (7) (2019) 200.
- [24] W.H. Fawcett, Optimum capacity of shared accommodation: yield management analysis, *Facilities* (2009).
- [25] K.L. Fonner, L.C. Stache, All in a day's work, at home: teleworkers' management of micro role transitions and the work–home boundary, *New Technol., Work Employment* 27 (3) (2012) 242–257.
- [26] M. Fu, J.A. Kelly, J.P. Clinch, F. King, Environmental policy implications of working from home: modelling the impacts of land-use, infrastructure and socio-demographics, *Energy Policy* 47 (2012) 416–423.
- [27] F. Garde, E. Ottenwelter, A. Bornarel, P. M. Tardif. “Integrated Building Design in Tropical Climates: Lessons learned from the ENERPOS Net Zero Energy Building.” *ASHRAE Transactions* (2012) 118(1): alainbastide.
- [28] C. Gerdenitsch, C. Korunka, G. Hertel, Need–supply fit in an activity-based flexible office: a longitudinal study during relocation, *Environ. Behav.* 50 (3) (2018) 273–297.
- [29] T. Gill, Countering the economic effects of bird flu through teleworking, *J. Bus. Continuity Emergency Plann.* 1 (1) (2006) 27–36.
- [30] E. Giovanis, The relationship between teleworking, traffic and air pollution, *Atmos. Pollut. Res.* 9 (1) (2018) 1–14.
- [31] B. Graizbord, Teleworking as a mobility strategy for Mexico City, *International Plann. Stud.* 20 (1–2) (2015) 112–130.
- [32] S. Gubins, J. van Ommeren, T. de Graaff, Does new information technology change commuting behavior?, *Ann. Reg. Sci.* 62 (1) (2019) 187–210.
- [33] H.B. Gunay, W. O'Brien, I. Beausoleil-Morrison, Development of an occupancy learning algorithm for terminal heating and cooling units, *Build. Environ.* 93 (Part 2) (2015) 71–85.
- [34] H.B. Gunay, W. O'Brien, I. Beausoleil-Morrison, S. Gilani, Modeling plug-in equipment load patterns in private office spaces, *Energy Build.* 121 (2016) 234–249.
- [35] H. Hambly, J.D. Lee, The rural telecommuter surplus in Southwestern Ontario, Canada, *Telecommun. Policy* 43 (3) (2019) 278–286.
- [36] R. Hamer, E. Kroes, H. Van Ooststroom, Teleworking in the Netherlands: an evaluation of changes in travel behaviour, *Transportation* 18 (4) (1991) 365–382.
- [37] G. Happle, J.A. Fonseca, A. Schlueter, Context-specific urban occupancy modeling using location-based services data, *Build. Environ.* (2020) 106803.
- [38] L. Harrington, B. Nordman. “Beyond network standby: A policy framework and action plan for low energy networks.” A report prepared for the IEA 4E Standby Annex. Warragul, Australia (2014).
- [39] A. Helling, P.L. Mokhtarian, Worker telecommunication and mobility in transition: consequences for planning, *J. Plann. Literature* 15 (4) (2001) 511–525.
- [40] V. Helminen, M. Ristimäki, Relationships between commuting distance, frequency and telework in Finland, *J. Transp. Geogr.* 15 (5) (2007) 331–342.
- [41] D.K. Henderson, P.L. Mokhtarian, Impacts of center-based telecommuting on travel and emissions: analysis of the Puget Sound Demonstration Project, *Transp. Res. Part D: Transport Environ.* 1 (1) (1996) 29–45.
- [42] B.W. Hesse, Using telework to accommodate the needs of employees with disabilities, *J. Organ. Comput. Electronic Commerce* 6 (4) (1996) 327–343.
- [43] D. Holloway, Gender, telework and the reconfiguration of the Australian family home, *Continuum* 21 (1) (2007) 33–44.
- [44] C. Hood, G. Nagy, K. Lister, J. Brand. 2017 State of Telecommuting in the U.S. *Employee Workforce*: (2017) 65.
- [45] A. Hook, B. Sovacool, S. Sorrell, A systematic review of the energy and climate impacts of teleworking, *Environ. Res. Lett.* (2020).
- [46] P. Hopkinson, P. James. “UK report on national SUSTEL fieldwork.” For: Sustainable Telework. Bradford (2003) [retrieved from].
- [47] A. Horvath. Environmental analysis of telework: What we know, and what we do not know and why. In *Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology*, IEEE (2010).
- [48] B. Huchuk, W. O'Brien, S. Sanner, A longitudinal study of thermostat behaviors based on climate, seasonal, and energy price considerations using connected thermostat data, *Build. Environ.* 139 (2018) 199–210.
- [49] M. Hynes. What's smart about working from home? Telework and the sustainable consumption of distance in Ireland, *Research-Publishing* (2013).
- [50] S. Karjalainen, Thermal comfort and use of thermostats in Finnish homes and offices, *Build. Environ.* 44 (6) (2009) 1237–1245.
- [51] C. Kennedy, Key threshold for electricity emissions, *Nat. Clim. Change* 5 (3) (2015) 179–181.
- [52] Y. Kestens, M. Thériault, F. Des Rosiers, Heterogeneity in hedonic modelling of house prices: looking at buyers' household profiles, *J. Geogr. Syst.* 8 (1) (2006) 61–96.
- [53] J. Kim, C. Candido, L. Thomas, R. de Dear, Desk ownership in the workplace: the effect of non-territorial working on employee workplace satisfaction, perceived productivity and health, *Build. Environ.* 103 (2016) 203–214.
- [54] S.-N. Kim, Is telecommuting sustainable? An alternative approach to estimating the impact of home-based telecommuting on household travel, *Int. J. Sustain. Transp.* 11 (2) (2017) 72–85.
- [55] S.-N. Kim, S. Choo, P.L. Mokhtarian, Home-based telecommuting and intra-household interactions in work and non-work travel: a seemingly unrelated censored regression approach, *Transp. Res. Part A: Policy Practice* 80 (2015) 197–214.
- [56] Y.-S. Kim, J. Srebric, Impact of occupancy rates on the building electricity consumption in commercial buildings, *Energy Build.* 138 (2017) 591–600.
- [57] E. Kitou, A. Horvath, Energy-related emissions from telework, *Environ. Sci. Technol.* 37 (16) (2003) 3467–3475.
- [58] E. Kitou, A. Horvath, Transportation choices and air pollution effects of telework, *J. Infrastruct. Syst.* 12 (2) (2006) 121–134.
- [59] E. Kitou, A. Horvath, External air pollution costs of telework, *Int. J. Life Cycle Assess.* 13 (2) (2008) 155.
- [60] C. Knapp, K. Vickroy, L. De Bruyn, D. Kwong, Are the myths of space utilization costing you more than you know?, *J. Corporate Real Estate* 11 (4) (2009) 237–243.
- [61] B.E. Koenig, D.K. Henderson, P.L. Mokhtarian, The travel and emissions impacts of telecommuting for the state of California Telecommuting Pilot Project, *Transp. Res. Part C: Emerging Technol.* 4 (1) (1996) 13–32.
- [62] U. Lachapelle, G.A. Tanguay, L. Neumark-Gaudet, Telecommuting and sustainable travel: reduction of overall travel time, increases in non-motorised travel and congestion relief?, *Urban Stud.* 55 (10) (2018) 2226–2244.
- [63] J. Langevin, J. Wen, P.L. Gurian, Simulating the human-building interaction: development and validation of an agent-based model of office occupant behaviors, *Build. Environ.* 88 (2015) 27–45.
- [64] A. Lari, Telework/workforce flexibility to reduce congestion and environmental degradation?, *Procedia-Social Behav. Sci.* 48 (2012) 712–721.
- [65] W. Larson, W. Zhao, Telework: urban form, energy consumption, and greenhouse gas implications, *Econ. Inq.* 55 (2) (2017) 714–735.
- [66] B. Lasternas, J. Zhao, R. Yun, C. Zhang, H. Wang, A. Aziz, K. P. Lam, V. Loftness. “Behavior oriented metrics for plug load energy savings in office environment.” In *Proceedings of the 2014 ACEEE Summer Study on Energy Efficiency in Buildings* (2014).
- [67] C. Lattemann, D. Siemon, D. Dorawa, B. Redlich. Digitization of the Design Thinking Process Solving Problems with Geographically Dispersed Teams, Cham, Springer International Publishing (2017).
- [68] P. Li, T.M. Froese, G. Brager, Post-occupancy evaluation: state-of-the-art analysis and state-of-the-practice review, *Build. Environ.* 133 (2018) 187–202.
- [69] K. Lister, T. Hamish. WORKshift Canada: The bottom line on telework, *Telework Research Network* (2011).
- [70] H.S. Matthews, E. Williams, Telework adoption and energy use in building and transport sectors in the United States and Japan, *J. Infrastruct. Syst.* 11 (1) (2005) 21–30.
- [71] A. Meier, C. Aragon, B. Hurwitz, D. Mujumdar, T. Pepper, D. Perry, M. Pitroni. How people actually use thermostats. ACEEE Summer Study on Energy Efficiency, Pacific Grove, CA (2012).

- [72] P.C. Melo, J. d. A. e Silva. "Home telework and household commuting patterns in Great Britain." *Transportation Research Part A: Policy and Practice* (2017) 103: 1–24.
- [73] J. Meyer, H. Becker, P.M. Bösch, K.W. Axhausen. *Autonomous vehicles: the next jump in accessibilities?*, *Res. Transp. Econ.* 62 (2017) 80–91.
- [74] N.G. Miller. *Workplace trends in office space: implications for future office demand*, *J. Corporate Real Estate* 16 (3) (2014) 159–181.
- [75] L.J. Millward, S.A. Haslam, T. Postmes. *Putting employees in their place: the impact of hot desking on organizational and team identification*, *Organ. Sci.* 18 (4) (2007) 547–559.
- [76] P. Mokhtarian. *If telecommunication is such a good substitute for travel, why does congestion continue to get worse?*, *Transp. Lett.* 1 (1) (2009) 1–17.
- [77] P.L. Mokhtarian. *A synthetic approach to estimating the impacts of telecommuting on travel*, *Urban Stud.* 35 (2) (1998) 215–241.
- [78] P.L. Mokhtarian, G.O. Collantes, C. Gertz. *Telecommuting, residential location, and commute-distance traveled: evidence from State of California employees*, *Environ. Plann. A* 36 (2004) 1877–1898.
- [79] P.L. Mokhtarian, S.L. Handy, I. Salomon. *Methodological issues in the estimation of the travel, energy, and air quality impacts of telecommuting*, *Transp. Res. Part A: Policy Practice* 29 (4) (1995) 283–302.
- [80] P.L. Mokhtarian, I. Salomon, S. Choo. "Data and measurement issues in transportation, with telecommuting as a case study." (2004).
- [81] P.L. Mokhtarian, I. Salomon, S. Choo. *Measuring the measurable: why can't we agree on the number of telecommuters in the US?*, *Qual. Quant.* 39 (4) (2005) 423–452.
- [82] P.L. Mokhtarian, K.V. Varma. *The trade-off between trips and distance traveled in analyzing the emissions impacts of center-based telecommuting*, *Transp. Res. Part D: Transport Environ.* 3 (6) (1998) 419–428.
- [83] M. Moos, J. Andrey, L.C. Johnson. *The sustainability of telework: an ecological-footprinting approach*, *Sustain.: Sci., Practice Policy* 2 (1) (2006) 3–14.
- [84] M. Moos, A. Skaburskis. *The probability of single-family dwelling occupancy: comparing home workers and commuters in Canadian Cities*, *J. Plann. Educ. Res.* 27 (3) (2008) 319–340.
- [85] H. Nakanishi. *Does telework really save energy?*, *Int. Manage. Rev.* 11 (2) (2015) 89.
- [86] L. Nijland, M. Dijst. *Commuting-related fringe benefits in the Netherlands: interrelationships and company, employee and location characteristics*, *Transp. Res. Part A: Policy Practice* 77 (2015) 358–371.
- [87] J. Nilles. *Telecommunications and organizational decentralization*, *IEEE Trans. Commun.* 23 (10) (1975) 1142–1147.
- [88] J. Nilles. "The state of California telecommuting pilot project final report." Los Angeles: JALA associates, inc (1990).
- [89] J.M. Nilles, F.R. Carlson, P. Gray, G. Hanneman. *Telecommuting—an alternative to urban transportation congestion*, *IEEE Trans. Syst., Man, Cybernetics* 2 (1976) 77–84.
- [90] W. O'Brien, L. Gaetani, S. Carlucci, P.-J. Hoes, J.L.M. Hensen. *On occupant-centric building performance metrics*, *Build. Environ.* 122 (2017) 373–385.
- [91] W. O'Brien, H. B. Gunay. "Do building energy codes adequately reward buildings that adapt to partial occupancy?" *Science and Technology for the Built Environment* (2019) 1–14.
- [92] D. Ong, T. Moors, V. Sivaraman. *Comparison of the energy, carbon and time costs of videoconferencing and in-person meetings*, *Comput. Commun.* 50 (2014) 86–94.
- [93] D.T. Ory, P.L. Mokhtarian. *Which came first, the telecommuting or the residential relocation? An empirical analysis of causality*, *Urban Geogr.* 27 (7) (2006) 590–609.
- [94] R.M. Pendyala, K.G. Goulias, R. Kitamura. *Impact of telecommuting on spatial and temporal patterns of household travel*, *Transportation* 18 (4) (1991) 383–409.
- [95] M. Pérez Pérez, A. Martínez Sánchez, M. Pilar de Luis Carnicer, M. José Vela Jiménez. "The environmental impacts of teleworking: A model of urban analysis and a case study." *Management of Environmental Quality: An International Journal* (2004) 15(6): 656–671.
- [96] J. Pohl, L.M. Hilty, M. Finkbeiner. *How LCA contributes to the environmental assessment of higher order effects of ICT application: a review of different approaches*, *J. Cleaner Prod.* (2019).
- [97] J.H. Pratt. *Home teleworking: a study of its pioneers*, *Technol. Forecast. Soc. Chang.* 25 (1) (1984) 1–14.
- [98] J.H. Pratt. *Asking the right questions about telecommuting: avoiding pitfalls in surveying homebased work*, *Transportation* 27 (1) (2000) 99–116.
- [99] J.H. Pratt. *Teleworkers, trips, and telecommunications: technology drives telework—but does it reduce trips?*, *Transp. Res. Rec.* 1817 (1) (2002) 58–66.
- [100] P. Pyöriä. *Managing telework: risks, fears and rules*, *Manage. Res. Rev.* (2011).
- [101] H.-J. Rhee. *Telecommuting and urban sprawl*, *Transp. Res. Part D: Transport Environ.* 14 (7) (2009) 453–460.
- [102] D. Röder, K. Nagel. *Integrated analysis of commuters' energy consumption*, *Procedia Comput. Sci.* 32 (2014) 699–706.
- [103] K.W. Roth, T. Rhodes, R. Ponoum. *The energy and greenhouse gas emission impacts of telecommuting in the US*, *Electronics and the Environment*, 2008. ISEE 2008. IEEE International Symposium on, IEEE (2008).
- [104] M. Schweiker, S. Carlucci, R. K. Andersen, B. Dong, W. O'Brien. *Occupancy and Occupants' Actions. Exploring Occupant Behavior in Buildings*. Cham, Switzerland, Springer (2018) 7–38.
- [105] R. Shabanpour, N. Golshani, M. Tayarani, J. Auld, A.K. Mohammadian. *Analysis of telecommuting behavior and impacts on travel demand and the environment*, *Transp. Res. Part D: Transport Environ.* 62 (2018) 563–576.
- [106] Y. Shimoda, Y. Yamaguchi, K. Kawamoto, J. Ueshige, Y. Iwai, M. Mizuno. "Effect of telecommuting on energy consumption in residential and non-residential sectors." *International Building Performance Simulation Association. Proceedings: Building Simulation* (2007) 1361.
- [107] M. Souppaya, K. Scarfone. *Guide to Enterprise Telework, Remote Access, and Bring your Own Device (BYOD) Security*, National Institute of Standards and Technology, 2016.
- [108] W. Tang, P.L. Mokhtarian, S.L. Handy. *The impact of the residential built environment on work at home adoption and frequency: an example from Northern California*, *J. Transport Land Use* 4 (3) (2011) 3–22.
- [109] A.-M. Tillman, T. Ekvall, H. Baumann, T. Rydberg. *Choice of system boundaries in life cycle assessment*, *J. Cleaner Prod.* 2 (1) (1994) 21–29.
- [110] T. van Lie, A. de Witte, C. Macharis. *How worthwhile is teleworking from a sustainable mobility perspective? The case of Brussels Capital region*, *Eur. J. Transport Infrastruct. Res.* 14 (3) (2014).
- [111] B. Vilhelmson, E. Thulin. *Who and where are the flexible workers? Exploring the current diffusion of telework in Sweden*, *New Technol., Work Employment* 31 (1) (2016) 77–96.
- [112] S. Vu, U. Vandebona. *Telecommuting and its impacts on vehicle-km travelled*. *International Congress on Modelling and Simulation*, University of Canterbury, Christchurch, New Zealand, Citeseer (2007).
- [113] M. Walls, P. Nelson. *Telecommuting and emissions reductions: Evaluating results from the ecommute program* (2004).
- [114] E.D. Williams. *Assessing the potential of telecommuting as an energy savings technology in Japan*, *Electronics and the Environment*, 2003. IEEE International Symposium on, IEEE (2003).
- [115] J.B. Windeler, K.M. Chudoba, R.Z. Sundrup. *Getting away from them all: managing exhaustion from social interaction with telework*, *J. Organ. Behav.* 38 (7) (2017) 977–995.
- [116] J.-R. Yen. *Interpreting employee telecommuting adoption: an economics perspective*, *Transportation* 27 (1) (2000) 149–164.
- [117] P. Zhu, S.G. Mason. *The impact of telecommuting on personal vehicle usage and environmental sustainability*, *Int. J. Environ. Sci. Technol.* 11 (8) (2014) 2185–2200.
- [118] James Kirk, Robert Belovics. *Making e-working work*, *J. Employment Couns.* 43 (1) (2006) 39–46, <https://doi.org/10.1002/j.2161-1920.2006.tb00004.x>.
- [119] Adriana Bernardino, Moshe Ben-Akiva. *Modeling the Process of Adoption of Telecommuting: Comprehensive Framework*, *Transp. Res. Rec.: J. Transp. Res. Board* 1552 (1) (2016) 161–170, <https://doi.org/10.1177/2F0361198196155200122>.
- [120] Matthew J. Grawitch, Larissa K. Barber, Logan Justice. *Rethinking the work-life interface: It's not about balance, it's about resource allocation*, *Appl. Psychol.: Health and Well-Being* 2 (2) (2010) 127–159, <https://doi.org/10.1111/j.1758-0854.2009.01023.x>.
- [121] Hamidreza Asgari, Xia Jin, Yiman Du. *Examination of the Impacts of Telecommuting on the Time Use of Nonmandatory Activities*, *Transp. Res. Rec.: J. Transp. Res. Board* 2566 (1) (2016) 83–92, <https://doi.org/10.3141/2F2566-09>.