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Rebound Effects of Changing Shopping and Commute Patterns

Rebound-Effekte veränderter Einkaufs- und Berufspendlergepflogenheiten

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Zusammenfassung

Die fortschreitende Digitalisierung bringt bedeutende gesellschaftliche und wirtschaftliche Veränderungen mit sich, die in einigen Fällen die Art und Weise, wie wir leben und arbeiten, tiefgreifend verändern. Dieser Trend bringt auch verschiedene und potenziell weitreichende energetische und ökologische Auswirkungen mit sich. Der unmittelbare Energie- und Umweltfussabdruck der Digitalisierung beispielsweise gibt zunehmend Anlass zur Sorge, insbesondere im Zusammenhang mit den jüngsten Entwicklungen im Bereich der künstlichen Intelligenz (KI). Die Digitalisierung kann jedoch auch indirekte Vorteile in anderen Bereichen mit sich bringen, durch verschiedene Mechanismen wie z.B. Effizienzgewinne, Dematerialisierung, bessere Koordinierung oder Simulation und Vorhersage.

Leider häufen sich die Hinweise, dass genau diese Mechanismen oft auch umweltschädliche indirekte Auswirkungen mit sich bringen. Diese unerwünschten Nebeneffekte treten aufgrund der Preissenkungen, der Zeitersparnis oder des erhöhten Komforts auf, die durch die oben genannten positiven Entwicklungen hervorgerufen werden. Sie können den ursprünglichen positiven Effekt verringern oder sogar umkehren und werden in den Wirtschaftswissenschaften häufig unter dem Oberbegriff Rebound-Effekte beschrieben. Im Gegensatz zu ihrem direkten Fussabdruck und ihren positiven indirekten Effekten, haben die Rebound-Effekte der Digitalisierung bislang wenig Beachtung gefunden.

Die aktuelle Studie beleuchtet die Rebound-Effekte, die in zwei Bereichen auftreten, die in jüngster Zeit, insbesondere seit der Pandemie, stark von der Digitalisierung beeinflusst wurden: Einkaufen und Berufspendeln. Durch die Digitalisierung ermöglicht und durch die Pandemie beschleunigt, haben E-Commerce und Telearbeit die Art und Weise, wie wir einkaufen und arbeiten, erheblich verändert. Sowohl der elektronische Handel als auch die Telearbeit verringern die Notwendigkeit, persönlich zum Einkaufen und zur Arbeit zu gehen, und haben somit das Potenzial, den Energieverbrauch und die Emissionen von Treibhausgasen und Schadstoffen zu verringern.

Auf der Grundlage umfassender Literaturrecherchen in beiden Bereichen zeigt diese Studie jedoch, dass beide Bereiche auch durch starke Rebound-Effekte gekennzeichnet sind. Beim elektronischen Handel werden Rebound-Effekte durch die zusätzlich benötigten IKT-Systeme, die in der Regel zusätzlich verwendeten Verpackungen, die (in der Regel per Lieferwagen erfolgende) Zustellung auf der letzten Meile, fehlgeschlagene Lieferungen mit anschliessender erneuter Zustellung sowie die Rücksendungen ausgelöst, die beim Online-Einkauf eine wesentlich höhere Rate haben als beim traditionellen Einkauf im Geschäft. Bei der Telearbeit kommt es zu Rebound-Effekten aufgrund der zusätzlichen IKT, die zur Unterstützung des Prozesses benötigt werden, des zusätzlichen Energieverbrauchs im Haushalt, der häufigeren Fahrten ausserhalb des Arbeitsplatzes und des längeren Arbeitsweges, den die Telearbeiter an den Tagen, an denen sie doch zur Arbeit pendeln, auf sich nehmen.

Insgesamt sind beide Rebound-Effekte ähnlich gross und belaufen sich auf einige Kilogramm CO_2 pro Online-Einkaufsvorgang bzw. Telearbeitstag. Aggregiert man diese Effekte über die Dutzenden von Online-Einkaufsvorgängen und Telearbeitstagen pro Jahr, ergibt sich ein geschätzter Median von 111 kg CO2/Jahr Rebound-Effekte des E-Commerce pro durchschnittlichem Schweizer Haushalt und 91 kg CO2/Jahr Rebound-Effekte der Telearbeit pro Schweizer Einwohner, was – für die Schweiz – 1,02% bzw. 1,82% der Pro-Kopf-Treibhausgasemissionen entspricht.

In beiden Fällen führt die zusätzlich benötigte IKT-Infrastruktur nur zu einem marginalen Effekt. Abgesehen von der für die Telearbeit zusätzlich benötigten Haushaltsenergie sind die meisten anderen Arten von Rebound-Effekten sowohl beim elektronischen Handel als auch bei der Telearbeit auf den zusätzlich erzeugten Verkehr zurückzuführen. Die Substitution traditioneller Verkehrsmittel durch umweltfreundliche Alternativen trägt also in beiden Fällen zur Abschwächung der Rebound-Effekte bei. Solche Substitutionen können aus der allgemeinen Verkehrsinfrastruktur und -kultur, der öffentlichen Politik, der Unternehmenspolitik sowie individuellen Entscheidungen resultieren.

Von den beiden Bereichen scheint der Rebound der Telearbeit höher zu sein, aber gleichzeitig auch klarer definiert und in seinem Umfang begrenzt, so dass er relativ leicht zu verstehen und – soweit möglich – abzumildern ist. Für den elektronischen Handel gibt es jedoch noch weitere, recht subtile,

schwer zu erfassende und zu kontrollierende Ursachen für den Rebound: die konsumfördernde Wirkung der erhöhten Bequemlichkeit und der neuen Marketingkanäle, die interkontinentalen, oft flugzeuggestützten Lieferungen und Rücksendungen, die durch die neuen Vertriebsplattformen ermöglicht werden, und die hohe Zerstörungsrate der zurückgesandten Artikel, die sich sowohl aus der hohen Rücksendequote des elektronischen Handels als auch aus der Unverkäuflichkeit schnell veralteter Waren wie Fast Fashion und Elektronik ergibt. Es besteht Forschungsbedarf, um diese Auswirkungen besser zu verstehen und politische Massnahmen zu ihrer Abschwächung zu entwerfen sowie um die indirekten Auswirkungen der Digitalisierung konzeptionell besser zu beschreiben.

Résumé

La numérisation en cours entraîne d'importants changements sociétaux et économiques, modifiant parfois profondément nos modes de vie et de travail. Cette tendance induit également des effets énergétiques et environnementaux variés, et potentiellement lourds de conséquences. L'empreinte énergétique et environnementale directe de la numérisation, par exemple, est une source de préoccupation, en particulier dans le contexte des derniers développements en matière d'intelligence artificielle (IA). Toutefois, la numérisation peut également induire des avantages indirects dans d'autres domaines par le biais de divers mécanismes tels que les gains d'efficacité, la dématérialisation, l'amélioration de la coordination ou la simulation et la prévision.

Malheureusement, des preuves de plus en plus nombreuses montrent que ces mêmes mécanismes induisent souvent des effets indirects préjudiciables à l'environnement. Ces effets secondaires indésirables apparaissent en raison de la baisse des prix, du gain de temps ou de l'amélioration de la commodité apportés par les développements positifs mentionnés ci-dessus. Ils peuvent réduire, voire annuler l'effet positif initial et sont souvent décrits en économie sous le terme générique d'effets de rebond. Contrairement à son empreinte directe et à ses effets indirects positifs, les effets de rebond de la numérisation ont reçu peu d'attention jusqu'à présent.

La présente étude met en lumière les effets de rebond qui se produisent dans deux domaines qui ont récemment été profondément affectés par la numérisation, en particulier depuis la pandémie : les achats et le travail. Favorisés par la numérisation et accélérés par la pandémie, le commerce électronique et le télétravail ont considérablement modifié notre façon de faire des achats et de travailler. Le commerce électronique et le télétravail réduisent tous deux la nécessité de se rendre en personne dans les magasins et sur le lieu de travail, et peuvent donc réduire la consommation d'énergie et les émissions de gaz à effet de serre et de polluants.

S'appuyant sur des analyses documentaires approfondies dans les deux domaines, cette étude montre toutefois que les deux domaines sont également caractérisés par de forts effets de rebond. Pour le commerce électronique, les effets de rebond sont déclenchés par les systèmes TIC supplémentaires nécessaires, l'emballage supplémentaire généralement déployé, la livraison (généralement par camionnette) du dernier kilomètre, les livraisons manquées suivies de nouvelles livraisons, et les retours, qui sont considérablement plus élevés pour les achats en ligne que pour les achats traditionnels en magasin. En ce qui concerne le télétravail, les effets de rebond sont dus aux TIC supplémentaires nécessaires pour soutenir le processus, à la consommation supplémentaire d'énergie domestique, à l'augmentation de la fréquence des trajets hors domicile et à l'allongement des trajets que les télétravailleurs sont prêts à effectuer les jours où ils se rendent au travail.

Dans l'ensemble, les deux effets de rebond sont de taille similaire, s'élevant à quelques kilogrammes de CO_2 par session d'achat en ligne et par jour de télétravail, respectivement. L'agrégation de ces effets sur les douzaines de processus d'achat en ligne et de jours de télétravail par an donne une estimation médiane de 111 kg de CO2/an d'effets de rebond du commerce électronique par ménage suisse moyen, et de 91 kg de CO2/an d'effets de rebond du télétravail par habitant suisse, ce qui – pour la Suisse – représente respectivement 1,02 % et 1,82 % des émissions de gaz à effet de serre par habitant.

Dans les deux cas, l'infrastructure TIC supplémentaire requise n'a qu'un effet marginal. À l'exception de l'énergie domestique supplémentaire requise pour le télétravail, la plupart des autres types d'effets de rebond pour le commerce électronique et le télétravail proviennent du trafic supplémentaire généré. Le remplacement des moyens de transport traditionnels par des moyens de transport respectueux de l'environnement contribue donc à atténuer les effets de rebond dans les deux cas. Ces substitutions peuvent résulter de l'infrastructure et de la culture générale des transports, des politiques publiques, des politiques d'entreprise ou des choix individuels.

Parmi ces deux domaines, le rebond du télétravail semble plus important, mais en même temps plus clairement défini et limité dans sa portée, et donc relativement simple à comprendre et – dans la mesure

du possible – à atténuer. Pour le commerce électronique, cependant, il existe d'autres sources de rebond, assez subtiles, difficiles à saisir et à contrôler : l'effet d'incitation à la consommation d'une plus grande commodité et de nouveaux canaux de commercialisation, les livraisons et les retours intercontinentaux, souvent effectués par avion, permis par les nouvelles plateformes de distribution, et le taux élevé de destruction des articles retournés, résultant à la fois du taux élevé de retour du commerce électronique et de la non-vendabilité des biens rapidement périmés tels que la mode rapide et l'électronique. Des recherches supplémentaires sont nécessaires pour mieux comprendre ces effets et concevoir des mesures politiques pour les atténuer, ainsi que pour mieux décrire conceptuellement les effets indirects de la numérisation.

Summary

The ongoing digitalisation brings about significant societal and economic changes, in some instances profoundly changing the ways we live and work. This trend also induces various and potentially far-reaching energetic and environmental effects. The direct energy and environmental footprint of digitalisation, for example, is a growing source of concern, in particular in the context of the latest developments within artificial intelligence (AI). Digitalisation can, however, also induce indirect benefits in other domains through various mechanisms such as efficiency gains, dematerialisation, better coordination, or simulation and forecasting.

Unfortunately, increasing evidence shows that these very mechanisms, often induce environmentally detrimental indirect effects as well. These undesired side-effects appear because of the decreased prices, saved time, or increased convenience brought about by the positive developments mentioned above. They can reduce or even reverse the initial positive effect, and are often described in economics under the umbrella term of *rebound effects*. Unlike its direct footprint and its positive indirect effects, the rebound effects of digitalisation have received little attention so far.

The current study sheds light on the rebound effects that occur in two domains that have recently been profoundly affected by digitalisation, especially since the pandemics: shopping and working. Enabled by digitalisation and accelerated by the pandemics, e-commerce and teleworking have substantially altered the way we shop and work. E-commerce and teleworking both reduce the need for in-person trips to stores and work, and thus have the potential to reduce energy consumption and reduce emissions of greenhouse gases and pollutants.

Building on comprehensive literature reviews in both domains, this study shows, however, that both domains are also characterised by strong rebound effects. For e-commerce, rebound effects are triggered by the additional ICT systems needed, the additional packaging usually deployed, the (typically van-based) last-mile delivery, failed deliveries followed by re-deliveries, and the returns, which are substantially higher for online than for traditional in-store shopping. For teleworking, rebound effects occur due additional ICT needed to support the process, the additional domestic energy consumption, the more frequent non-commute trips, and the longer commute that teleworkers are willing to perform on the days when they do commute to work.

Overall, both rebound effects are similarly-sized, amounting to a few kilograms of CO_2 per online shopping instance and teleworking day, respectively. Aggregating these effects over the dozens of online shopping processes and teleworking days per year results in an estimated median of 111 kg CO_2/year rebound effects of e-commerce per average Swiss household, and 91 kg CO_2/year rebound effects of teleworking per Swiss inhabitant, which – for Switzerland – represent 1.02% and 1.82% of the per-capita greenhouse gas emissions, respectively.

In both cases, the additionally required ICT infrastructure induces only a marginal effect. Except the additional domestic energy required for teleworking, most other types of rebound effects for both e-commerce and teleworking stem from additionally generated traffic. Substituting environmentally friendly transportation means for traditional ones thus helps mitigating the rebound effects in both cases. Such substitutions can result from the general transportation infrastructure and culture, public policies, company policies, or individual choices.

Among the two domains, the rebound of teleworking seems higher, but at the same time more clearly defined and limited in scope, and thus relatively straightforward to understand and – to the extent possible – mitigate. For e-commerce, however, there are further, quite subtle, hard to grasp and to control sources of rebound: the consumption-inducing effect of increased convenience and new marketing channels, the intercontinental, often airplane-based deliveries and returns enabled by new distribution platforms, and the high destruction rate of returned items, resulting both from the high return rate of e-commerce and the non-saleability of quickly outdated goods such as fast fashion and electronics. More research is needed to better understand these effects and to devise policy measures for their mitigation, as well as to better conceptually describe the indirect effects of digitalisation.

Main findings

- Both for e-commerce and teleworking, there are several sources of rebound effects:
    - for e-commerce: IT infrastructure, additional packaging, last-mile delivery, redeliveries, and returns.
    - for teleworking: IT infrastructure, additional domestic energy, induced non-commute trips, and longer physical commute, when still required.
- Taken together, they account for a few kilograms of CO_2eq. per online shopping process and teleworking day, respectively. Based on the literature,
    - for e-commerce, the median and the 1^{st}-3^{rd} quartile interval are 2.15 (0.73 – 5.39) kg CO_2eq. / online shopping process.
    - for teleworking, the median and the interquartile interval are 6.43 (4.01 – 9.42) kg CO_2eq. / teleworking day.
- Assuming these worldwide numbers to be characteristic for Switzerland, they correspond to non-negligible shares of the country's emissions, in particular when related to the relatively low 5t CO_2eq. / (year and person) from a production perspective.
- According to these assumptions, the rebound effects of e-commerce amount to
    - 1.02% (0.41% – 3.08%) of the Swiss GHG footprint from a production perspective,
    - 0.39% (0.16% – 1.19%) of the Swiss GHG footprint from a consumption perspective.
- Similarly, the rebound effects of telework amount to:
    - 1.82% (1.14% – 2.66%) of the Swiss GHG footprint from a production perspective,
    - 0.7% (0.44% – 1.02%) of the Swiss GHG footprint from a consumption perspective.
- Among the rebound sources, the impact of the additional IT infrastructure is negligible in both cases.
- As most rebound effects occur as additional traffic for both domains, measures that foster environmentally-friendly transportation modes are the most effective mitigating measure.
- For e-commerce, there are additional rebound mechanisms that yield more subtle, far-reaching, and hard-to-grasp rebound effects: the additional consumption fostered by e-commerce, worldwide deliveries and returns, and a much larger share of unused goods being destroyed. They all require more research.

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Abbreviations

B2C	business-to-consumer
BEV	battery electric vehicle
BFE	Bundesamt für Energie (synonymous to Swiss Federal Office of Energy, SFOE)
BTU	British thermal unit, a measure for heat
C2C	consumer-to-consumer
CHF	Swiss franc
EV	electric vehicle
FMCG	fast-moving consumer good
FU	functional unit
HVAC	heating, ventilation and air conditioning
FTE	full-time employee
GB	gigabyte (10^9 bytes)
GDP	gross domestic product
GHG	greenhouse gas
Gt	gigatonne (10^9 tonnes)
HQ	headquarters (of a company or organisation)
ICE	internal combustion engine
IEA	International Energy Agency
IT	information technology
ICT	information and communication technology
kt	kiloton (10^3 tonnes)
LCA	life-cycle assessment
MB	megabyte (10^6 bytes)
MJ	megajoule (a measure of energy)
VPN	virtual private network
RADR	road automated delivery robot
SADR	sidewalk automated delivery robot
TB	terabyte (10^12 bytes)
UNEP	United Nations Environment Programme
USD	United States dollar (currency)
WWW	worldwide web

1 Introduction

1.1 Background information and current situation

Rebound effects occur when environmentally positive initial developments (such as increased production efficiency) make a good or a service more attractive (through lower prices or additional benefits), which in turn either boosts demand for the same good or service (which is now more attractive), or possibly for other products due to increased disposable income or time saved. These usually undesired consequences of the initial positive development is often referred to as a *direct rebound effect* and *indirect rebound effect*, respectively (Sorrell 2009).

Although the rebound effect was already identified in the second half of the 19th century by British economist William Stanley Jevons for the usage of coal (Jevons 1865), the concept lay dormant for more than 100 years until it was brought back to scientific and public attention by the US economist J. Daniel Khazzoom in 1980 (Khazzoom 1980). As a result, the concept is now relatively established in economics. There is, however, still disagreement on how exactly to categorise rebound effects and their generating mechanisms. Additionally, their quantitative assessment remains challenging. Indirect rebound effects, which can have economy-wide impacts through various mechanisms (such as income and substitution effects, time savings, or reduction of transaction costs – see Section 2.1 below and (Coroamă and Pargman 2020) – are particularly difficult to measure.

Rebound effects have not been thoroughly investigated for digital goods and services, and even less for the comprehensive digitalisation of entire industrial and economic sectors or areas of life (Coroamă and Mattern 2019). This is understandable, since rebound effects – as outlined above – are extremely diverse, operate through subtle mechanisms and have far-reaching consequences. Bridging this knowledge gap is nonetheless important for three reasons:

- As cross-cutting technology, digitalisation pervades more and more areas of our economies and societies, changing – sometimes fundamentally – established processes and norms.
- As a result, and due to the associated efficiency gains and its dematerialisation potential, digitalisation is often hailed as a key technology to bring about society- and economy-wide energy and resource efficiency and therefore also to contribute to the reduction of greenhouse gases (GHG) and thus combat the climate crisis.
- However, due to induced time savings (Binswanger 2001), efficiency, general acceleration and globalisation (Coroamă and Mattern 2019), which are directly promoted by digitalisation, it is also particularly susceptible to triggering rebound effects.

Digitalisation is thus a double-edged sword – and relatively unexplored on both sides: On one hand, it can trigger significant society- and economy-wide savings of energy, resources and greenhouse gases (GHGs), but it can also lead to higher energy and resource consumption (and consequently to more GHG emissions) via various rebound effects.

1.2 Purpose of the project

These indirect effects of digitalisation are steadily gaining importance, often unnoticed, and are likely to do so even more in the future. This is true both for the positive indirect effects (through, for example, efficiency, dematerialisation, better coordination, simulation or forecasting), but unfortunately also for the negative ones. In particular, the rebound effects of digitalisation are still poorly understood. A better understanding of their development mechanisms, but also of possible countering measures, has both scientific and strategic political relevance.

In this context, the main objective of this study is to investigate the rebound effects triggered by digitalisation, and to quantify to the extent possible their energy and GHG impacts. To achieve this goal, the study performs an in-depth analysis of two digital use cases that already have significant societal and economic consequences, and thus also energetic and GHG ones: online shopping and teleworking. These two use cases are fundamentally changing established socio-economic processes. They were already gaining importance before the Covid pandemic, and their importance has considerably grown during the pandemic. They have both substantial energy saving potentials. Through a variety of mechanisms, they can, however, also trigger rebound-based boomerang effects.

Insights into their rebound effects, how they might reduce potential savings, and how the rebound effects might be counteracted upon, are thus of high theoretical and practical relevance. Furthermore, they might allow for a generalisation of the conclusions beyond the two use cases to the entire field of digitalisation-triggered rebound effects.

The main research questions (RQs) addressed in this study thus are:

1. Which are the mechanisms through which online shopping and teleworking lead to energy savings and GHG emission reductions?
2. What pre-pandemic (qualitative and quantitative) assessments exist?
3. Which rebound-inducing mechanisms are immanent to the two use cases?
4. Which pre-pandemic (qualitative and quantitative) assessments of rebound effects exist?
5. How has the pandemic (and especially the measures to fight it) affected these two domains? What data are available for Switzerland and beyond?
6. How did the end of the pandemic, and the worldwide lifting of the pandemic control measures, change these two domains? How did rebound effects develop?
7. What are effective measures to avoid or mitigate rebound effects in these use cases? Can anything be learned from the comparison of RQ5 and RQ6?
8. Can insights from the two use cases be extrapolated to digitalisation in general? How can the potential savings be exploited while minimising the rebound induced by digitalisation?

1.3 Structure of the report

The remainder of this report is organised as follows: Section 2 introduces the backdrop of the study. It provides a concise introduction to various types of rebound effects and introduces more formally both e-commerce and teleworking together with a short historic overview of their respective developments. Section 3 presents the methodology deployed for the study, which mainly consist of a systematic literature review. Sections 0 and 5 then present thorough analyses of the rebound effects of e-commerce and teleworking, respectively. They are the most substantial parts of this report, consisting of both qualitative but also quantitative analyses of the sources and magnitudes of the rebound effects in the two important societal paradigm shifts enabled by digitalisation. Section 6 discusses the results, highlighting in particular 3 aspects: the commonalities and differences between the rebound effects in the two domains including an analysis of the more worrisome of the two, the mitigation options available for the two domains together with their potential and limitations, and the situation in Switzerland for both domains. Finally, Section 6.4 draws the conclusions, indicating some policy recommendations and future research needs.

2 Background

This section introduces rebound effects in more detail, presenting their various triggering mechanisms, and consequently distinguishing different types of rebound effects and existing taxonomies thereof. It then discusses the two domains under scrutiny (i.e., online shopping and teleworking), motivating both why they represent digital developments with a significant socio-economic impact, and why they are particularly prone to rebound effects.

2.1 Rebound effects[1]

The rebound effect was first identified in the second half of the 19th century by British economist William Stanley Jevons for the production of coal (Jevons 1865). Without calling it "rebound" (the term was coined over a century later, as will be addressed below), Jevons described in a lengthy book the main mechanisms behind rebound effects as well as their outcome: more resource (i.e., coal) consumption because of efficiency gains instead of less: "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth […] Every […] improvement of the engine, when effected, does but accelerate anew the consumption of coal" (Jevons 1865).

As discussed at length in (Alcott 2005), Jevons theoretical argument that coal efficiency ultimately increases coal consumption relies on bringing together the concepts of *profitability*, *new inventions and uses* and *consumer behaviour*. Improved efficiency, for one, improves profitability (for example of a coal-powered furnace), which will increase the demand for it: "[If] the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig iron will fall, but the demand for it increases and eventually the greater number of furnaces will more than make up for the diminished consumption of each" (Jevons 1865). This is what today we would call a *direct rebound effect*, where the increased consumption occurs for the same good that has originally become more efficient (the more coal-efficient furnace in this example).

Improved profitability, however, also broadens the application domains of a coal-powered device such as the steam engine: "Whatever, however, conduces to increase the efficiency of coal, and to diminish the cost of its use, directly tends to augment the value of the steam-engine, and to enlarge the field of its operations […] But no one must suppose that coal thus saved is spared – it is only saved from one use to be employed in others, and the profits gained soon lead to extended employment in many new forms" (Jevons 1865). This is a classic example of what we would call today an *indirect rebound effect*: efficiency gains make the consumption of one good cheaper, leading to more disposable income that can be spent both for the old usage as well as new ones (i.e., direct and indirect rebound): "the quantity consumed by each individual is a composite quantity, increased either by multiplying the scale of former applications, or finding wholly new applications […] But the new applications of coal are of an unlimited character […] Old applications of coal have been extended, and yet admit of great extension, while new ones are continually being added" (Jevons 1865).

2.1.1 The direct rebound effect

Interestingly, Jevons' observations lied dormant for more than 100 years. It was only towards the end of the 20th century that economists started to become aware and interested in the subject. (Khazzoom 1980) undertook a first systematic analysis of the rebound effect. His approach relies on a single-service model; i.e., there are no repercussions from this service to the rest of the economy. The service is an energy-intensive one such as mobility (measured in passenger-km) or room temperature. According to neoclassical economic theory, when the price of a good decreases, the demand for it increases, all other things equal. If, due to advances in energy efficiency (i.e., more fuel-efficient vehicles or better house

[1] Parts of this subsection rely on (Coroamă and Mattern 2019).

insulation), the passenger-km or an hour of a certain room temperature cost less, and as long as their needs are not saturated, users will tend to use them more: more kilometres will be driven, the room temperature set to a higher value or not turned off overnight. This effect may partly or entirely offset the savings from the original energy efficiency measure.

In this narrow sense, the rebound is often referred to as *direct rebound effect* – direct because the rebound occurs for the same service that had originally gained in efficiency, and because it is a direct consequence of the price reduction that follows less input to produce it. Although originally defined for energy markets, the effect appears for any resource efficiency measure: if less of a resource (any physical resource but also more general work or capital) is needed to produce a good or services, its price will decrease and as a result more of it will be demanded.

2.1.2 "Jevon's paradox" or backfire

The effect originally described by Jevons is different from Khazzoom's rebound in that it is more general (caused by more mechanisms) than the mere direct rebound put forward by Khazzoom. This will be discussed further down. Despite attributing it to different causes, Jevons and Khazzoom agree on the rebound's size. They both assume that it is larger than 100%, i.e. it is postulated to overcompensate the original savings. As broadly discussed by (Alcott 2005), Jevons argues in his original work that the rebound effect not only reduces the potential savings of the energy efficiency measure, but that it actually overcompensates the reductions, leading to an overall net energy increase: "[if] the quantity of coal used in a blast furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig iron will fall, but the demand for it increases and eventually the greater number of furnaces will more than make up for the diminished consumption of each" (Jevons 1865, page 156).

This particular case, when the magnitude of the rebound effect is more than 100%, is known in the literature as *Jevons' paradox*, or under further names such as boomerang or, more commonly, *backfire*. A well-known formulation of Jevons' paradox is given by Saunders: "with fixed real energy prices, energy-efficiency gains will increase energy consumption above what it would be without these gains" (Saunders 1992), who calls it "the Khazzoom-Brookes postulate", Brookes being another economist who has intensely studied rebound (Brookes 2000). As both (Alcott 2005) and (Sorrell 2009) observe, however, 'postulate' is the correct term in this context, as there is not enough evidence to support that the rebound always exceeds 100%. Discussing Jevons' work, Alcott observes "Jevons thus makes rebound theoretically plausible, but he has not yet proven that the amount of coal consumed must 'more than' make up for engineering savings" (Alcott 2005). Likewise, (Sorrell 2009) concludes that "such evidence does not yet exist".

2.1.3 Indirect rebound: Induction effects, income and substitution effects

The citations from Jevons' work above already hint towards more mechanisms than the mere direct rebound. Another revealing portion is on page 144: "*Whatever, however, conduces to increase the efficiency of coal, and to diminish the cost of its use, directly tends to augment the value of the steam-engine, and to enlarge the field of its operations*" (Jevons 1865). The mechanism here reminds the "induction effect" (Hilty 2008), which other researchers consider just a special form of rebound effect (Börjesson Rivera et al. 2014).

Such mechanisms that lead to different types of rebound were more formally presented soon after Khazzoom's work. Both (Binswanger 2001) and (Berkhout, Muskens, and W. Velthuijsen 2000) discuss the income effect and the substitution effect as further causes for rebound. The effects, well-described by (Binswanger 2001), are observed by leaving the single-service model behind, and considering a model consisting of two services, A and B, that can partially be substituted for each other. A lower price for service A, as a consequence of efficiency gains for one of its inputs, has two consequences: i) consuming the same amount of A and B becomes cheaper, the consumer has a larger budget at his disposal, leading – ceteris paribus – to more consumption of both A and B (income effect); and ii) as service A becomes relatively cheaper, it will partially substitute service B (substitution effect). The total effect is equal to the sum of the two effects, as reflected by the Slutsky equation (Varian 2009). Both effects lead to more consumption of service A, and thus also of the resource that had originally gained efficiency, triggered these very effects.

2.1.4 Time rebound

(Binswanger 2001) introduces what he calls the time rebound, which stems from time saving technological progress. He argues that a decline in the time needed to acquire a service (such as travel a certain distance) reduces the costs associated with time. This rests on the economic model that someone's time can be monetarily represented by the foregone earnings one could have achieved in that time. Economists say in this context that "wages are the opportunity costs (i.e., the not taken alternative, hence 'opportunity costs') of time."

A time efficiency measure, thus, leads to a time saving, which can be monetarily expressed as its opportunity costs, i.e., the earnings that could theoretically be achieved in the time that was saved. For the amount that the costs of the time-saving measure keep being cheaper that the costs of saved time, the former will be substituted for the latter. Time-saving technologies, however, are often quite energy intensive, such as the technologies enabling fast means of travel or transportation. The energy thus spent to save time, is what Binswanger calls "time rebound." Unfortunately (in this context), however, digitalisation – including its two flavours discussed in this study, e-commerce and teleworking – makes life much more time-efficient.

2.2 E-commerce / online shopping

Shopping from home is not a phenomenon new to the digital age. Instead, it continues a century-long tradition of mail ordering via catalogues. What began with small newspaper adverts, increasingly grew into standalone catalogues of the rising department stores throughout the 19th century, and was a firmly established – and increasingly democratised – shopping method by the end of the 19th century (Platman 2020). Some argue that sporadically, catalogues appeared more than a century earlier, e.g. in 1767 with a catalogue of seed prices published by an English gardener, or even as early as 1498, when a Venetian scholar founded an early printing company, and published a catalogue listing the books printed by his company (Adelina 2019).

The first digital instantiation of "shopping from home" was not based on the Internet and the WWW protocol, which made the Internet so popular starting with 1992. While some special-purpose shopping systems – usually not open to the general public, such as airline reservation systems for travel agencies – predated it, the first general-purpose and widely used online shopping instantiation arguably appeared in the beginning of the 1980s in France, as one of the services enabled by the "Minitel" system.

Minitel were simple computer terminals distributed for free, and in the millions, to French households and businesses by the former French telecommunication monopolists, France Telecom (Mailland 2017). With an integrated modem and tightly connected to the telephone lines, Minitel could connect to central services, many of which – including online shops – were precursors of the WWW-based services: "With free terminals at home or work, people in France could connect to more than 25,000 online services long before the world wide web had even been invented. Many services of the dotcom-and-app eras had precursors in 1980s France. With a Minitel, one could read the news, engage in multi-player interactive gaming, grocery shop for same-day delivery, submit natural language requests like "reserve theater tickets in Paris," purchase said tickets using a credit card, remotely control thermostats and other home appliances, manage a bank account, chat, and date" (Mailland 2017).

Starting in the second part of the 1990s, various types of online stores started to appear. 1995 is a pivotal year, which saw the emergence of both Amazon (as an online bookstore in the beginning) and of the online auction house eBay – both still among the largest B2C and C2C online shopping businesses, respectively. Global online sales are steadily growing, having reached over 5 trillion USD in

2021 and being projected to reach over 8 trillion USD by 2026 (Statista 2022b), which will by then represent a share of almost 25% of global trade (Statista 2022a). While North America and Europe dominated worldwide online sales until the early 2010s, over the past decade, the balance has massively shifted towards the Asia-Pacific region, which now accounts for roughly two thirds of the global market share (Statista 2023).

Current world GDP is around 100 trillion USD (World Bank 2023). Online sales are thus responsible for about 5% of the world GDP, with a fast-growing share. Additionally, a majority of humankind's emissions are embodied in trade – international trade alone was responsible for an estimated 33.6 Gt CO_2eq in 2018 (OECD.Stat 2022), which represented slightly more than 66% of the total 48.9 Gt CO_2eq emissions that year (WRI 2021). The environmental impact of trade is thus crucial, and online shopping already represents a substantial share of trade, and one that is growing at a rapid pace. Even small changes in the patterns of online shopping can thus induce quite substantial consequences for the global energy consumption and GHG emissions. Digitalisation enabled online shopping in the first place and its new and evolving possibilities continue profoundly influencing the field.

2.3 Teleworking

As with e-commerce earlier, teleworking is also not a new phenomenon. While not reaching as far back as ordering from home via catalogues, it certainly predates the nowadays dominating Internet application, the World Wide Web (WWW), which prompted the fast widespread of Internet connectivity into offices and homes more than three decades ago. Long before this WWW-triggered triumph of the Internet, although not widespread, teleworking was already being actively used and had been conceptualised as a term. It built on the technology available at the time; that is, mainly phones and adjacent means such as fax machines. Back in the day, it was thus of course much less interactive than today.

2.3.1 Definitions, narratives, and a little historic overview

The formal definition for both "telecommuting" and "teleworking" was put forward in the 1970s by the pioneering work of Jack Nilles. According to him, *telecommuting* is "the partial or total substitution of telecommunications, with or without the assistance of computers, for the twice-daily commute to work" (Nilles 1988). It is, at the same time, a subset of *teleworking*, which "includes all work-related substitutions of telecommunications and related information technologies for travel (from substitution of telephone calls or electronic mail for personal visits to the use of full-motion videoconferencing as a substitute for executive travel)" (Nilles 1988). Additionally to telecommuting, teleworking might thus also include virtual business meetings (Borggren et al. 2013) or conferences that have been partly or entirely virtualised (Coroama, Hilty, and Birtel 2012). In this study, while referring to the broader sense of teleworking, most of its analysed instances are in fact the telecommuting; while acknowledging the distinction, we will thus largely use the two terms interchangeably.

The electronic substitute for travel is also known under various names: It may, for example, be referred to as 'virtual work/meeting', 'distance work/meeting' or 'mediated work/meeting' (Borggren et al. 2013). This study mostly uses the term 'telework', with occasional occurrence of other, related terms, if a specific particularity needs to be highlighted.

2.3.2 Information and communication technologies as enabler for telework

The ability to telework is essentially dependent on the availability of suitable information and communication technologies (ICT). As early as 1975, it has been recognised that developments in "telecommunications and information-processing technologies are providing the catalyst" for telework (and in particular telecommute) to strive (Nilles 1975). Later, the same author would argue that "of primary importance to teleworking are developments in microcomputers and digital telecommunications. The rate of these developments […] is likely to continue into at least the early 21st century. The primary implication of this is that substantial information processing and transmission power (including transmission of high resolution images) is available, or soon will be, to anyone within reach of a telephone line" (Nilles 1991).

2.3.3 Environmental concerns as reasons for telework

From the beginning, environmental and societal issues related to road traffic have been among the chief reasons behind early experiments with teleworking. According to its pioneer, telecommuting could bring about "new urban and organizational forms and which mitigate transportation-related problems" (Nilles 1975), such as traffic congestion, energy consumption, emissions and air pollution (Nilles 1991).

3 Methodology

3.1 Systematic literature review

We conducted literature searches in common databases (Scopus[2], ScienceDirect[3], Google Scholar), in order to find relevant articles on the following topics:

- Energy savings and GHG reductions brought about by online shopping and telework (RQ1, RQ2),
- Rebound effects of online shopping and telework (RQ3, RQ4),
- Impact of pandemic measures - and then their relaxation - on online shopping and teleworking and therefore on the energy and GHG of shopping, commuting to work and business meetings (RQ5, RQ6).

The following database queries were carried out (here using the Scopus database as an example; the syntax varies between the individual databases):

RQ1, RQ2

- Search 1.1: TITLE-ABS-KEY ((“online shop*” OR “ecommerce” OR “e-commerce”) AND (“energy efficien*” OR “GHG*” OR “greenhouse gas” OR “greenhouse-gas”))
- Search 2.1: TITLE-ABS-KEY ((telework* OR homework* OR telecommut*) AND (“energy efficien*” OR “GHG*” OR “greenhouse gas” OR “greenhouse-gas”))

RQ3, RQ4

- Search 1.2: TITLE-ABS-KEY ((“online shop*” OR “ecommerce” OR “e-commerce”) AND (“rebound effect*” OR “jevons paradox” OR “khazzoom-brookes postulate”))
- Search 2.2: TITLE-ABS-KEY ((telework* OR homework* OR telecommut*) AND (“rebound effect*” OR “jevons paradox” OR “khazzoom-brookes postulate”))

RQ5, RQ6

- Search 1.3: TITLE-ABS-KEY ((“online shop*” OR “ecommerce” OR “e-commerce”) AND (“energy efficien*” OR “GHG*” OR “greenhouse gas” OR “greenhouse-gas” OR “rebound effect*” OR “jevons paradox” OR “khazzoom-brookes postulate”) AND (“sars-cov-2” OR “covid*” OR “pandemic*”))
- Search 1.4: TITLE-ABS-KEY ((“online shop*” OR “ecommerce” OR “e-commerce”) AND (“energy efficien*” OR “environmental impact*” OR “GHG*” OR “greenhouse gas” OR “greenhouse-gas”) AND (“Schweiz” OR “Suisse” OR “Svizzera” OR “Svizra” OR “Swiss” OR “Switzerland”))
- Search 2.3: TITLE-ABS-KEY ((telework* OR homework* OR telecommut*) AND ("energy efficien*" OR "GHG*" OR "greenhouse gas" OR "greenhouse-gas" OR “rebound effect*” OR “jevons paradox” OR “khazzoom-brookes postulate”) AND ("sars-cov-2" OR "covid" OR "pandemic*"))
- Search 2.4: TITLE-ABS-KEY ((telework* OR homework* OR telecommut*) AND ("energy efficien*" OR "GHG*" OR "greenhouse gas" OR "greenhouse-gas" OR “rebound effect*” OR “jevons paradox” OR “khazzoom-brookes postulate”) AND (“Schweiz” OR “Suisse” OR “Svizzera” OR “Svizra” OR “Swiss” OR “Switzerland”))

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[2] See https://www.scopus.com/search/form.uri?display=advanced.
[3] See https://www.sciencedirect.com/search/entry.

The articles thus found (several hundred of them in total) have then been checked for relevance by reading their abstracts. Those classified as immediately relevant were read and served as basis for the intended conceptualisation and knowledge gain. The focus was placed on recent documents and different attributes were noted (for shopping and commuting separately), such as geographical area of study, theoretical/case study, qualitative/quantitative, energy/greenhouse gases, savings/rebound effects.

After filtering the relevant primary results, for each of the papers comprised in this remaining set, what is called “snowballing” has been performed. Snowballing relies on the fact that there is a good chance to find further relevant papers either among the papers cited in a certain paper (called “backward snowballing”) or in newer ones which cite a certain paper (“forward snowballing”). Backward snowballing is always performed by considering all references of a paper, forward snowballing was performed via google scholar.

3.2 Review results

Table 1 and Table 2 below show the numbers of the literature searches 1.1 – 1.4 and 2.1 – 2.4, respectively. The first column in each table shows the search number (the corresponding searches being listed in Section 3.1). The second column shows the number of results retrieved from each search. After reading abstract (sometimes already after seeing the title, while occasionally also reading further parts of the paper), the relevance of the paper was determined. Examples for reasons for deeming papers non-relevant included:

- non-scientific results such as entire conference proceedings or journal editorials, wrongly appearing among the results,
- methodological contributions to other fields such as the audit of building energy efficiency,
- search terms being used with a different semantic (e.g., one paper title reads “On the road to a green economy: How do European Union countries ‘do their homework’?”),
- papers on the introduction of sustainability education in engineering curricula,
- studies of related topics such as virtualised conferences, and
- studies with a different focus, yet a connection to the changed working or shopping patterns during the pandemics, such as the carbon footprint of 5G base station antennas (which were more intensely used due to teleworking), or of building maintenance requests (which decreased due to teleworking).

The remaining number of relevant papers is shown in column 3 of each of the two tables, from which we show in column 4 how many had already been found in previous searches, so the sum is correct. Remaining relevant and new papers (column 3 - column 4, not explicitly shown) constituted the basis for snowballing. The number of further relevant papers found during both backward and forward snowballing are listed in column 5. Column 6 finally shows the total number of papers (column 3 - column 4 + column 5).

As searches 1.3 and 1.4 are special cases of (a combination of) searches 1.1 and 1.2 with additional constraints, their respective results are necessary a subset of the results of searches 1.1 and 1.2 combined. It is thus not surprising that all their relevant results had already been found – we kept the information here nevertheless to convey a feeling for the size of the result space, The same applies to the snowballing results: As all relevant primary search papers had already been found in previous searches, all the relevant snowballing had also already been performed.

Table 1 Number of results for searches 1.1 – 1.4. Search 1.4 yields only one result (Chen and Han 2014), which is a book on the impact of e-commerce logistics in China and only appears at the Swiss-specific search because it was edited in Switzerland. There are thus no relevant primary search results on the environmental impact on e-commerce in Switzerland. The only Switzerland-relevant paper that was found, (Hischier 2018), actually appeared during snowballing of search 1.1. We did not include it there but in the row of search 1.4

(although this is wrong and illogical; when there is no relevant results, there can be no snowballing and thus also no new results at this stage), to highlight that there is one paper with Swiss relevance after all.

Search	#results	of which relevant	- already found	+ snowballing	Total
1.1	218	43	0	41	84
1.2	11	6	5	0	1
1.3	27	12	12	0	0
1.4	1	0	0	1	1
					86

In Table 2 as well, searches 2.3 and 2.4 are special cases of (a combination of) searches 2.1 and 2.2 with additional constraints, so there are unsurprisingly no newly found relevant papers. The information was kept nevertheless to convey a feeling for the size of the result space for each of these searches.

For similar reasons, there should be no new snowballing results either. For Search 2.4, we nevertheless placed here the two Switzerland-relevant papers found during snowballing, although they had been found while snowballing after search 2.2 and would actually belong in that row. The reason for this small inaccuracy is to highlight in the table the number of papers with Swiss relevance: 3 primary search papers + 2 snowballed = 5 papers.

The content of the rich literature found through primary search, filtering, and snowballing is discussed in Sections 0 and 5 below.

Table 2 Numbers for searches 2.1 – 2.4, the filtering of results and snowballing. With 20 relevant papers out of 26 search results, search 2.2 has proven particularly (and atypically) accurate.

Search	#results	of which relevant	- already found	+ snowballing	Total
2.1	157	**35**	0	44	79
2.2	26	20	10	0	10
2.3	29	12	12	0	0
2.4	3	3	3	2	2
					91

4 The rebound effect of e-commerce / online shopping

Comparisons between traditional shopping and online shopping in terms of their energy consumption and GHG emissions have been around since the early 2000s, soon after the WWW had reached the general public and online shops emerged. Early analysed use cases include, for example, groceries in Finland (Siikavirta et al. 2002), books in Japan (E. Williams and Tagami 2002) or DVD rental (in store vs. via postal mail) in the US (Sivaraman et al. 2007). Most of these early assessments are outdated, treating cases that partially do not longer exist (e.g., DVD rental either in-store or via postal mail has been entirely replaced by video streaming). But they have already shown that for the comparison of traditional shopping with its online counterpart, system boundaries are complex, the results very sensitive to various contextual parameters (and sometimes counterintuitive), and general conclusions thus difficult to draw.

The section starts by introducing a simple model of e-commerce. Section 0 then progressively grows the complexity of the model and lists typical sources of rebound effects for e-commerce. Section 4.3 then analyses each of these rebound effects both qualitatively and, to the extent possible, also quantitatively. Section 4.4 brings together all quantifications, discussing them jointly and commenting on the main insights gathered from the analysis and the challenge of quantifying the rebound effects. Finally, Section 4.5 presents subtler, more intricate and difficult to assess (even qualitatively, and more so quantitatively) rebound effects of e-commerce, which have so far received little attention in the literature and clearly deserve more of it.

4.1 The B2C online shopping process for physical goods

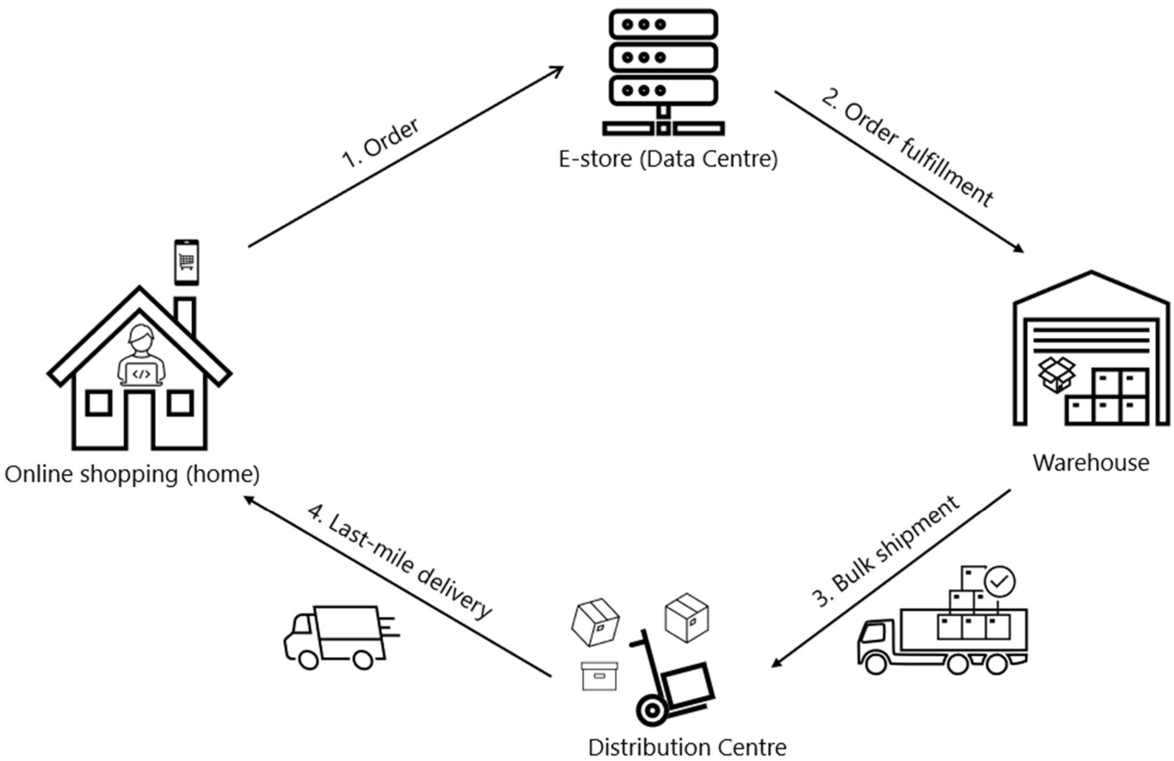

Figure 1 Simplified representation of the B2C online shopping process.

Figure 1 schematically presents an online shopping process: In a first step, the customer places the order from their home, office, etc. The order is transmitted to the E-store, typically located in a data centre, which can be either internal to the company or an externalised cloud DC. The E-store performs various tasks (such as clearing the payment, stock update on the website, etc), among which it also sends the order fulfilment information to the physical warehouse (step 2). In step 3, the warehouse will bulk ship the desired items – typically together with items from various other orders – to the local distribution centre, from where in the last step the items will reach the customer through the last-mile delivery.

4.2 Rebound effects of B2C e-commerce

As compared to traditional in-store shopping, the B2C shopping process introduces some new processes, which are also new sources of energy consumption and GHG emissions. They are represented in blue in Figure 2: the IT needed both at home (such as computer and router for the Internet connectivity) and in the infrastructure (both the network carrying the data and the DC where the E-store is located) as well as the last-mile delivery, which does not exist in traditional shopping.

The energy and GHG sources marked in green, on the other hand, exist in the traditional shopping counterfactual as well, albeit possibly in a different form. Warehouses and bulk transportation, for example, exist in both models. And while the distribution centres of the e-commerce model substitute the physical stores of traditional shopping, but both require lighting as well as heating, ventilation, and air conditioning (HVAC). This is why these sources of energy and GHGs are marked in green in Figure 2, to show that they are not newly introduced but merely modified by e-commerce.

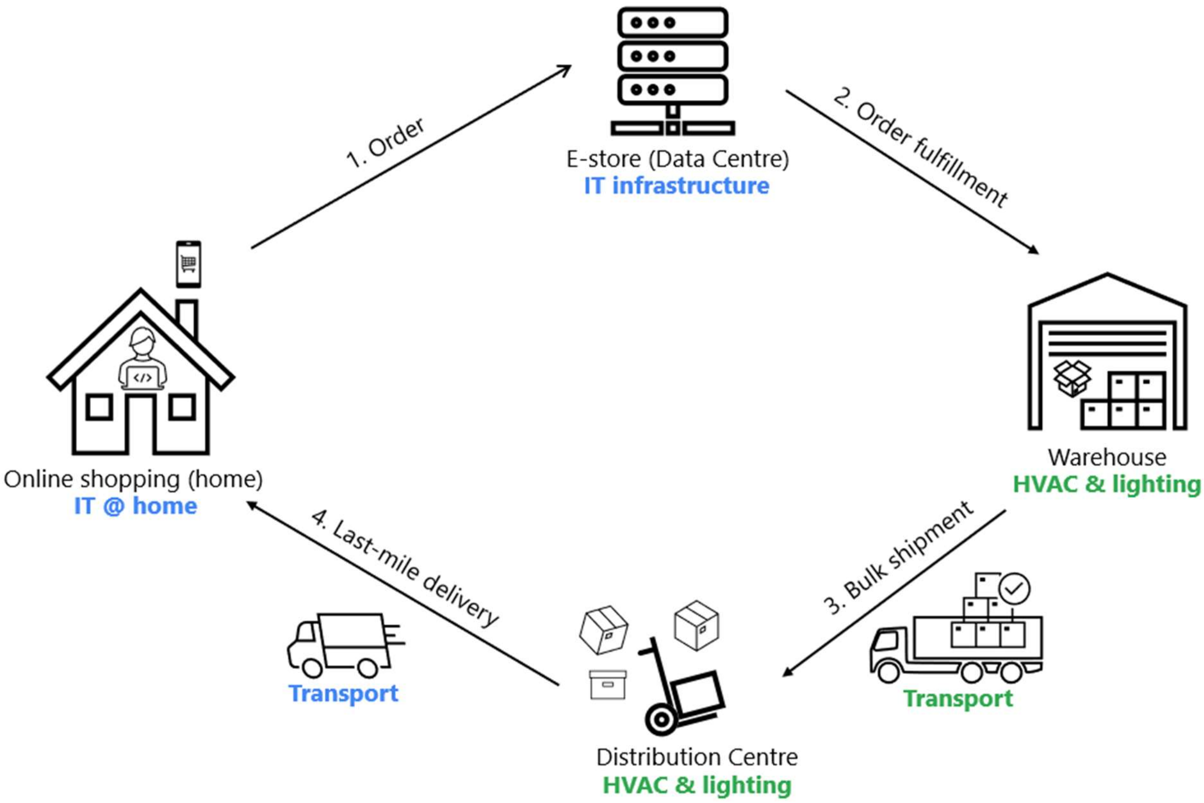

Figure 2 New sources of energy consumption and GHG emissions in the e-commerce scenario (in blue), and sources of energy consumption and GHG emissions that also exist in the traditional shopping process and are merely modified by e-commerce (in green). IT stands for “information technology”, HVAC for “heating, ventilation and air conditioning”.

While similar, such processes might of course induce different energy requirements and GHG emissions in the two shopping paradigms. Comparative assessments of the environmental impact of traditional and online shopping thus typically consider them within the system boundaries, taking their respective impacts into account for the overall result (E. Williams and Tagami 2002; Zhang and Zhang 2013).

For two reasons, however, the current study does not take them into account: First, due to its different aim. This study does not perform a comparative life-cycle assessment (LCA), but explores qualitatively and quantitatively the rebound effects of e-commerce. These processes that merely modify (and often are quite similar to) the processes of traditional shopping are not conceptually new and do not represent rebound effects. Secondly, even for comparative LCAs it only makes sense to compare the energy consumption of the respective warehouses, for example, for a specific case study and not in general. For both traditional and online shopping, the exact instantiation of these processes depends on various factors such as the type of products being purchased, the geography (urban vs. rural), the logistics of sellers and distributers, and many more. This leads to such a large variation between the individual instantiations within either traditional or online shopping, that it makes generic comparisons between the two futile.

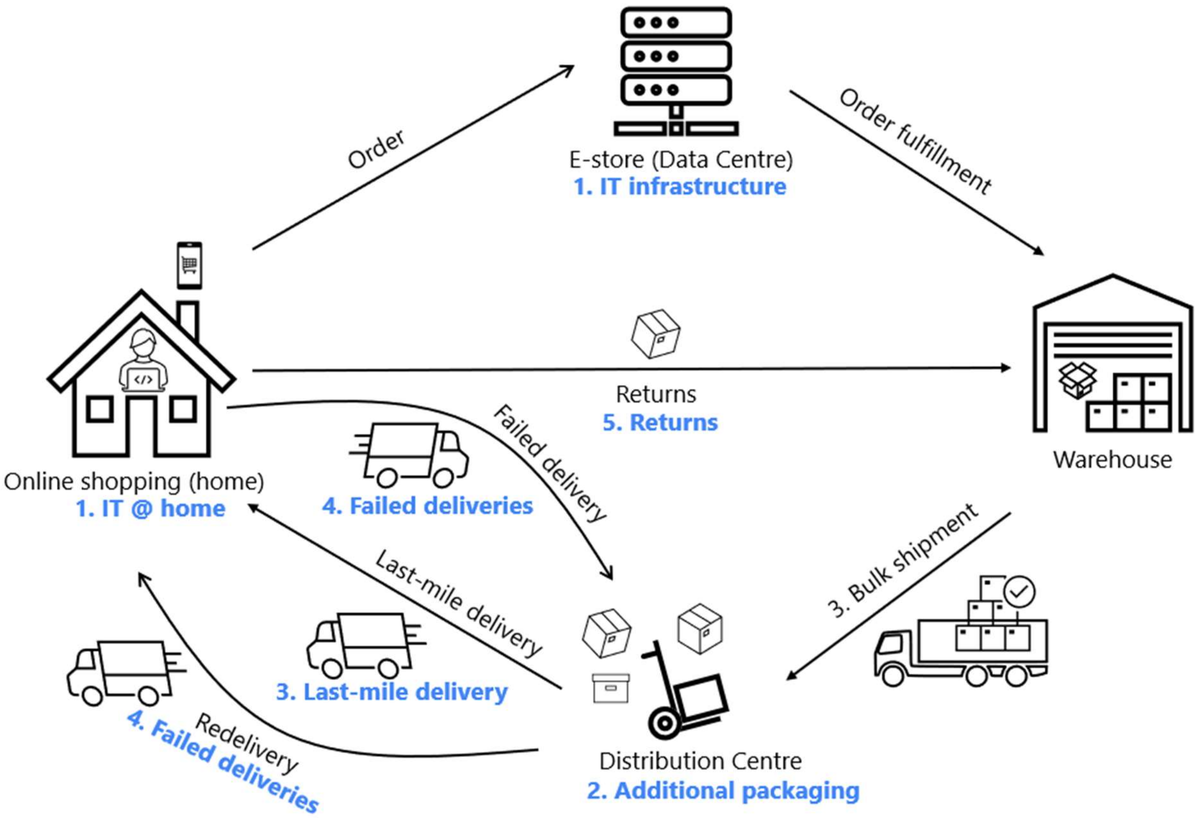

Figure 3 A more comprehensive figure of the online shopping and delivery process, which includes the additional packaging often used by last-mile deliverers, the additional runs triggered by failed deliveries, and the product returns, which exist in traditional shopping as well but are much more widespread for e-commerce.

While Figure 2 sketches some straightforward sources of rebound prompted by e-commerce, more such sources exist. They are perhaps a little more subtle but no less typical. Figure 3 presents them. Compared to Figure 2, in the new figure the sources of impact that were merely modified by e-commerce (formerly in green) have been removed. However, 3 new sources of rebound that are typical for e-commerce have been added: the additional packaging often used by deliverers for the last-mile delivery, the failed deliveries (and corresponding redeliveries) resulting in additional runs, and the returns which also lead to additional trips (and typically longer ones all the way to the originating warehouse, not merely to the local distribution centre). While last-mile additional packaging and failed deliveries are typical to e-commerce, product returns exist in traditional shopping as well. As will be argued in Section 4.3.4 below, however, they are so much more common for e-commerce that they can be regarded as specific as well.

Together with the sources that had already been introduced in Figure 2, this yields a comprehensive list of 5 sources for rebound effects for e-commerce, as shown in Figure 3:

1. IT (both at home and infrastructure),
2. additional packaging,
3. last-mile delivery,
4. failed deliveries (under which we also group the required redeliveries), and
5. returns.

They are discussed in detail in the next section.

4.3 Qualitative and quantitative analysis of the rebound effects

This section discusses in turn each of the rebound effects of e-commerce. It analyses them both from a qualitative and a quantitative perspective (the latter to the extent possible and with various involved uncertainties).

4.3.1 Required information technology (IT)

Although a source of rebound, with few notable exceptions such as (Chiara Siragusa and Tumino 2022), the literature on the environmental impacts of online shopping largely ignores the IT needs induced by e-commerce. This might be either because the research in this area stems from environmental and other related sciences and the authors might have been unaware of the IT requirements, or because there is already an understanding that these impacts are relatively minor as compared to the induced road traffic and other rebound effects. Nevertheless, as the energy intensity of the IT infrastructure is relatively well understood, the IT-related energy consumption and GHG emissions of an online shopping process are also fairly easy to derive. We discuss them here for completeness.

A self-experiment of buying a book on the site of the leading online retailer amazon showed that the author needed about 5:48 minutes to navigate to the page, read a couple of reviews, reach the decision and perform the purchase. This correlates quite well with data from a consultancy that analyses web behaviour and which argues that the average visit duration on amazon's site is 7:11 minutes per customer.[4] A simple tool integrated into the browser was used to measure the data sent across the network; as Figure 4 shows, it was 17.8 megabytes (MB).

Even if allowing for much more laborious online shopping processes (e.g. for a much more expensive or customisable product such as a laptop or for a large monthly online grocery shopping) that would take one hour to complete by simple extrapolation we would arrive to 180 MB of data sent. Under the assumption that the same amount of data also needs to be stored in the data centre (which is simplifying and conservative, as it excludes traffic in the other direction and that the same stored data being sent multiple times), we can thus estimate the following energy for an online shopping process as:

- Network energy: The network energy intensity is currently around 7 Wh/GB (Coroamă 2021b). Hence, to send 0.18 GB across the network, around 0.18 GB * 7 Wh/GB = 1.26 Wh are needed.
- DC storage energy: As computed in (Coroamă 2021a) based on primary data from (Shehabi et al. 2016), the energy intensity of data storage in DCs lies between 5.7-10.5 kWh/TB annually.

[4] See https://www.similarweb.com/website/amazon.com/#overview.

For one hour, which is 1/8760 of a year, this reduces to 0.5 – 1 Wh/TB, and correspondingly 0.5-1 mWh/GB and hour. Mili-Watthours do not need to be taken into consideration, so the storage energy can be ignored.

- Device energy: The energy consumption of the device depends largely on the type of device: when in use, a smartphone requires 2-4 W of power, while a laptop is typically required 10-15W. An external monitor might require another 20-30W of power (the typical power consumption of 27 inch monitors today), and to 60-70W if two such monitors are connected or a large curved one.

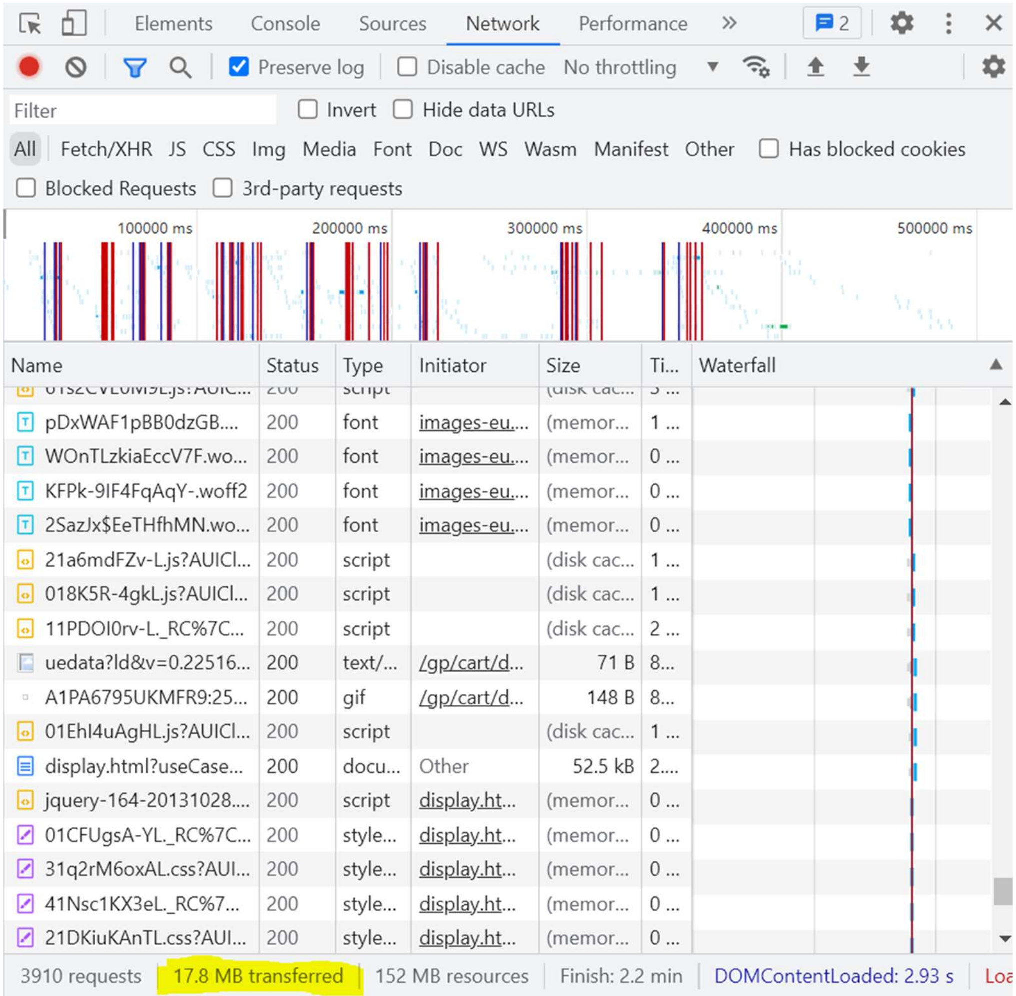

Figure 4 A tool built into the browser (Google Chrome) reveals the amount of data sent across the network in the process of buying one book on amazon.de.

For a one-hour long, and thus very conservatively assumed online shopping instance, the DC would consume negligible Milli-Watthours, the network about one Watthour, while the devices have a large span of roughly 2 – 85 Wh, and thus dominate the overall energy consumption. Taking today's global average carbon intensity of electricity of about 400 g CO_2/kWh, this yields GHG emissions of between

- 1 – 35 g CO_2 per hour-long instance of online shopping.

A more focused online shopping session such as my 6-minute session for the book would correspondingly be responsible for

- 0.1 – 3.5 g CO_2.,

depending mainly on the end device used in the process.

4.3.2 (Additional) Packaging

Additional packaging required for home deliveries can be an important source of rebound effects. From 17 studies reviewed in (Pålsson, Pettersson, and Winslott Hiselius 2017), 16 have considered packaging within their system boundaries and the results are unequivocal: While 14 studies conclude that the footprint of packaging is larger for e-commerce than traditional shopping, only 2 come to the contrary conclusion.

Packaging can be a substantial, even a dominating factor for an e-commerce delivery's overall footprint particularly for relatively small items individually wrapped in an extra package for e-commerce. When comparing online versus traditional book sales in Japan, for example, it is the additional packaging used for books that tilts the balance to the detriment of online shopping in all three scenarios (E. Williams and Tagami 2002). Packaging was also responsible for the opposite conclusion in (Sivaraman et al. 2007), which compared traditional DVD rental in one branch of a large chain (i.e., Blockbuster) with online renting the same amount of DVDs, which were then delivered via postal mail by the then-largest DVD rental chain in the US (i.e., Netflix). Because in this special case, online rental required less packaging than traditional rental (DVDs were shipped in paper envelopes rather than the plastic sleeves used by physical rental stores), this made the difference, yielding online rental less impactful than its physical counterpart. In fact, this study by (Sivaraman et al. 2007) represents one of the two out of 16 examples in (Pålsson, Pettersson, and Winslott Hiselius 2017) in which packaging was worse for in-store shopping than for e-commerce. Finally, in one extreme case (books packaged individually for home deliveries), packaging was computed to represent 98% of the overall GHG emissions of the e-commerce case (Pålsson, Pettersson, and Winslott Hiselius 2017).

While for larger goods packaging is relatively less important, it often remains a substantial contributor to the overall impact of e-commerce. The GHG impact of cardboard often used in the extra packaging of e-commerce is about 1.1 kgCO_2/kg cardboard (Eriksson et al. 2010), while that of plastic bags is about 1.5 kgCO_2/kg plastic (Environment Agency 2011). And across all of e-commerce, it remains intensively used: In 2016, the US alone produced 35 million tonnes of cardboard, a substantial part of which was used in e-commerce, while only the main recycler of San Francisco receives 100 tonnes of cardboard daily (Richtel 2016). A recent study in Korea found that for the same amount of spending, e-commerce generates 4.8 times more packaging waste than traditional shopping (Y. Kim, Kang, and Chun 2022). According to the authors, for every hundred dollars spent, e-commerce generated 3.4 kg of additional waste as compared to traditional shopping, consisting mainly of cardboard boxes, plastic bags, tape, and buffer materials such as polystyrene.

Per e-commerce order, the literature estimates the climate impact of additional packaging as follows, as also shown in Figure 5. While the first two studies refer to fast-moving consumer goods (FMCGs) a term that comprises a variety of products such as food and drinks, confections personal care and homecare products[5], the latter refer specifically to clothing.

- 358 – 441 g CO_2 (Van Loon et al. 2015),
- 450 g CO_2 – Zalando in 2016, as cited by (Hischier 2018),
- 154 g CO_2 in the scenario of (Hischier 2018),
- 15 – 450 g CO_2 (Shahmohammadi et al. 2020).

[5] See https://www.investopedia.com/terms/f/fastmoving-consumer-goods-fmcg.asp.

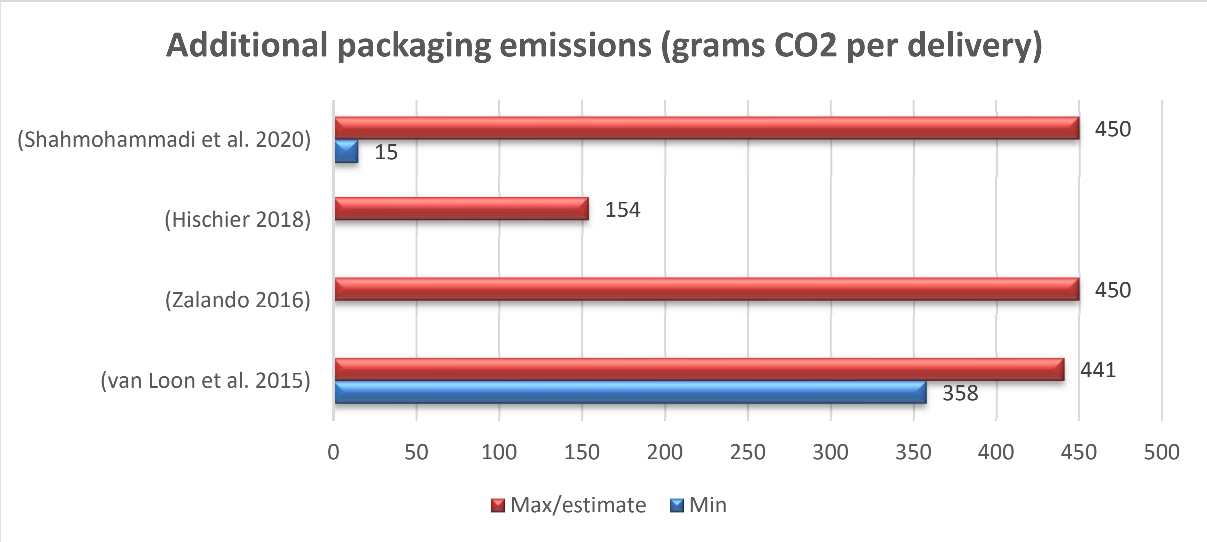

Figure 5 Per delivery GHG emissions generated by the additional packaging often deployed in e-commerce. The lower two references indicate ranges, the upper two single values. While the upper two references refer to clothing specifically, the lower two analyse FMGCs more generally.

Some of the sources indicate the impact per item delivered, while others put forward the impact per delivery. To make the results comparable, we transformed them all into values per delivery as follows: The scenario in (Hischier 2018) assumes a cardboard of 140 grams per delivery; considering the emission factor of 1.1 kg CO_2/kg cardboard from (Eriksson et al. 2010) yields 154 g CO_2 per delivery. The same (Hischier 2018) cites Zalando data for 2016, in which the company puts forward 2.8 kg CO_2 on average per parcel, of which 16% due to the additional last-mile packaging; this yields 450 g CO_2. (Van Loon et al. 2015; Shahmohammadi et al. 2020) were both transformed from per-item values to per-delivery by multiplying their per-item values with the average number of items per delivery: 5 items per delivery for (Shahmohammadi et al. 2020) and 45, 55, and 2 items per delivery for scenarios B&C1, PP1, and PP2 of (Van Loon et al. 2015), respectively.

4.3.3 Last-mile delivery

As stated in the beginning of this section, last-mile delivery is characteristic for e-commerce and does not exist in traditional shopping. While various novel last-mile delivery paradigms emerged in recent years (and will be discussed in Section 6.2.5. below), traditionally it has been performed by delivery vans. As one such van substitutes several individual trips to the store, the naïve expectation might be that online ordering and bulk delivery to many customers to be substantially more energy efficient and less GHG intensive than the traditional alternative.

Whether this holds true or not, however, depends on a variety of factors, among which the type of goods being purchased, the geography (urban vs. suburban vs. rural), and in particular the local transportation infrastructure and culture. An early study on book deliveries in Japan, for example, was among the first to raise doubts. In urban environments in particular, where most customer trips are performed by very energy-efficient public transportation, the opposite is actually the case: Because in the online shopping alternative, the books were shipped via less energy-efficient vans, the average energy spent to ship a book was substantially higher than the cumulated trips of customers to the bookstore (E. Williams and Tagami 2002). The authors only compare the energy consumption of the two alternatives (0.16 vs 0.04 MJ per order, fourfold larger for e-commerce) and do not comment on the GHG footprint. But as the vans at the time were running exclusively on fossil fuels (i.e., diesel), while part of the public transportation was likely to be electric, the discrepancy for GHGs was presumably even larger. In a different geographic context, in particular for a country where in urban environments many trips are performed via private cars as well, the result might have been quite different.

But even for Japan, in suburban or rural environments, many more shopping trips are performed by private cars, and are also longer on average. It would thus be reasonable to expect that in these geographic contexts at least, the bulk delivery via a van to be significantly more energy-efficient than numerous individual trips to the shops, a substantial share of which in cars. And so it would, were the reality as simple that each online shopping instances replaces one trip to the store. In reality, however, online shopping is *fragmented*, i.e., often several online shopping instances may replace one trip to the shops, and they may also not always entirely replace it – often, online shopping is additional to a visit to the physical shop, which might still occur (Buldeo Rai, Touami, and Dablanc 2023). At the same time, rides are often *multipurpose* – i.e., one does not drive only for shopping, but combines shopping, with travel to work, taking the kids to and from school, stopping by the gym, eating out, going to the movies, and so on. The environmental impact of each trip thus needs to be allocated to the various purposes of each trip – this allocation (ISO 2006) being a known topic in the field of life-cycle assessment (LCA).

Eliminating physical shopping will thus frequently not eliminate a trip entirely, but just (and perhaps only slightly) reduce its length by the detour to the shops. Taking these complexities into account, as also shown in Figure 6, (E. Williams and Tagami 2002) conclude that last-mile delivery is always worse than self-pickup at stores irrespective of the geography, just to different extents. In urban environments, where public transportation dominates among individual trips, delivery performs much worse (by a factor of 4). In rural areas, delivery addresses are sparse and far between, so shipping is not too efficient either. Individual trips, on the other hand, are overwhelmingly multipurpose, only a small part of each being allocated to the bookstore shopping of the study; shipping is thus worse by a factor of 2.3. Overall, for this study, shipping came closest (by a factor of 1.85) to individual, multipurpose trips only in suburban environments, where cars account for a substantial share of individual trips, while deliveries are efficient due to the proximity of destinations.

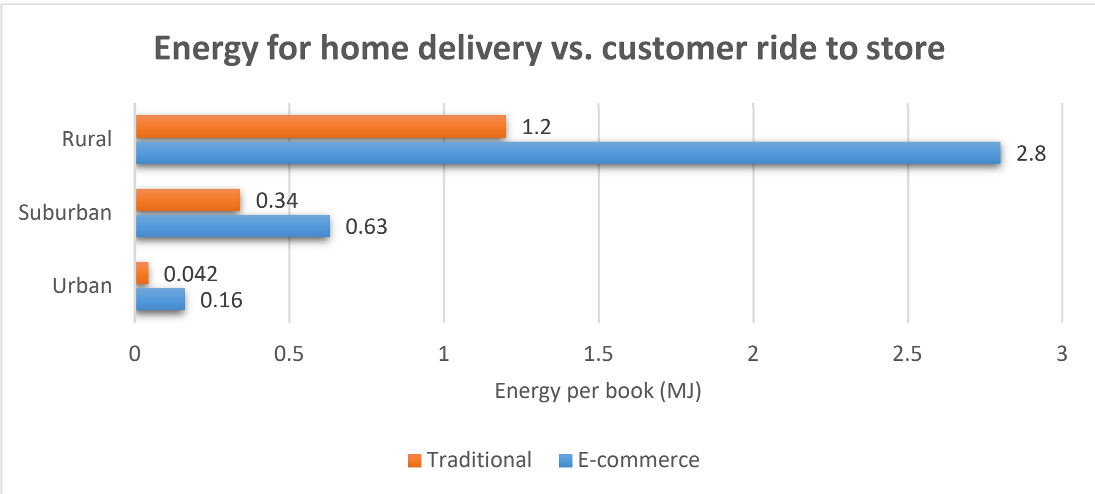

Figure 6 Per-book energy for shipping versus energy for collection by the customer in urban, suburban, and rural areas of Japan. While the further apart the geography, the larger the impact, in all three geographies, e-commerce shipping is worse than traditional shopping store collection, by factors of 4, 1.85, and 2.3, respectively. Redrawn after (E. Williams and Tagami 2002)

The study on book sales in Japan (E. Williams and Tagami 2002), while early, is thus a good illustration of the context-dependence as well as the complexity of system boundaries for comparisons between online and traditional shopping. As not all the literature considers the same system boundaries or takes into account all of these phenomena, and due to all the other differences among products, countries of assessment, local infrastructure and transportation culture, and so on, the results in the literature unsurprisingly show quite some spread, as shown in Figure 7:

- 142 g CO_2 (Zhang and Zhang 2013),
- 503 – 1797 g CO_2 (Van Loon et al. 2015),
- 150 – 2150 g CO_2 (Shahmohammadi et al. 2020), and
- 3760 – 4640 g CO_2 (Kemp et al. 2022) – human delivery ICE vehicles from Figure 3.

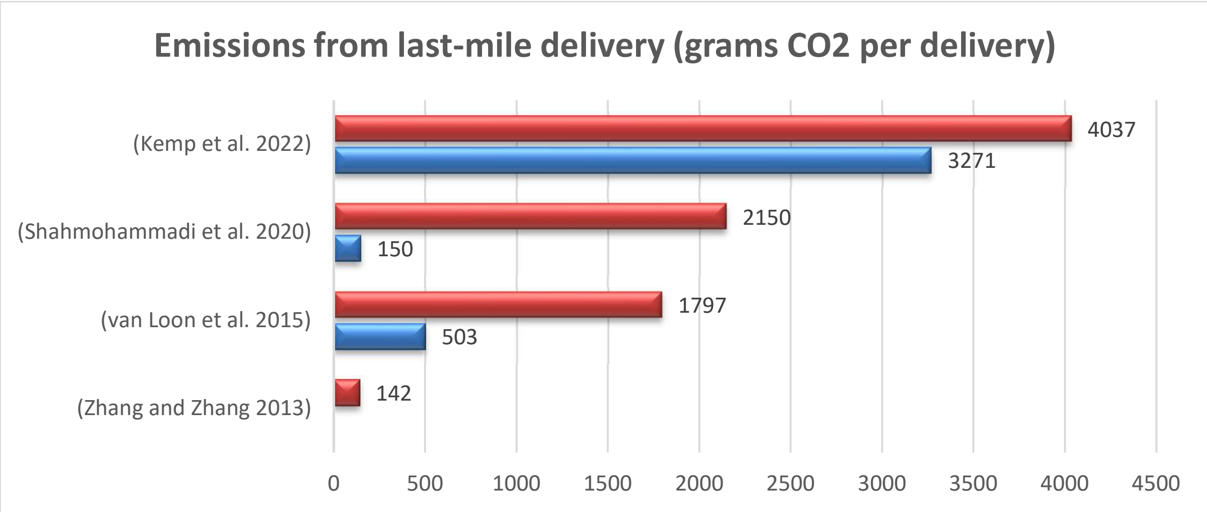

Figure 7 Per delivery GHG emissions generated by unmitigated last-mile delivery (i.e., via diesel van without customer self-collection points), for the following products and geographies: single book in urban China (Zhang and Zhang 2013), FMGC in the UK (Van Loon et al. 2015; Shahmohammadi et al. 2020), and a basket of 36 grocery items in the US (Kemp et al. 2022).

As before, to make the results comparable, we transformed them all into values per delivery as follows: (Zhang and Zhang 2013), which looks at one-item book deliveries, was left untouched. (Van Loon et al. 2015; Shahmohammadi et al. 2020) were both transformed from per-item values to per-delivery as described in Section 4.3.2 above. (Kemp et al. 2022) already yield the result for a 36-item grocery basket; however, they argue that 13% of the impact is due to the 14% failed deliveries (and corresponding redeliveries). As this study considers the original last-mile delivery separately from the failed deliveries and redeliveries, we allocated 87% of the impact to last-mile deliveries, and 13% to the failed deliveries, as also described in Section 4.3.4 below. The remaining discrepancies are most likely explained by both the goods under survey – grocery items in (Kemp et al. 2022) versus a single book in (Zhang and Zhang 2013) and FMCGs in the other two studies – as well as the geography – the wide-spread US for (Kemp et al. 2022), China for (Zhang and Zhang 2013) and the UK for (Van Loon et al. 2015; Shahmohammadi et al. 2020), respectively.

4.3.4 Failed deliveries

Another source of rebound effects are failed deliveries (i.e., when recipients are not at home). Failed first delivery rates can be as low as 2% and as high as 30% or even more (Edwards, McKinnon, and Cullinane 2010). They imply either at least one later trip, which can be a redelivery to the same place, a redelivery to another point (such as a pickup point) or by the customer to a pickup location (Buldeo Rai, Touami, and Dablanc 2023).

As will be discussed in Section 6.2.6 below, from these options, redelivery to a self-collection point where the customers later need to pick up their parcels individually is likely to incur the least additional costs, as it only induces one additional trip of all undelivered items to the pickup point. Delivery failure is a risk that only applies to home deliveries and not for self-collection (Zhao et al. 2019).

Despite their importance, a large part of the literature does not seem to take failed deliveries into account, although it is not always clear whether they might have been devised as part of the last-mile delivery, as in (Kemp et al. 2022). When explicitly addressed, some early studies suggested that failed deliveries (in particular of groceries) might represent the dominating share within overall last-mile delivery, as much as 50% (Kämäräinen, Saranen, and Holmström 2001) or even 60% (Punakivi, Yrjölä, and Holmström 2001). As Figure 8 shows, however, later research agrees that while still important, failed deliveries (and the corresponding redeliveries) are less important than the original last-mile delivery. More specifically, more recent research estimates the GHG impact of failed deliveries as follows:

- 31 (at 12% failure rate) – 113 (at 25% failure rate) g CO_2 (Edwards, McKinnon, and Cullinane 2010),
- 164 g CO_2 (Nabot and Firas 2016) at a 30% failed delivery rate,
- 124 – 178 g CO_2 (Van Loon et al. 2015) for a 40% rate of failure,
- 489 – 603 g CO_2 (Kemp et al. 2022) despite a relatively low failed delivery rate of only 14%.

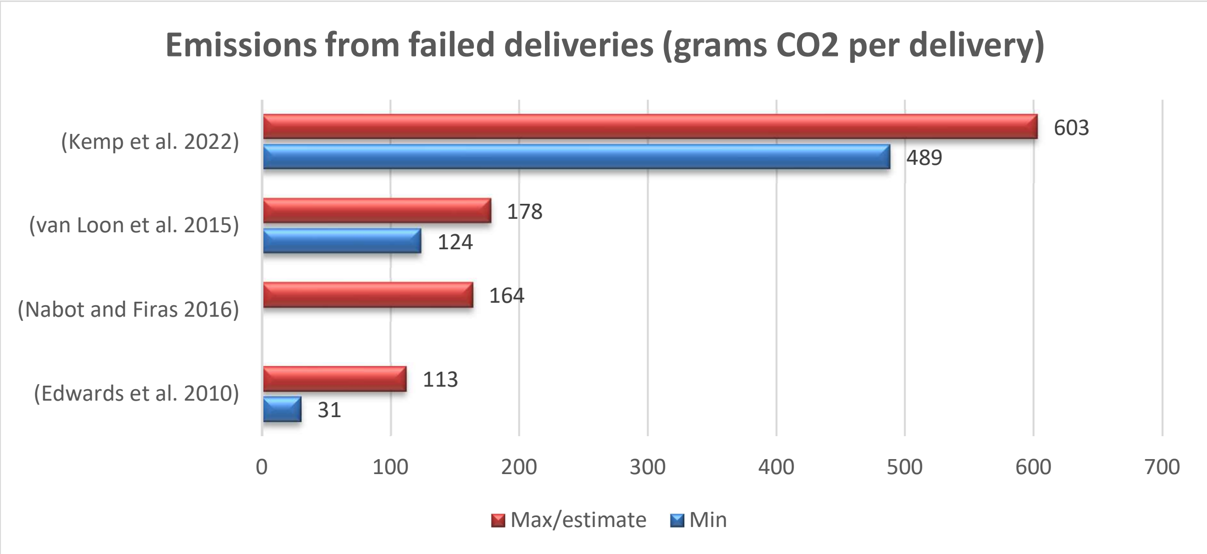

Figure 8 Per delivery GHG emissions generated by failed deliveries and corresponding redeliveries, for the following products and geographies: varied / unspecified types of products in the UK and Jordan, respectively (Edwards, McKinnon, and Cullinane 2010; Nabot and Firas 2016), FMGCs in the UK (Van Loon et al. 2015), and groceries in the US (Kemp et al. 2022). Assumed failed delivery rates were: 12-25% (Edwards, McKinnon, and Cullinane 2010), 30% (Nabot and Firas 2016), 40% (Van Loon et al. 2015), and 14% (Kemp et al. 2022).

As stated earlier, some of the results are per-item, other are per-delivery. To harmonise them, we proceeded as follows: we left those untouched that were already per-delivery (Nabot and Firas 2016; Kemp et al. 2022). For the latter, no specific value for the failed deliveries was given; however, the authors stated that 13% of the last-mile delivery impact is due to the 14% failed deliveries, of which half are redelivered. This share of last-mile delivery was thus allocated to failed deliveries. The two studies presenting per-item results were upscaled to an entire delivery, taking their stated average number of items per delivery: 2 for (Van Loon et al. 2015) and 1.4 – 2.5 for (Edwards, McKinnon, and Cullinane 2010). For the latter, we used the lower number to scale the lower end of the per-item result and the higher number to scale the upper end of the per-item result; hence the relatively large bandwidth of the result.

4.3.5 Returns

Returns can be a main source of rebound in shopping. They occur for both traditional and online shopping, but to substantially different extents: A study shows that while typically 6 – 10% of traditionally bought goods are returned, for online shopping this percentage is about three times higher at 25 – 30 % (Edwards, McKinnon, and Cullinane 2010).

For e-commerce, the rate of returns further depends on the type of product being purchased. Due to strict hygiene regulations, it is very low to non-existent for groceries. While for general, small, non-food items it is typically below 25%, for clothing it is as high as 35 – 40 % (Edwards, McKinnon, and Cullinane 2010; Wiese, Toporowski, and Zielke 2012). And the rate of returns represents only a lower boundary for the rate of additional trips: Even for a partial return (i.e., when just one or a few items from an order are returned), this implies an additional trip, either by the deliverer (for return pickup) or the customer (to the store, postal office or alike).

A recent review even works with an assumption of 60% returns for clothing (Buldeo Rai, Touami, and Dablanc 2023). This high return rate, together is its various negative environmental consequences, is why some of the literature sees them as the main source of environmental impact for online shopping (Wiese, Toporowski, and Zielke 2012). As summarised in Figure 9, the studies putting forward GHG numbers for returns are the following:

- 226 – 362 g CO_2 (Edwards, McKinnon, and Cullinane 2010),
- 1030 – 1.526 g CO_2 (Wiese, Toporowski, and Zielke 2012),
- 127 g CO_2 (Van Loon et al. 2015),
- 295 – 1066 g CO_2 (Nabot and Firas 2016).

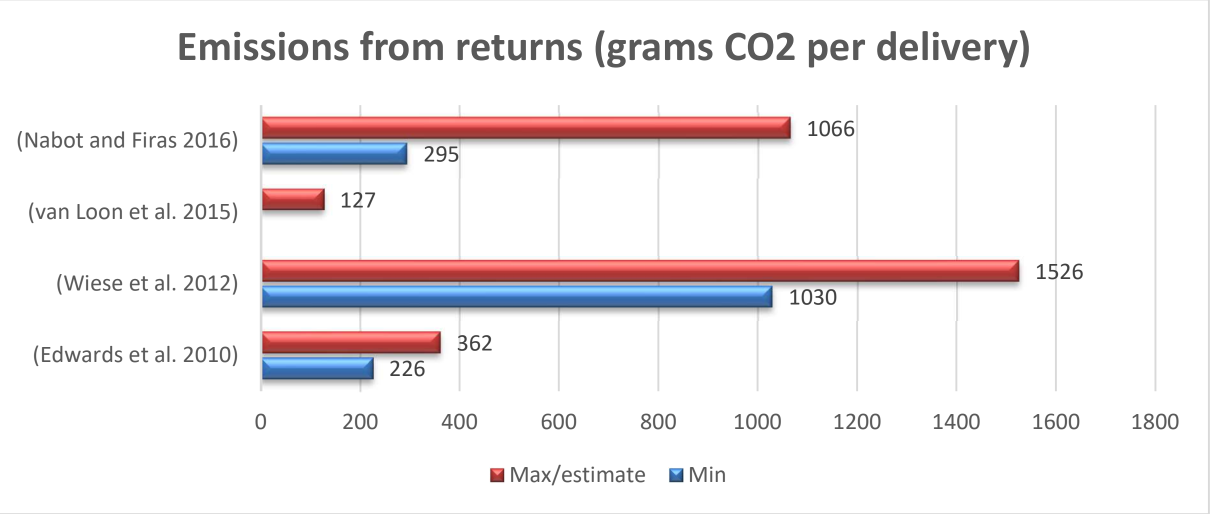

Figure 9 Per delivery GHG emissions generated by product returns, for the following products and geographies: varied / unspecified types of products in the UK and Jordan, respectively (Edwards, McKinnon, and Cullinane 2010; Nabot and Firas 2016), FMGCs in the UK (Van Loon et al. 2015), and clothing in Germany (Wiese, Toporowski, and Zielke 2012).

For returns, devising results per delivery is inherently more challenging than for the other categories, as it is always individual items that are returned. Additionally, it is not always clear whether the values put forward by some of the studies refer to a single item or the entire delivery. We thus proceeded as follows: When a number FP_I refers to the return footprint per item, we transform it to the return footprint per delivery FP_D by using the following equation:

$$FP_D = FP_I * \#I * RR,$$

where $\#I$ represents the average number of items per delivery and RR the average return rate ($0 \leq RR \leq 1$). With this extrapolation, results were computed as follows: It is not specified in the paper, but it seems from the text around Table 4 in (Nabot and Firas 2016), that they devise their values per-delivery, already taking into account the return rate, so their range was left unchanged. According to their Table 2 in (Wiese, Toporowski, and Zielke 2012), the return footprint is per-delivery, already taking into account the return rate, so that was left unchanged as well. The 66g of impact per returned item in (Van Loon et al. 2015) were extrapolated according to the equation above with the 55 items per delivery in scenario PP1 and the very low return rate of 3.5%. Similarly, the per-item value of 362g from (Edwards, McKinnon, and Cullinane 2010) was scaled using the 2.5 average items per delivery and the range of 25-40% return rate considered in the study.

4.4 Overall per-delivery rebound effects and complexity of quantitative assessments

As the bar chart in Figure 10 indicates, the variations across estimates for the five categories of rebound effects are quite substantial. As discussed throughout the last section, they stem from various sources such as different products, basket sizes, delivery distances, rates of failed deliveries and of returns, geography (in particular urban, suburban, or rural), local transportation infrastructure and culture.

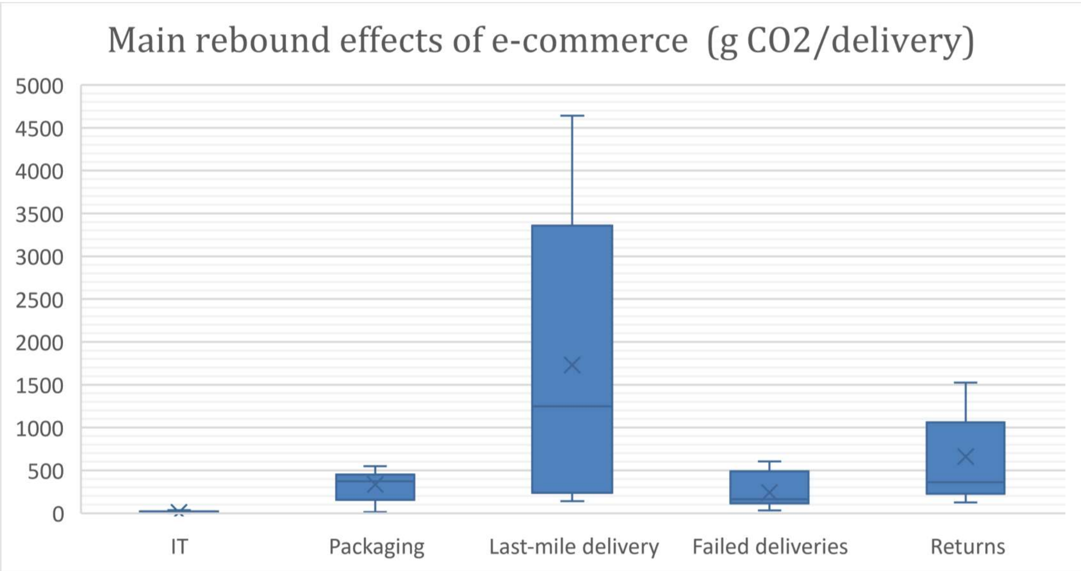

Figure 10 Per delivery GHG emissions generated by the 5 types of straightforward rebound effects of e-commerce, as detailed in Section 4.3. Analysis based on the literature that puts forward quantifications, i.e. (Edwards, McKinnon, and Cullinane 2010; Wiese, Toporowski, and Zielke 2012; Zhang and Zhang 2013; Van Loon et al. 2015; Nabot and Firas 2016; Hischier 2018; Shahmohammadi et al. 2020; Kemp et al. 2022), as well as own calculations for the GHG emissions of the IT devices and infrastructure and data put forward by the Zalando online shopping platform in 2016, as cited by (Hischier 2018). Assumptions and scaling from per-item to per-delivery impact described below Figures 5, 7, 8, and 9.

4.4.1 Insights from the quantitative assessment

Despite all the involved uncertainties and variations, some statements can be made: First, the energy consumption and GHG emissions of the IT required for e-commerce are negligible. As has been argued before (Bremer et al. 2023; Coroamă and Mattern 2019; Widdicks et al. 2023), the direct environmental effects of IT are usually much less important than the indirect effects of IT (both the environmentally beneficial as well as the detrimental ones). For e-commerce as well, not the tiny direct footprint of IT infrastructure and of end devices is a source of concern, but the possible indirect rebound effects that are triggered by it.

Secondly, packaging, a main source of concern in numerous of the early studies, does no longer seem to dominate the overall picture. Its outstanding importance in early studies was most likely given by the fact that the goods under scrutiny were small items such as books (E. Williams and Tagami 2002; H.S. Matthews et al. 2002), CDs or DVDs (Sivaraman et al. 2007), shipped individually often through regular postal mail, each of them wrapped in additional last-mile packaging. Going over to larger goods and more complex and dedicated delivery pathways, the relative importance of additional packaging decreases. It remains nevertheless a source of impact and one of the low-hanging fruits in terms of mitigation, as argued in Section 6.2.1 below.

The most important source of rebound is the additional traffic of last-mile deliveries. Important are not only the first-time deliveries themselves but also the associated failed deliveries (and required redeliveries) as well as product returns. While this study focuses on GHG emissions, deliveries generate other types of negative externalities as well, such as congestion, air pollution (in particular NO_x and particulate matter), and noise. While the first delivery represents the main source, for some scenarios returns can be quite important as well, in particular for clothing with its very high return rates (Edwards, McKinnon, and Cullinane 2010; Wiese, Toporowski, and Zielke 2012; Buldeo Rai, Touami, and Dablanc 2023). In fact, as will be discussed in Section 4.5 below, international deliveries and returns are increasing. Returns might also lead to the wilful destruction of unused goods no longer deemed worthy of being sold. Both these aspects have so far barely been taken into account by existing studies, and they might make returns the main source of concern for some e-commerce scenarios.

It is also clear that not all sources are equally important for every e-commerce scenario. Food (as in cooked food) deliveries, for example, inherently have a return rate of zero, so returns are no concern for them. Delivery is increasingly performed by bicycle couriers from local restaurants, and the rate of failed deliveries is also virtually zero, so the overall impact delivery is much less important than in other e-commerce scenarios. However, packaging is inherently needed and almost impossible to avoid, so for food deliveries packaging is likely to remain a main source of rebound (Caspers et al. 2023). Returns, on the other hand, are crucial not only for clothing but also for electronic devices (Buldeo Rai, Touami, and Dablanc 2023).

Finally, while the uncertainties and variations are quite high, the order of magnitude of the overall impact is relatively clear. The sum of the medians of all 5 categories in Figure 10 is 2150 g CO_2 (i.e, 2.15 kg CO_2), while the sum of the averages is slightly higher at 2.8 kg CO_2 (2979 g, more precisely). This is in the same “a few kilograms CO_2“ ballpark with the recent literature that puts forward numbers for the overall impact of e-commerce (Shahmohammadi et al. 2020; Kemp et al. 2022; Buldeo Rai, Touami, and Dablanc 2023).

This can amount to a significant overall impact: In Switzerland, for example, in 2021 (the most recent year for which statistics are available), over 5.5 million persons performed online shopping.[6] While it is unclear how many orders they performed, in the same year, the overall turnover of B2C e-commerce in Switzerland was 14.4 billion Swiss francs (Handelsverband 2023). If everyone would have ordered just once, this would lead to an entirely unrealistic average order value of 2,600 Swiss francs (CHF) per order. Assuming 8 orders on average per person and year would still imply an average order value of over 325 CHF; most likely an upper bound and thus a conservative assumption in terms of amount of orders. Nevertheless, working with this number implies 44 million online orders in 2021 in Switzerland. Assuming the 2.15 – 2.8 kg CO_2 per order yields a corresponding overall rebound GHG impact of 95 – 123 kt CO_2; a share of 0.27 – 0.35 % of Switzerland’s entire 2021 GHG emissions of 35 Mt CO_2.[7]

Beyond what has been called here “straightforward types of rebound of e-commerce”, there are more subtle, and potentially more important, macroeconomic rebound effects. So far, they have rarely been addressed, and never quantified. We discuss them in Section 4.5 below.

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[6] See Einzelpersonen und E-Commerce und E-Banking. PxWeb (admin.ch).
[7] See Switzerland: CO2 Country Profile - Our World in Data.

4.4.2 Challenges of a quantitative assessment

Overall, there are relatively few articles quantitatively comparing traditional and online shopping. A review article from 2017 found 17 such articles (Pålsson, Pettersson, and Winslott Hiselius 2017). A very recent review article, which looked into the three main scientific databases (Science direct, Scopus, and Google scholar, the same as we also used), found 46 such articles, of which only 18 compared the GHG emissions of the two (Buldeo Rai, Touami, and Dablanc 2023). Adding after snowballing another 3 articles and a Master thesis, the review took 22 studies into considerations. Some of these are around 20 years old from the beginnings of B2C e-commerce and usually outdated. Some even compare goods and distribution channels that no longer exist today, such as DVD rental via postal mail vs. video stores (Sivaraman et al. 2007). Several others only put forward overall numbers, without distinguishing among the individual contributions of the various causes or only discuss relative difference between traditional and online shopping (Figliozzi 2020), and do not allow any conclusions to be drawn about the absolute impact. Data availability is thus quite limited, yielding the statistical relevance of any statements difficult.

Additionally, even among the relatively few studies that do quantify GHG impacts, comparability is challenging. Some present overall GHG impacts, without distinguishing among individual sources, others do distinguish. System boundaries are also different: some, for example, consider failed deliveries, others do not. Similarly, while some do take returns into account, others do not. Some of the studies compare various last-mile delivery options, others only focus on one such option, and often a relatively exotic one such as terrestrial or aerial drones (Koiwanit 2018; Figliozzi 2020; Cokyasar et al. 2023). As discussed at length in Section 4.3, some studies put forward per-delivery results, others per-item, while others do not state this, and it must be implicitly understood what they refer to. And even when it is clear, the transformation between the two is not always trivial, as the underlying assumptions about the basket size are not clearly specified. Finally, as discussed in the previous subsection, different types of goods imply different types of deliveries and encounter varying challenges. Clothing and electronics are confronted with substantial return rates, while food deliveries have particular packaging requirements. Groceries and food are always delivered locally, while other goods might be delivered from greater distances and even internationally. This not only adds to the difficult comparability, but also means that in each category of goods, there are only a few studies. Given the overall poor data availability, this renders statements for any individual product category statistically not significant.

Adding to the complexity, the assumption that an online shopping instance replaces one physical shopping instance would be simplistic and wrong. First, as discussed in Section 4.3.3, online shopping is often additional to traditional shopping and does not substitute it. And even when it does replace it, the trip to the physical store in the counterfactual would not have been solely for the purpose of shopping. It would have been a multi-purpose trip, combined with other activities such as work commute, taking kids to school, sports, leisure, or other shopping. As the other purposes do not disappear, the trip often still takes place, reduced by the visit to the one store. Finally, the two worlds of traditional and online shopping are not distinct but more and more intertwined. In what has been called "omnichannel purchasing", customers increasingly do in-store research (i.e., physically inspecting a product) before shopping online, and online research before an in-store purchase. These "showrooming" and "webrooming" paradigms (Buldeo Rai, Touami, and Dablanc 2023) dilute the borders between the two types of shopping and add to the difficulty of their individual assessment.

4.5 The subtle and hard-to-grasp, but crucial effects of changed behavioural patterns and business practices

Next to the five sources of rebound introduced in Section 4.2 (which were graphically represented in Figure 3 and thoroughly analysed in Section 4.3), there are several further sources of environmental effects of online shopping. What they have in common is that they are all quite subtle, intertwined (among themselves, with technological, societal, behavioural or economic phenomena), and thus difficult to grasp, sometimes even qualitatively – and much more so quantitatively. They are also quite recent and have typically not been quantitatively assessed so far. Moreover, some have only sporadically been mentioned in the academic literature, and are rather discussed in the grey (i.e., non-academic) literature. Despite being difficult to assess, these subtle but far-reaching effects might in fact be at least as important as the more straightforward ones (Bremer et al. 2023; Widdicks et al. 2023); discussing them at least qualitatively is thus important.

In principle, these subtle effects can be environmentally either beneficial or detrimental. During the literature review, however, only one such positive effect was identified, and one that seems of rather marginal importance. It refers to the optimisation of trips to physical stores thanks to the information that e-commerce can also provide next to online purchases: "This finding brings evidence for the optimizing effect that e-commerce can have on store travel, providing practical information on opening hours and stock availabilities of stores, for example."(Buldeo Rai, Touami, and Dablanc 2023). Other than this one limited effect, the other seem to be rebound-inducing and thus detrimental from an environmental perspective. They are presented in the subsections below.

4.5.1 Substituting trips

Introducing a digital good that can substitute a physical one, does not imply that this substitution will have taken place for each usage instance of the digital good. Digital versions of a newspaper or magazine, for example, are in many instances simply complements of the physical edition, not replacing them (Achachlouei and Moberg 2015; Coroama, Moberg, and Hilty 2015). Similarly, for e-commerce, online shopping processes do not necessarily always substitute traditional trips to the shops; often, they may simply complement them.

(Buldeo Rai, Touami, and Dablanc 2023) call this phenomenon the "fragmentation of online purchases" and define it as "the concept that they [the online purchase] do not replace store visits fully, but only in parts" (Buldeo Rai, Touami, and Dablanc 2023). Based on previous work, (Van Loon et al. 2015), for example, show that regular online grocery shopping reduces shopping trips to the supermarket only by 25%, as there will still be small items to be bought. Most online shopping is thus not a substitute for in-person trips, but mere additional shopping instances; a typical direct rebound effect of digital technologies as theorised in (Coroamă et al. 2020).

It is true, however, that having to purchase much less (as heavy and long-lasting items were delivered), might increase the likelihood of using low-emission transportation modes to the store (as no car is needed to carry home substantial amounts of groceries) and perhaps also to include these extra shopping trips in other activities, such as commuting to work, sports, or other shopping. While the total amount of customer trips to the shop might not change substantially as a result of online shopping, their nature and environmental impact might – good news from an environmental perspective.

Nevertheless, (Van Loon et al. 2015) further argue that for goods other than groceries, the substitution percentage is likely to be even lower, and rebound correspondingly higher. On top of the emissions generated by e-commerce, they thus include in their scenarios 75% and 90%, respectively, of consumer trips to physical stores still happening.

Considering this additionality of e-commerce on top of what would otherwise have been consumer trips to the stores – and which are, when additionality is considered, to a large extent still happening – fundamentally worsens the environmental balance of e-commerce. Considering this effect, the systematic quantitative review by (Buldeo Rai, Touami, and Dablanc 2023) sees the GHG impact of a non-food online purchase grows by a factor of 2.6 from 1.75 kg CO_2 to 4.56 kg CO_2, and by a factor of 1.2 (from 1.35 kg CO_2 to 1.6 kg CO_2) for grocery shopping.

4.5.2 Induced additional consumption

Through its efficiency gains not only in production processes, but also in monitoring, control, and communication, digitalisation is an important factor behind the acceleration of national economies and globalisation, and thus ultimately to increased consumption (Coroamă and Pargman 2020). Beyond this general trend, on an individual level, online shopping is quite prone to increase purchases and thus consumption, and as a consequence production, energy use, pollution and GHG emissions.

The reason lies in the convenience of online shopping, which is likely to bring about various forms of rebound effects: As it can be performed at any hour and from anywhere (e.g., late at night from the couch, from the train while travelling, or while attending a boring family reunion) without the need to go to a physical store, it triggers both a time rebound (for the individual rebound types, see Section 2.1) and it lowers transaction costs. Transaction costs are also reduced because price comparisons and quality assessments are so much easier than for traditional retail. This reduction of transaction costs is likely to spur consumption. Easy price comparisons as well as new commercial channels (such as weekly or daily offers advertised via mailing lists or the enabled possibility of “virtual window shopping”) also contribute to, on average, both cheaper prices and a decrease of transaction costs, thus yielding a tendency towards both direct and indirect rebound effects. Figure 11 shows an example for such consumption-fostering measures enabled by new e-commerce channels.

Figure 11 Example for the “daily offer” presented on the opening page of a popular online electronics store in Switzerland. The reduced price and the prominent product placement are likely to lead to both direct and indirect rebound effects, and thus increase consumption.

Taken together, these cumulated rebound effects are quite likely to lead to an increase in individual purchases (from both online and offline retail channels) as compared to traditional retail. Consequently, they lead to an increase in consumption, production, use of resources and energy, together with the negative externalities of increase resource depletion, pollution and GHG emissions. Additionally, they can also lead not only to increased consumption, but also to overconsumption, and subsequently to underutilised or returned, and eventually destroyed goods; a phenomenon that will be discussed in Section 4.5.4 below.

These consumption-inducing effects are complex, far-reaching, depending on various other socio-economic factors, and might develop over longer periods of time. They are thus notoriously hard to estimate. They might, however, be much more important than the easier to estimate sources of rebound discussed in Section 4.3.

4.5.3 Cross-border deliveries and returns

Traditionally, the delivery routes of e-commerce orders were those discussed in Sections 4.1 – 4.3 and presented in Figure 1 – Figure 3: Similarly to traditional retail, goods are delivered from a central, large warehouse to local distribution centres (which replace the stores in traditional retail), from where they are brought to customers via vans or other local transportation methods. Returns are brought either by customers to physical stores, picked up by delivery vans on their delivery route or sent by postal mail to either the local distribution centres or (more often) the national warehouses. Overall, and despite the considerations so far, this is a relatively efficient, centralised system.

There is a recent tendency, though, towards much more decentralised e-commerce ecosystems. Such platforms often do not sell any goods themselves, but connect overseas vendors, particularly from China, with inland customers, mainly in Europe and North America. Deliveries are made directly cross-border, and so are often the returns. One such platform, which only entered the Swiss market in 2023, quickly became the number one shopping app in both the Apple AppStore and Android PlayStore[8], a place it still occupies to this day. The direct deliveries from overseas take place via aircraft and do not follow the normal practices of e-commerce, i.e., using the more convenient and environmentally friendly shipping via container ships. In this process, the delivery was estimated to be responsible for a 50-fold increase in transportation GHGs, making product shipping by far the dominating GHG source in a life-cycle assessment of many products.[9] And the shop's return policy states that free returns are possible for the first 90 days[10]; presumably cross-border as well.

Shipping GHG footprints between a couple of kilograms CO_2 for small and light items and up to several dozen kilograms CO_2 for larger items are in an entirely different league than the rebound effects we have considered so far. Next to the environmental externalities, the "Kassensturz" weekly consumption and consumer protection show of the Swiss national broadcaster SRF found further irregularities involved in this cross-border e-commerce scheme. They were of legal nature (concerning the avoidance of Swiss VAT and import taxes by splitting deliveries into several small packages, each of which was below the taxing threshold), concerning the safety of products (such as chemicals used in production or insufficient shattering safety), and with respect to the pressure the platform exercises on local producers in the countries of origin.[11]

While this trend is thus quite worrying, it is very recent and with a uncertain development. It is also so far "largely neglected by research" (Buldeo Rai, Touami, and Dablanc 2023).

4.5.4 Destruction of returned items

Sometimes, returned items are not re-conditioned or re-packaged for sale at all. The possibility to return purchased goods thus entails the possible scrapping of the returned good. This might happen especially for generous return policies that also accept the return of goods that have been used for a certain period of time. While this might be a competitive advantage for the company offering this policy, there is a high likelihood of the goods to be unsellable afterwards and be in the best case donated to charity, in the worst case destroyed.

But even for unused goods, destruction is more likely for those that are quickly either out-of-fashion or technologically obsolete. The goods that fall into these two categories – i.e., garments and consumer electronics – are precisely those that have highest return rates for e-commerce; see (Edwards, McKinnon, and Cullinane 2010; Wiese, Toporowski, and Zielke 2012; Buldeo Rai, Touami, and Dablanc 2023) and (Van Loon et al. 2015), respectively. As with used goods, for unused goods too it would seem that the more generous the return policy (in terms of time, i.e., for how long after purchase an unused good can be returned), the more likely it is to be out of fashion or technologically no longer attractive, and thus likely to be scrapped.

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[8] See https://www.argoviatoday.ch/welt/das-steckt-hinter-temu-der-beliebtesten-app-der-schweiz-152488491.
[9] See https://www.zhaw.ch/de/ueber-uns/aktuell/news/detailansicht-news/event-news/die-billig-produkte-von-temu-haben-ihren-preis/.
[10] See https://www.temu.com/ch/where-does-temu-ship-from.html.
[11] See https://www.srf.ch/play/tv/kassensturz/video/temu-im-fokus---gefaehrliche-produkte-und-miese-arbeitsbedingungen?urn=urn:srf:video:f4475f67-cc61-49b2-b72b-352208de273d.

The environmental harm associated with the wilful destruction of returned products is problematic from a sustainability point of view – it contributes to poor waste management systems (Roberts et al. 2023) and in the long term to overproduction due to wrong sales' figures and thus future projections. Even ignoring this last long-term effect aside, the impacts are substantial: In the EU, it is estimated that 4-9% of all textiles put on the market are destroyed without ever having been used (EEA 2024). This estimate amounts to approximately 264,000 – 594,000 tonnes of textiles destroyed per year. Given the large range of estimates for the GHG emissions generated by the production of the fibres used in clothing, 0.5 – 9.5 kg CO_2 / kg of fibre (EEA 2022) – this amounts to anywhere between 132 kt – 5.6 mt CO_2 per year emitted only for the clothing destroyed in the EU. This estimate, whose higher end is slightly lower than the yearly emissions of Sweden, only covers the production of the fibres, not of the clothing itself. And for e-commerce, the relative numbers are much bleaker: In a BAU scenario, it is estimated that 43% of returned garments end up being destroyed (EEA 2024); in a market with return rates of 25-40% and in some instances perhaps even 60%, as discussed in Section 4.3.5 above.

5 The rebound effect of teleworking

This section is similarly structured to Section 0 on e-commerce above: It starts in Section 5.1 by introducing three types of teleworking and showing where the focus of our analysis lies, and also by introducing some early assessments of the environmental impact of teleworking. Section 5.2 conceptually introduces the main sources for both savings and rebound effects of teleworking. Section 5.3 then presents a qualitative and quantitative analysis of each of these rebound effects in turn, while Section 5.4 brings all quantifications together, discussing their main insights jointly. Finally, Section 5.5 discusses one more potential reason for rebound for which quantifications do not exist.

5.1 Teleworking flavours and early environmental assessments

As addressed in Section 2.3 above, advancements in information and communication technologies represented the catalyst for teleworking, and the alleviation of environmental and societal traffic-related issues (such as congestion, loss of time, air pollution, energy consumption, and GHG emissions) have been among the important reasons to imagine and advocate teleworking from the beginning. In the very early days, however, the vision was not working from home, but rather to have employees still physically commuting. They would, however, commute shorter distances to local hubs, in which the (at the time still expensive and not readily available for home deployment) information and communication technologies would be available to connect them to the company headquarters (HQ), e.g.: “Large organizations that engage primarily in information processing can effectively utilize these technologies to decentralize and relocate their organizational elements within regional centers” (Nilles 1975). These first visions could thus be called “shorter commute to hubs, followed by telecommute to HQ”. By not clogging the main highways, most of the traffic could thus be avoided, and with it a large part of the environmental and societal issues.

During the 1980s, however, there was a shift towards our current understanding of telecommuting, which typically means “work from home” and not “work from a local hub”. At the same time, during the 1980s and 1990s, the first assessments of the traffic-related and environmental effects of telecommuting started to emerge. Possibly the first such analysis stems from Jack Nilles himself (Nilles 1988); it combines a qualitative assessment with quantitative predictions based on scenarios for different adoption rates.

Another early assessment, (Koenig, Henderson, and Mokhtarian 1996), assessed the effect of one of the first teleworking pilot projects. Taking place between 1988-1990, the pilot compared a study group of 40 Californian government employees starting to telecommute at least once per week. It compared the traffic implications both to their behaviour before starting to telecommute, and to a control group of 58 non-commuting peers. Both commute and non-commute trips were analysed. For telecommuting days, the study found a 77% decrease in distance travelled and a 27% decrease in the number of trips (Koenig, Henderson, and Mokhtarian 1996).

Beyond the traffic-related savings, the early assessment by (Koenig, Henderson, and Mokhtarian 1996) also found two sources of rebound (without calling it as such): One is that even on telecommuting days, 6% of telecommuters would (entirely counterintuitively) still commute to work. The explanation of the authors is that they “were apparently telecommuting partial days and still making the trip to the regular office” (Koenig, Henderson, and Mokhtarian 1996). This yielded a 6% rebound. The other is the observation that on teleworking days, the non-commute trips increased, partly offsetting the travel reduction. As the authors put it, “the 27.4% reduction in trips may be viewed as the net of a 40.7% decrease in total PV [personal vehicle] trips due to eliminating the commute and a 13.3% increase in total PV trips due to non-commute trip generation” (Koenig, Henderson, and Mokhtarian 1996). As the rebound trips are on average, however, much shorter than the commute that was saved, the overall traffic-reduction effect for teleworking days is still a substantial 77%.

Overall, three types of telework can be distinguished: "(1) teleworking at home for all or part of a day (e.g. to avoid rush hour); (2) itinerant telework (e.g. on a train); (3) teleworking in third places, which may be dedicated (e.g. co-working spaces) or not (cafés, etc.)" (Ravalet and Rérat 2019). While acknowledging and sometimes mentioning the others, this study focuses on the first type, which is arguably the dominating post-pandemic form, and understanding, of telecommuting.

5.2 Savings and rebound effects of teleworking

On the beneficial side, next to the possibility for traffic reduction, another important environmental potential of teleworking lies in the reduction of energy consumption (and thus GHGs) of office buildings. This can potentially yield a substantial effect: According to a joint study by the IEA and UNEP, building construction and operation are responsible for 36% of global final energy use and 39% of energy-related CO2 (IEA and UNEP 2019). While 17% of these emissions are in the residential sector (and thus not relevant here), 11% of the global energy-related emissions occur in the non-residential sector, which consists mainly of offices and commercial buildings (as industrial buildings are devised separately). A part of these emissions could thus be addressed by a reduction in needed office space. Likewise, a share of the 11% energy-related emissions of the construction sector, part of which are due to the construction of offices, could also be addressed. These two potentially beneficial effects, less office energy and less frequent commutes, are schematically shown in the upper part of Figure 12, as main potential impact-reducing factors.

On the other hand, there are four main potential sources for rebound effects, as schematically shown in the lower part of Figure 12: the new ICT infrastructure required for the work for home (mainly at home, but also along networks due to increased communication needs), ii) the additional domestic energy (which appears due to increased home presence by the telecommuters), iii) newly induced non-commute trips due to activities such as shopping, bringing kids to school, sports, etc, which used to be combined with the commute, but now need to be performed individually, and iv) induced longer commute distances because frequent telecommuters wo physically commute to their offices much less frequent, might be willing to move further away from their workplace for reasons such as more affordable housing, increased safety and tranquillity, cleaner air and environment, better schools, etc.

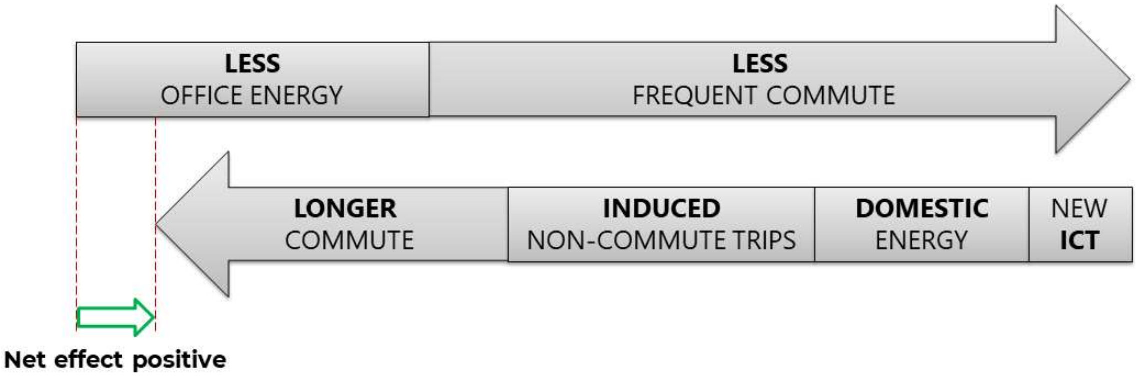

Figure 12 Schematic representation of the main sources of environmental savings due to teleworking as well as the main sources of rebound effects. The former consist of a) potential savings in offices, which could need less heating, lighting, etc and b) the impact saved by the reduced work commute. Main sources of rebound include i) the newly required ICT infrastructure at home and along the network, ii) the additional domestic energy due to increased home presence, iii) the newly induced non-commute trips, which used to be combined with the commute, and iv) the longer commute possibly induced over the long term by the tendency of frequent telecommuters to move further away from their workplace, making physical commutes less frequent but longer, and perhaps also requiring less sustainable means of transportation. Figure inspired by (O'Brien and Aliabadi 2020).

The lower part of Figure 12 shows these impact-increasing activities schematically in its lower part. The net overall effect (i.e., environmentally beneficial minus detrimental effects) might be positive, as shown in Figure 12, but it might as well be negative, as represented in Figure 13. In this case, the cumulated rebound effects overcompensate the savings, resulting in *backfire* (see Section 2.1).

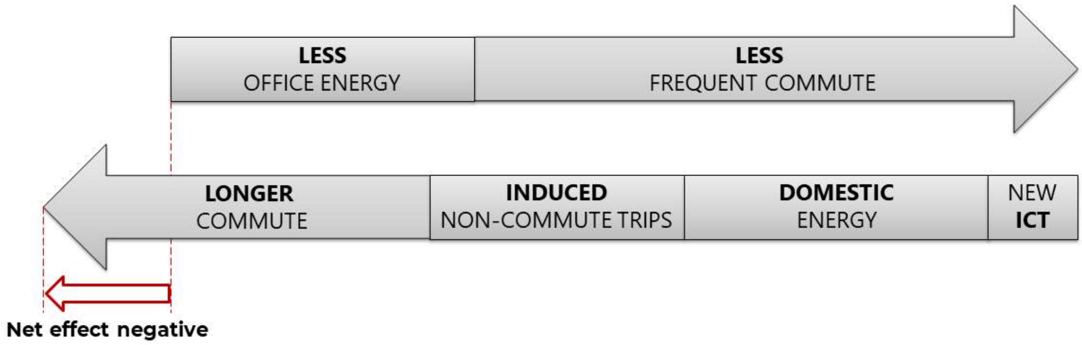

Figure 13 Similar schematic representation of the main sources of environmental savings due to teleworking as well as the main sources of rebound effects. Unlike Figure 12, here the overall net effect is negative; the rebound effects thus results in backfire.

5.3 Qualitative and quantitative analysis of the rebound effects of teleworking

The literature distinguishes various types of rebound effects of teleworking. They are sometimes categorised in short-term versus long-term effects, the difference being that “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)” (O’Brien and Aliabadi 2020). We present them here roughly following this structure, and advancing from obvious and immediate rebound effects to the more subtle and long-term ones.

5.3.1 Required information technology (IT)

As with online shopping, an obvious source of rebound also for teleworking is the additional information technology required for the service to work. Its footprint depends on several factors, among which:

- the complexity of the setup, which can range from a simple laptop screen with built-in camera to a complex “telepresence” setup with one or two large screens and motion-following camera(s) in the room (Borggren et al. 2013),
- whether only the operational electricity consumption is taken into account, or (more correctly) also the impact embodied during production,
- the expected lifespan of devices to which the impact embodied at production is allocated to, and
- the assumptions on the daily additional usage due to teleworking, i.e., how many hours of additional connectivity are required by teleworking as compared to a regular working day in the office.

As the literature is using various assumptions, we norm them to the following functional unit (FU): “a one-day teleworking-specific IT usage consisting of 3 hours of videoconferencing using an external 27” screen and a dedicated camera”. This means we scale up (e.g., from 1h) or down (e.g., from 8h) to 3h of videoconferencing. This is a very conservative assumption – not only are 3h of meetings rather on the high side, but the implicit assumption is also that the laptop and external screen would not have been used otherwise during those 3 hours; when in fact at least a part of this time, they would have been in use for activities not related to videoconferencing. When available, life-cycle data are used; when not, data on the operation must suffice.

Similarly to the case of e-commerce, with few notable exceptions such as (Borggren et al. 2013), the literature on the environmental impacts of telework largely ignores the domestic IT needs induced by teleworking and telecommuting. This might be either because the research in this area stems from environmental and other related sciences and the authors might have been unaware of the IT requirements, or because there is already an understanding that these impacts are relatively minor as compared to the induced road traffic and other rebound effects.

We make a quick back-of-the-envelope calculation as follows:

- Core network energy: Microsoft's recommended bitrate for the MS Teams videoconferencing programme is 1.5 mbps for one-to-one video (and an additional negligible 58 kbps for audio) or 2.5-4.0 mbps for larger meetings (Microsoft 2023). Over one hour, this induces 5.4 – 14,4 gigabits, or 0.675 – 1.8 gigabytes (GB). As these are data volumes are in each direction, we double the bitrate for one-to-one video, as we attribute both streams to the teleworker, but leave the meeting bitrate unchanged, attributing their one-way upstream to each participant. Overall, we thus have a data volume of 1.35 – 1.8 GB / hour. As the network energy intensity of the core Internet is currently around 7 Wh/GB (Coroamă 2021b), for these data volumes, 9.5 – 12.5 Wh/hour are needed.
- User devices: We assume the following equipment: A laptop computer (10-15W), an external 27" screen (20-60W), and a WiFi router (10W). Taken together, these devices consume 40-85 Wh/hour.

Together, network and devices need 50-100W. For our assumed 3h of videoconference per teleworker per day, this yields 0.15 – 0.3 kWh/day. With a world average carbon intensity of electricity of about 400 g CO_2 / kWh, this yields

- 40 – 80 g CO_2 / day of teleworking due to the IT infrastructure.
- (Borggren et al. 2013), on the other hand, put forward 74 – 95 g CO_2 / hour for the IT infrastructure, which yields a range of 222 – 285 g CO_2 / day according to our 3-hours per day assumption.
- (Shi, Sorrell, and Foxon 2023) compute 20 kg CO_2 yearly emissions due to the IT infrastructure of a full-time teleworker. Distributing them over 236 working days per year (261 days as put forward by the authors minus 20 of holidays and 5 of sickness) yields 85 g CO_2 / day, a value very close to the upper margin of our computed range.

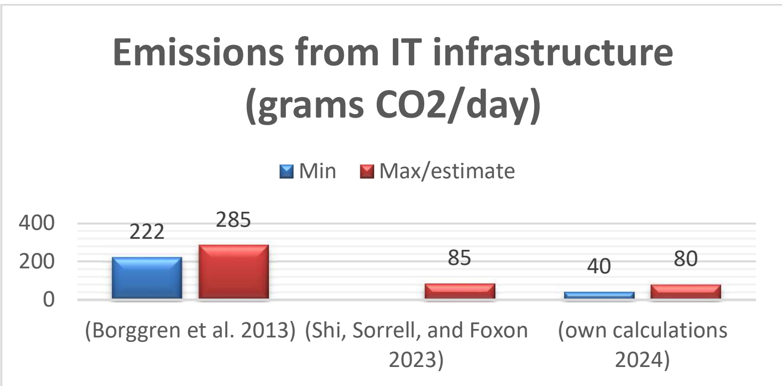

Figure 14 Daily GHG emissions generated by the additionally required ICT infrastructure of the teleworker computed by (Borggren et al. 2013), (Shi, Sorrell, and Foxon 2023), as well as own calculations. The larger part stems from the end devices at home, which consume substantially more energy than the network energy required for the remote communication. The decade-old data are likely outdated and the newer data from (Shi, Sorrell, and Foxon 2023) as well as the own calculations likely to be correct, as they take into account the substantial energy efficiency gains over this period.

5.3.2 Additional domestic energy demand

Another source of rebound is the increased energy consumption at home. The teleworking-induced additional presence of inhabitants in their homes brings about additional energy consumption due to the additional ICT required (discussed in the previous subsection), but also additional lighting as well as (and above all) the additional energy required to heat and/or cool the home.

The size of the effect depends on various factors. An important one is the magnitude of change in occupancy patterns. As also noticed in the domain of smart heating systems (which aim at switching off the heating in properties while unoccupied and turn it back on just in time before the return of inhabitants), the largest savings are achieved for single households of employed persons, where the differences to the baseline can be highest. The smallest saving potential, meanwhile, occurs for relatively large households with inhabitants having different daily schedules which induce high overall presence, such as retired, unemployed or children with schedules different from their parents, which means that the heating can only be optimised for relatively brief periods of time (Becker et al. 2018). Likewise, for teleworking, the substantial occupancy changes compared to the baseline are likely to induce the highest additional energy consumption for lighting and heating.

The following studies put forward numbers for the GHG emissions of this additionally induced energy demand, as shown in Figure 15:

1. 765 (Japan) – 2,318 (the US) g CO_2 / day (H. Scott Matthews and Williams 2005),
2. 1,514 – 4,708 g CO_2 / day by the 2014 study commissioned by BFE/SFOE 2014 in Switzerland (Perch-Nielsen et al. 2014),
3. 8,468 g CO_2 / day (Larson and Zhao 2017),
4. 3,285 g CO_2 / day (Santos and Azhari 2022),
5. 606 – 3,153 g CO_2 / day (Shi, Sorrell, and Foxon 2023), and
6. 763 – 2,217 g CO_2 / day (Tao et al. 2023).

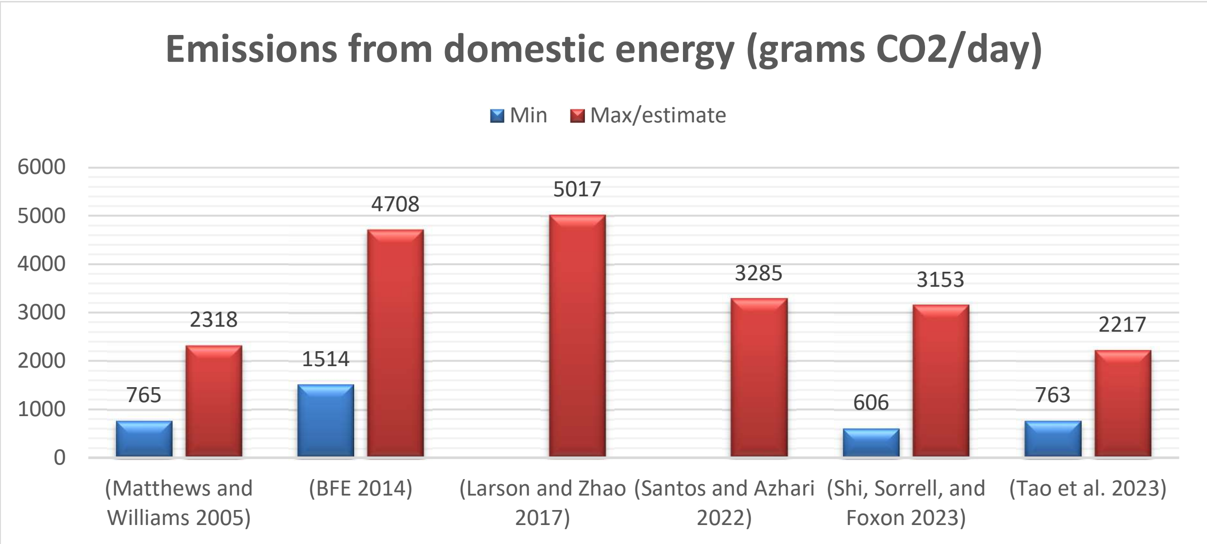

Figure 15 Estimates for the induced additional GHG emissions per teleworking day due to the increased domestic energy consumption, other than the energy required by the additional IT infrastructure. Estimates for Japan (H. Scott Matthews and Williams 2005), the US (H. Scott Matthews and Williams 2005; Larson and Zhao 2017; Tao et al. 2023), Switzerland (Perch-Nielsen et al. 2014), and the UK (Santos and Azhari 2022; Shi, Sorrell, and Foxon 2023).

1) For full-time teleworkers, (H. Scott Matthews and Williams 2005) estimate an additional yearly domestic energy consumption of 3,200 MJ in Japan and 9,700 MJ in the US. Assuming this to be natural gas and using the conversion factor of 0.0564 kg CO_2 / MJ, yields a range of 180.5 – 547 kg CO_2 / year additional, or 765 – 2,318 g CO_2 / day.

2) The early study on teleworking, commissioned already 2014 by the Swiss Federal Office of Energy (SFOE), considered two types of rebound effects, addressed as "compensation effects" ("Kompensationseffekte" in German) in the study: those from additional domestic energy demand, addressed here, and those from induced non-work trips, addressed in the subsection below. For both rebound types (and the overall net effect as a consequence), the study distinguishes among three scenarios: one without any rebound effects, one of minor rebound and one of substantial rebound. The first one is only theoretical (to highlight the beneficial environmental potential of teleworking in the hypothetical absence of rebound effects) and also out-of-scope for our current study; we also use it as baseline for calculations. The other two rely on the following assumptions: that every second Swiss employee uses a corner of 4 additional square metres for home office (which need to be lightened up and heated additionally) and that every second Swiss employee uses an additional 12 square metres room for home office, respectively (Perch-Nielsen et al. 2014).

The main results of (Perch-Nielsen et al. 2014) are presented in Figure 33 on page 48 of that report (also repeated as Figure 3 in the abstract) and the text around it, and are presented disjunct for traffic and office effects (both positive and negative in each category). For office energy, the savings through saved office space are estimated at 56 GWh / year for all of Switzerland (Perch-Nielsen et al. 2014). The numbers for the two scenarios that do consider rebound effects are unfortunately not explicitly addressed in the text. Approximating numbers from Figure 33 of (Perch-Nielsen et al. 2014), however, yields net negative effect of about 8 TWh per year for moderate rebound and about 143 TWh for strong rebound. Adding these to the savings of 56 GWh in the absence of rebound (as they cancel that effect and turn the net result into a negative one) yields 64 and 199 GWh yearly rebound of additional domestic energy demand, respectively.

As the study's survey showed that about 0.9 % of the work in Switzerland was done remotely at the time (Perch-Nielsen et al. 2014),

$$share_{rem} = 0.009,$$

given that the Swiss workforce 2014 was about

$$WF_{CH} = 4\, million\ FTE$$

(full-time equivalent) employees[12], and relatively conservatively assuming that all Swiss heating consisted of natural gas (and not the more polluting fuel oil) with a carbon intensity of

$$CI_{NG} = 0.201\ kg\ CO_2/kWh^{13},$$

the total energy rebounded country-wide over a year, $RE\_Dom(EN)_{CH*Year}$, (and which is 64 and 199 TWh, respectively) can be distributed per FTE and year and transformed to GHG emissions via the equation

$$RE\_Dom(GHG)_{FTE*Year} = \frac{RE\_Dom(EN)_{CH*Year}}{WF_{CH} * share_{rem}} * CI_{NG}$$

resulting in a range of 357.33 – 1111.08 kg CO_2 / year per FTE. Assuming this 236 working days per year (an average of 261 working days that already account for bank holidays minus 20 holidays and 5 days of sick leave per year), this yields the range of 1,514 – 4,708 g CO_2 / day mentioned in the beginning.

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[12] See https://www.bfs.admin.ch/bfs/en/home/statistics/work-income/employment-working-hours/economically-active-population/labour-market-status.html.
[13] See https://www.volker-quaschning.de/datserv/CO2-spez/index_e.php.

3) Between a full-time teleworker and a traditional worker with no telecommute, (Larson and Zhao 2017) compute an yearly household heating energy increase of by 19.9 million BTUs, from 138.6 to 158.5 million BTUs (Table 4, row "Dwelling"). They correspond to 20,995 MJ which, using the conversion factor of 0.0564 kg CO_2 / MJ as stated above, yields an additional 440.3 kg CO_2 / year, but this is for one day of teleworking per week only. Dividing this by the roughly 52 weeks of one year leads to 8,468 g CO_2 / day; clearly an outlier.

4) In a top-down analysis, (Santos and Azhari 2022) start from the number of 25.8 million households in England and Wales, for which they assume that 75% have at least one person of working age, for whom teleworking is thus relevant. This means that 19.35 million households are relevant for this analysis. In 5 teleworking scenarios, the yearly heating-related emissions of these households increase from 71.2 Mt CO_2 to 72.1 – 76.6 Mt CO_2. Each increase represents an increase of 6% of the working population that would be mainly telecommuting, from an initial baseline of 14% to 20% (Scenario 1) – 50% (Scenario 5). To each 6% increase of the share of teleworking households (i.e., 1.161 million from the 19.35 total households that have persons of working age), an increase of 0.9 Mt CO_2 is forecasted. This corresponds to an yearly increase of 775 kg CO_2 / year, and thus of 3,285 g CO_2 / day.

5) In probably the most thorough assessment to date, and in order to assess this induced additional energy demand while also modelling variability (of dwellings, heating patterns, etc) and uncertainties, (Shi, Sorrell, and Foxon 2023) deployed a deterministic model based on a representative sample of British home heating technologies. Together with probability distributions gained from a large dataset and running iterations of the model with combinations of variables from historical data (thus improving on a pure Monte Carlo approach), they reached a large number (hundreds of thousands) of iterations of about as many properties. Their results show that the additional heating of the property (for an extra 2h per teleworking day at 20° C) induces over the year an average of 168 kg CO_2 emissions for infrequent teleworkers (i.e., those telecommuting 1-2 days / week) and 434 kg CO_2 emissions for frequent teleworkers (i.e., those telecommuting 3-5 days / week). By comparison, lighting has a much smaller influence of 6 and 16 additional CO_2 emissions for the two groups, respectively, while the required ICT infrastructure yields negligible 1 and 3 extra kgs CO2 emissions, respectively.

To derive the daily impact we're interested in, we proceed as follows: we add the additional heating and lighting emissions of the frequent telecommuters to an average yearly 450 kg CO_2. As "frequent telecommuters" are defined as those working remotely 3-5 days per week, we assume this average to be typical for an average of 4 days per week, and scale it up to 562.5 kg extra CO_2 emissions for 5 days per week of telecommuting. Using the authors' own number of 21.75 working days per month (corresponding to 261 days per year) minus 20 yearly days free and 5 of sickness, we reach an average of 2.383 kg CO_2 emissions due to additional domestic energy consumption per telecommuting day.

6) Finally, (Tao et al. 2023) explicitly address residential energy use as source of rebound. In Figure 2D, the paper presents a graph of the daily distinct carbon footprint for residential energy use between office workers and teleworkers for 6 scenarios (for 1, 2, 3, 4, 5, and more than 5 teleworking days per week, respectively). Estimating from Figure 2D the carbon footprint difference between teleworkers and office workers for each of these 6 scenarios and corroborating with Table S1 of the supplementary material (which shows the averages of various types of home energy use per day for office workers and teleworkers for a specific region of the US), yields the approximate range of 763 – 2,216 g CO_2 / day.

5.3.3 Multi-purposeness of work-related trips and induced additional non-commute trips

As discussed from the outset, and especially in Section 5.1, the largest environmental promise of teleworking lies in the reduction of work-related travel. Unfortunately, while work-related travel may indeed often decrease (although not always, some counterarguments will be presented in Section 5.3.4 below), non-work-related trips could often increase to – at least partly – compensate.

As with e-commerce substituting traditional in-store shopping, the main reason for the increase in non-work-related trips is that work commute is often multi-purpose: While driving to or from work, one might do groceries or other types of shopping, go to the gym, bring kids to school or pick them up, solve various chores, and so on. If work commute ceases to exist or is substantially reduced, those other activities that used to be part of the work commute must still be performed, so there will be extra trips for them – in other words, rebound effects.

This phenomenon has been observed early-on: (Nilles 1988) writes that “demand may increase for additional trips, primarily shopping-oriented, that were previously chained together with the commute from work or that took place during lunch periods”, while (Koenig, Henderson, and Mokhtarian 1996) find in their data that “non-commute personal vehicle trips increased by 0.5 trips per person-day on average”. Striking a similar note, (Zhu and Mason 2014) note that “the total mileage not traveled to work may be offset by errands or other trips previously made during a person’s typical commute with trip-chaining”. Even more categorical, and combining this effect with the one that will be discussed in 5.3.4 below, (Shi, Sorrell, and Foxon 2023) write: “the savings in transport-related emissions from teleworking are either small or non-existent, owing to teleworkers having longer commutes than non-teleworkers, as well as engaging in more non-commute travel in the days when they work from home”.

A second reason for the possible increase in non-work trips lies in the fact that telecommuting yields vehicles less used for commute and thus more available to other members of the same household, who may thus increase their usage of the family vehicles (O’Brien and Aliabadi 2020). With few exceptions such as (S.-N. Kim 2016), the data available for this theorised effect is poor. We will thus not pursue it as an extra effect, but – to the extent that data is available – as part of the same effect: non-work trips additionally induced by the teleworking of someone in the household.

The studies use various metrics to devise this effect of increase non-commute trips as a result of teleworking: number of additional trips, additional distance (both of which are sometimes expressed relatively, not absolutely), additional energy or additional GHGs. For our analysis, we derived the following results, as shown in Figure 16:

1. 1,865 g CO_2 / day (Zhu 2012),
2. 1,688 g CO_2 / day (Zhu and Mason 2014),
3. 152 – 500 g CO_2 / day by the 2014 study commissioned by BFE/SFOE 2014 in Switzerland (Perch-Nielsen et al. 2014),
4. 539 g CO_2 / day (S.-N. Kim 2016),
5. 1,652 g CO_2 / km (Caldarola and Sorrell 2022),
6. 2,112 – 5,146 g CO_2 / km (Shi, Sorrell, and Foxon 2023), and
7. 2,600 g CO_2 / km (Tao et al. 2023).

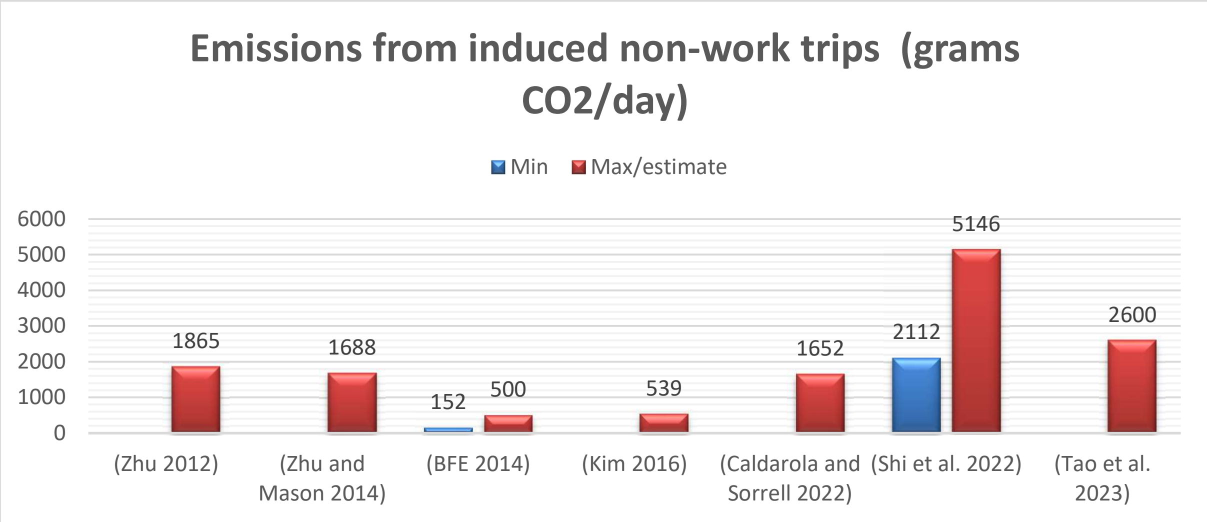

Figure 16 Additional average daily GHGs attributable to induced non-work related trips due to teleworking, as a consequence of the additional vehicle mileage. All studies quantifying this effect rely on national statistics – for the US (Zhu 2012; Zhu and Mason 2014; Tao et al. 2023), the BFE/SFOE commissioned study for Switzerland (Perch-Nielsen et al. 2014), Korea (S.-N. Kim 2016) and the UK (Caldarola and Sorrell 2022; Shi, Sorrell, and Foxon 2023), respectively – and they all achieve fairly similar results in the range of 4.5 – 7.5 additional km per day. The more substantial differences in the GHG effect stem from the differing fuel efficiencies in the different countries.

1) Analysing data from the US Household Travel Surveys, (Zhu 2012) finds that in 2009 teleworkers undertook on average 10.8% more non-work trips per day (4.18 instead of 3.77), which were also 15.7% longer on average (9 km instead of 8 km). This leads to an average additional daily travelled distance for non-work purposes of 7.46 km for teleworkers as compared to non-teleworkers. According to the US Environmental Protection Agency, a typical passenger-vehicle in the US emits around 400 g CO_2 / mile (EPA 2023), which transforms to 250 g CO_2 / km, thus yielding an average additional daily 1,865 g CO_2 due to induced non-work trips.

2) In a later paper based on the same survey, (Zhu and Mason 2014) observe that telecommuting increases six out of seven types of non-work travel, leading telecommuters to travel an average of 4.2 miles (i.e., 6.75 km) farther each day for non-work-related purposes compared to those who do not telecommute. According to the same assumptions as above, this yields 1,688 g CO_2 / day.

3) The SFOE-commissioned study concludes that the 0.9% of work performed from home was saving 2014 about 1% of Swiss commute trips, corresponding to about 140 million kilometres less driven and energy savings of 70 GWh (Perch-Nielsen et al. 2014). The two scenarios for mild and strong rebound effects (discussed in Section 5.3.2 above) lead to a rebound of 7% and 23%, respectively (Perch-Nielsen et al. 2014), i.e., 4.9 – 16.1 GWh/year for 0.9% of the 4 million FTE employees in Switzerland (see detailed assumptions and references in Section 5.3.2 above).

Deploying a similar equation to the one in Section 5.3.2 above

$$RE\_Trips(GHG)_{FTE*Year} = \frac{RE\_Trips(EN)_{CH*Year}}{WF_{CH} * share_{rem}} * CI_{Gasoline-and-Diesel}$$

where $RE\_Trips(GHG)_{FTE*Year}$ represents the rebound effect due to induced non-work trips measured in GHG per FTE and year, $RE\_Trips(EN)_{CH*Year}$ the rebound effect due to induced non-work trips measured in energy for the entire country and year (the 4.9 – 16.1 GWh/year for 0.9% of the Swiss FTE), WF_{CH} the amount of Swiss workforce measured in FTE equivalent, and $share_{rem}$ the share of remote work performed in 2014 (0.9%). The equation above yields about 36 – 118 kg CO_2 / year per FTE corresponding to 152 – 500 g CO_2 / day and FTE of rebound due to induced non-commute trips.

4) Based on a Korean dataset comprising over 15,000 households (SMA HTS – Seoul Metropolitan Area, Household travel survey), (S.-N. Kim 2016) shows that telecommuters drive an average additional 3.2 km per day on average, whilst their vehicles travel 2.31 additional km per day. Meanwhile, due to the second effect discussed earlier in this section, other household members also travel additionally, 13.6km on average, inducing further 2.18 km for the household vehicle(s), on top of those already induced by the telecommuter. This yields an average of 4.49 additional daily km for the vehicle, amounting to 539 g CO_2 / day attributable to this rebound effect – assuming a fleet average emission factor of 120 g CO_2 / km, given that this value was 140 g CO_2 / km in 2015, and the government was aiming for an average of 97 g CO_2 / km for new cars by 2020 (Bandivadekar and Kim 2015).

5) Using also national survey data, this time a dataset on the travel patterns of English households between 2005-2019, (Caldarola and Sorrell 2022) performed a very detailed study, one of the few that also takes into account various travel modes. They find that the mean value for non-work travel among teleworkers is 89.43 miles, as opposed to 70.26 miles among non-teleworkers, out the which the majority (77.89 and 62.68 miles, respectively) by car, and 8.72 versus 5.61 miles by public transportation. This means 15.21 additional miles per week, and 7.605 additional miles (or 12.24 km) more per teleworking day – assuming on average 2 days per week of teleworking, as these values are for a combination of occasional and frequent teleworkers before the pandemic. With an average emission factor of 135 g CO_2 / km in the UK (Yurday 2024), this yields 1,652 g CO_2 / day.

6) Utilising data of the same English National Travel Survey (NTS), (Shi, Sorrell, and Foxon 2022) focus specifically on the years 2017-2019 prior to the pandemic, offering a comprehensive assessment that includes the share of various modes of transportation. It is also the only study that presents GHG emissions as result. Distinguishing between "very frequent teleworkers" (i.e., those telecommuting 3-5 days per week) and "frequent teleworkers" (i.e., those commuting once or twice per week), the study's baseline is represented by the commute-related GHG emissions of non-teleworkers, which are on average 33 kg CO_2 / week. For very frequent teleworkers, the total transport-related GHG emissions are reduced by 6% compared to the baseline, while the commute-related emissions are reduced by 66% compared to the 19 kg CO_2 / week commute emissions for non-teleworkers. This means that the commute-related emissions of very frequent teleworkers are 6.46 kg CO_2 / week (as compared to 19 kg CO_2 / week for the baseline), while their overall travel emissions are 31.02 kg CO_2 / week (as compared to 33 kg CO_2 / week for the baseline). Their weekly non-work-related emissions thus amount to 31.02 – 6.46 = 24.56 kg CO_2 / week, as compared to the 33 – 19 = 14 kg CO_2 / week for non-telecommuters. The rebound effect thus represents 10.56 kg CO_2 / week, or 2.112 kg CO_2 / day.

Similarly, the frequent teleworkers have 39% more overall transport emissions (i.e., 45.87 kg CO_2 / week) and 6% more commute-related emissions (i.e., 20.14 kg CO_2 / week). The non-work-related emissions thus amount to 25.73 kg CO_2 / week, or 5.146 kg CO_2 / day.

7) Finally, the number for (Tao et al. 2023) is a rough approximation of the data in Figure 2G of that paper.

5.3.4 Less frequent commute encourages moving further out – and thus less frequent, but longer commute, possibly with less sustainable transportation modes

A more subtle, long-term, and hard to quantify possible rebound effect of teleworking lies in the fact that having to less frequently travel to their offices, telecommuters might choose to move further out. Such a decision can make sense for a variety of reasons such as more affordable housing (Caldarola and Sorrell 2022), increased safety and tranquillity, cleaner air and environment, better schools, etc. As a result of teleworkers living further out, "the gains from telecommuting (i.e. less frequent commuting) could be offset by longer commute distances (when they do commute) and longer non-work travel such as leisure trips" (Zhu and Mason 2014).

As in Section 5.3.3 before, here, too, we thus have two distinct sub-flavours of rebound effects. For the rebound in non-work trips from Section 5.3.3, these sub-flavours were the increased non-work trips of the telecommuters and those of their family members. Here, as the quote from (Zhu and Mason 2014) shows, they are the possibly longer commute trips as well as the perhaps longer non-work travel, both due to the more remote living potentially triggered by teleworking. As before, one of these sub-flavours (i.e., less frequent but possibly longer commute trips) is more thoroughly covered in the literature, and thus the main focus of our analysis. The other sub-flavour, the possibly also longer non-work trips due to residing remotely, are have already been included as part of the former phenomenon already analysed in Section 5.3.3.

These two distinct flavours are also listed in Table 1 of (O'Brien and Aliabadi 2020) as "increased commute time and distance because teleworkers tend to live further from their workplace" and "Increased transportation energy because teleworkers opt to live further from their workplace and thus potentially further from amenities and in less transit-accessible neighborhoods", respectively. This quote also shows that in terms of environmental impact, this rebound can be much more substantial than the mere added distance: Moving to outlying areas might also mean less public transport availability, or even a total lack thereof. In this case, even if distances increase only slightly or not at all, the modal shift might trigger a significantly worsened environmental performance.

This potential source for rebound also goes back to the pioneering work of Jack Nilles and Patricia Mokhtarian. In probably the first mentioning of this effect, Jack Nilles wrote more than 3 decades ago: "It seems plausible that telecommuting, with its ability to make work at least partly location independent, could have equal or even greater impacts on residence location decisions" (Nilles 1991). Only a few years later, and using a partial equilibrium model with fairly simple assumptions, (Lund and Mokhtarian 1994) argue that "the long-term effects of telecommuting are likely to include change in residential location farther from the workplace, diminishing the reduction in commute distance traveled per year from telecommuting", and shortly thereafter "Another potential impact is residential relocation to sites farther from the workplace, because longer commute distances can be compensated for by increased frequency of telecommuting […] Given the decrease in commute costs resulting from the reduced frequency of commuting, residential location models suggest that the weight of distance to work would be reduced and hence that greater distances would be acceptable" (Mokhtarian, Handy, and Salomon 1995).

However, not all studies agree that this effect leads to increased travel by the teleworkers. (S.-N. Kim, Mokhtarian, and Ahn 2012), for example, acknowledge the existence of this effect and find "evidence that (consistent with expectation) some telecommuter-headed households tend to live in less-accessible places (Table 3)". At the same time, however, "on average (*counter to expectation*) their residential accessibility matches or even exceeds that of other white-collar households, and their commute distance is shorter (Table 4)" (S.-N. Kim, Mokhtarian, and Ahn 2012). The explanation for this seemingly paradoxical phenomenon lies in the fact that, in Korea at that time at least, "firms allowing telecommuting *also* tend to be located in peripheral areas, with telecommuters having *shorter* commute distances compared to office workers" (S.-N. Kim, Mokhtarian, and Ahn 2012).

Finally, even when it is clear that teleworkers live farther away from their workplace and that yields indeed a rebound effect for travel to both work and/or other amenities, most of the studies do not establish the direction of causality: "do people telework to avoid a long commute, or do they choose to live further away from the workplace because their job enables them to telework?" (Caldarola and Sorrell 2022).

This effect which had been theorised early-on, has later been put to the test, yielding the following results, as shown in Figure 17:

1. 516 g CO_2 / day computed from (Helminen and Ristimäki 2007),
2. 725 g CO_2 / day derived from (Muhammad et al. 2007),
3. 3,800 g CO_2 / day from (Zhu 2012),
4. - 528 g CO_2 / day (that is, savings of 528 g CO_2 / day) derived from the apparent paradox in (S.-N. Kim, Mokhtarian, and Ahn 2012),

5. 1,836 – 2,249 g CO_2 / day computed from (Melo and de Abreu e Silva 2017).
6. 2,016 g CO_2 / day computed from (Caldarola and Sorrell 2022),
7. 1,954 – 2,660 g CO_2 / day from (Shi, Sorrell, and Foxon 2022).

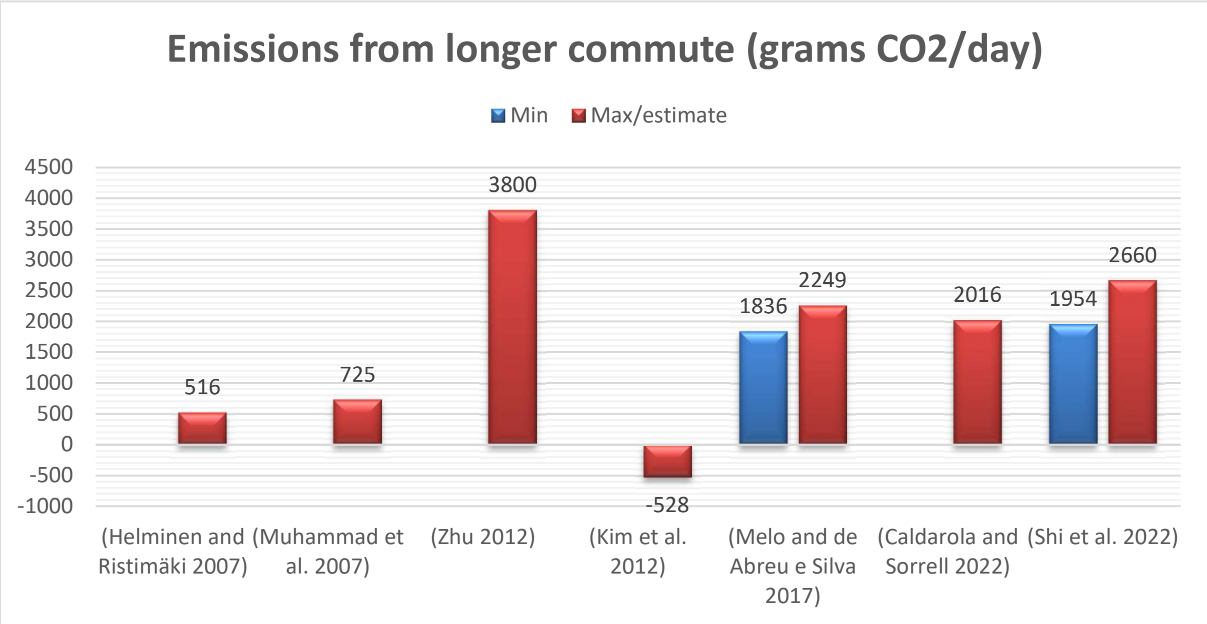

Figure 17 Additional average daily GHGs due to the longer work commute of teleworkers in Finland (Helminen and Ristimäki 2007), The Netherlands (Muhammad et al. 2007), the US (Zhu 2012), Korea (S.-N. Kim, Mokhtarian, and Ahn 2012), and the UK (Melo and de Abreu e Silva 2017; Caldarola and Sorrell 2022; Shi, Sorrell, and Foxon 2023). The negative result in (S.-N. Kim, Mokhtarian, and Ahn 2012) means that in that study, teleworkers actually have a shorter work commute than non-teleworkers on days when they do physically commute. Causality is theorised, but not proven in any of the examples.

1) A Finnish labour force survey was carried out in 2001 and comprised a large and representative random sample of over 37,000 individuals, among which 19,000 employed respondents, representing almost 1% of the Finnish workforce. This for the time quite high 4.7 % percentage was considered as typical for the Finnish workforce and was used by (Helminen and Ristimäki 2007) in their analysis of travel patterns between telecommuters and non-telecommuters. They found that the mean (one-way) commute trip for the former was 3.9 km longer than for the latter, 16.2 versus 12.3 km. Considering the percentage of 57.5% car-based commutes in Finland (Bashir 2024) and assuming a fleet average emission factor of 115 g CO_2 / km for Finland – given that the average for newly registered cars in Finland is the second-lowest in the EU after Sweden with 85.3 g CO_2 / km (ACEA 2023) – these 7.8 km rebound effect induce 516 g CO_2 / day on average.

2) An early study in the Netherlands found that compared to the 21 km average commuting distance in the Netherlands, telecommuters have a 6.3 km (3.13 km one-way) longer commute on average (Muhammad et al. 2007). As newly registered cars in the Netherlands also have very low emission values of about 86.6 g CO_2 / km, we apply the same assumption as for Finland of current fleet average emissions of 115 g CO_2 / km. As 65% of commuters use the car, this implies an induced effect of 725 g CO_2 / day.

3) Using the same data from the US Household Travel Surveys mentioned in the last subsection, (Zhu 2012) finds that in 2009 teleworkers' work trips were on average 43.3% longer than those of non-telecommuters (21.3 versus 13.7 km one-way). These additional daily 7.6 km one-way correspond to a rebound of 15.2 km per non-telecommute day by teleworkers and thus, given the high average fleet emission factor of 250 g CO_2 / km in the US, yield a GHG effect of 3,800 g CO_2 / day.

*) Based on the same survey, (Zhu and Mason 2014) claim that "on any random day, telecommuters on average travel 32.6 miles more by vehicles for their daily work trips than non-telecommuters in 2001, and 41.1 miles more in 2009". These 65.76 additional daily kilometres would imply 16,440 g CO_2 / day as rebound effect, but the number is too much of an outlier, so we ignore it for now.

4) Putting forward the apparent paradox mentioned earlier (shorter commutes for teleworkers despite living more remotely from city centres because their offices tend to also be on the outskirts), (S.-N. Kim, Mokhtarian, and Ahn 2012) find the average one-way commute distance of telecommuters to be 7.1 km, as compared to 12 km for full-time office workers and 10.9 km for part-time office workers. Making a simple average between the two values and considering the two-way commute yields an average difference of 4.4 km, which is travelled *less* by teleworkers as compared to the non-teleworkers, and thus *savings* of 528 g CO_2 / day.

5) Based on the UK National Travel Survey 2005-2012, (Melo and de Abreu e Silva 2017) find that British teleworkers commute on average 11 and 8 miles longer per week (in two-worker and one-worker households, respectively). This is not only the rebound, but the net effect of less frequent but longer commute. And while all types of telecommuters live on average farther away from work as compared to the non-telecommuting population, their effect is not equally distributed: Those telecommuting once or twice per week, have a total weekly commute of 112.9 miles (one-worker households) and 95.8 miles (two-worker households, taken individually), while those telecommuting at least 3 times per week have an average weekly commute of only 60.8 miles (one-worker households) and 65.5 miles (two-worker households, taken individually) – see Table 1 in (Melo and de Abreu e Silva 2017). The values for those commuting at least three times per week are lower than the average of the non-telecommuters, indicating that while rebound occurs due to the longer commute, there is no backfire (i.e., the additionally induced travel does not overcompensate the savings due to the less frequent physical commute). The average weekly travel distance for those telecommuting once or twice per week, however, is larger than the average distance of non-telecommuters (i.e., those telecommuting less than once per week); in this case, there seem to be backfire (i.e., a rebound effect of over 100%).

To extract the rebound effect from the compound net effect devised by the authors, we proceeded as follows: Taking the relative distribution of 4.6:1 between 1-2 weekly telecommutes to 3-5 weekly telecommutes (Table 1 in the paper), and assuming uniform distribution within these categories (and thus average weekly commutes of 1.5 and 4 days, respectively, in the two categories), this yields over all telecommuters an average telecommuting frequency of almost 2 (or 1.95, more precisely). To extract the rebound effect, we then solve the following equation system for one-worker households:

$$\begin{cases} 3 * (TC + R) = 5 * TC + 11 \\ 3.5 * (TC + R) = 112.9 \end{cases}$$

where TC is the average daily telecommute distance for non-telecommuters, and R the rebound effect of living more remotely due to teleworking. The first equation simply reflects that for one-worker households, 3 times physical commuting (5 days of the week minus the 2 times average telecommuting computed above) are 11 miles longer than the 5 telecommutes by the regular workers. The second equation is derived from Table 1 in (Melo and de Abreu e Silva 2017), which indicates that for telecommuting 1-2 times per week (i.e., assuming uniform distribution, 1.5 times on average), the remaining 3.5 times physical commute (including rebound) are 112.9 miles long. The solution of the equation system is $TC = 17.75$ and $R = 15.5$ miles (or 24.8km).

The corresponding equation system for two-worker households is

$$\begin{cases} 3 * (TC + R) = 5 * TC + 8 \\ 3.5 * (TC + R) = 95.8 \end{cases}$$

which solves for approximately $TC = 14.8$ and $R = 12.5$ miles (or 20 km).

Considering that about 2/3 (or 68%, to be more precise) of work commute in Britain is performed by car (Department for Transport 2023), and assuming no modal differences between teleworkers and non-teleworkers, this means that the rebound effect per non-teleworking day is 13.6 – 16.66 km. Deploying the average emission factor of 135 g CO_2 / km for the UK as argued in Section 5.3.3 above yields a range of 1836 – 2249 g CO_2 / day.

6) In their detailed study that takes into account not only distances, but also the shares of transportation modes for teleworkers and non-teleworkers alike, (Caldarola and Sorrell 2022) find that the mean work-related distance travelled per week is of 92.34 miles for teleworkers as opposed to 68.16 miles for non-teleworkers. The distances travelled by car, however, are much closer with 59.59 and 52.66 miles, respectively. From this weekly net difference of 6.93 miles by car (i.e., 11.1 km), the value of the rebound effect needs to be derived. As with the last study, and assuming again a 2-day teleworking average for teleworkers, we form a simpler equation system as follows:

$$\begin{cases} 3 * (TC + R) = 5 * TC + 11.1 \\ 5 * TC = 84.25 \end{cases}$$

From the second equation (for which we transformed the 52.66 miles car commute per week of non-teleworkers to 84.25 kilometres, we can directly conclude that $TC = 16.85$, yielding $R = 14.93$ km, which correspond to a GHG effect of 2,016 g CO_2 / day.

7) Finally, building on the same English National Travel Survey (NTS), but only considering its most recent pre-pandemic years 2017-2019, (Shi, Sorrell, and Foxon 2022) also present a detailed analysis that takes into account the share of different transportation modes. It is also the only study that presents GHG emissions as result. Distinguishing between “very frequent teleworkers” (i.e., those telecommuting 3-5 days per week) and “frequent teleworkers” (i.e., those commuting once or twice per week), the study’s baseline is represented by the commute-related GHG emissions of non-teleworkers, which are on average 19 kg CO_2 / week. Compared to this, the very frequent teleworkers have 66% less commute-related emissions, while the frequent teleworkers have a 6% increase in commute-related emissions. To compute the rebound effect, we proceed as follows: Assuming uniform distribution, the average very frequent teleworker (3-5 days of remote work) telecommutes 4 days per week and physically commutes 1 day. For this one day, the transport-related GHG emissions are 34% of 5 days physical commute by the non-teleworkers (100%-66% of savings, that is). Scaled up to 5 days would yield 170%, or a rebound effect of 70% – which represents 13.3 kg CO_2 / week and 2.66 per day. Similarly, in 3.5 days of physical commute, the frequent teleworkers (who telecommute 1.5 days on average) achieve 106% of the travel-related emissions of non-teleworkers. Scaled up to 5 days, this implies 151.4 % of the emissions, and thus 51.4% rebound. From 19 weekly kg CO_2, this means a rebound of 9.75 CO_2 / week and corresponding 1.95 kg CO_2 / day.

5.4 Overall daily rebound effect of teleworking

Figure 18 brings together the four main types of rebound effects of teleworking discussed in detail in the previous section. As for e-commerce in Section 0, for teleworking the spread of results in the literature is quite substantial, and there are numerous underlying assumptions and uncertainties. Nevertheless, some statements can be made, and various interesting points can be raised.

First, for teleworking as well, the energy and GHG impact of the information and communication infrastructure required to support teleworking is small and for most practical purposes, negligible (when compared to all the other sources of energy consumption and GHG emissions). As teleworking is an activity performed for a full working day, involving typically several hours of communication (both human-to-human through video calls but also machine-to-machine such as VPN) to the organisation’s headquarters, customers and other partners, its impact is larger than the truly tiny impact of the IT required for an online shopping process. As Section 5.3.1 has shown, it lies in the range of several dozens up to a few hundred grams of CO_2 per teleworking day, which is about one order of magnitude higher than the few grams to a maximum of a few dozen grams of CO_2 for one online shopping instance. As shown In Figure 18, however, it is still one-two orders of magnitude lower than the GHG emissions due to the other types of rebound of teleworking.

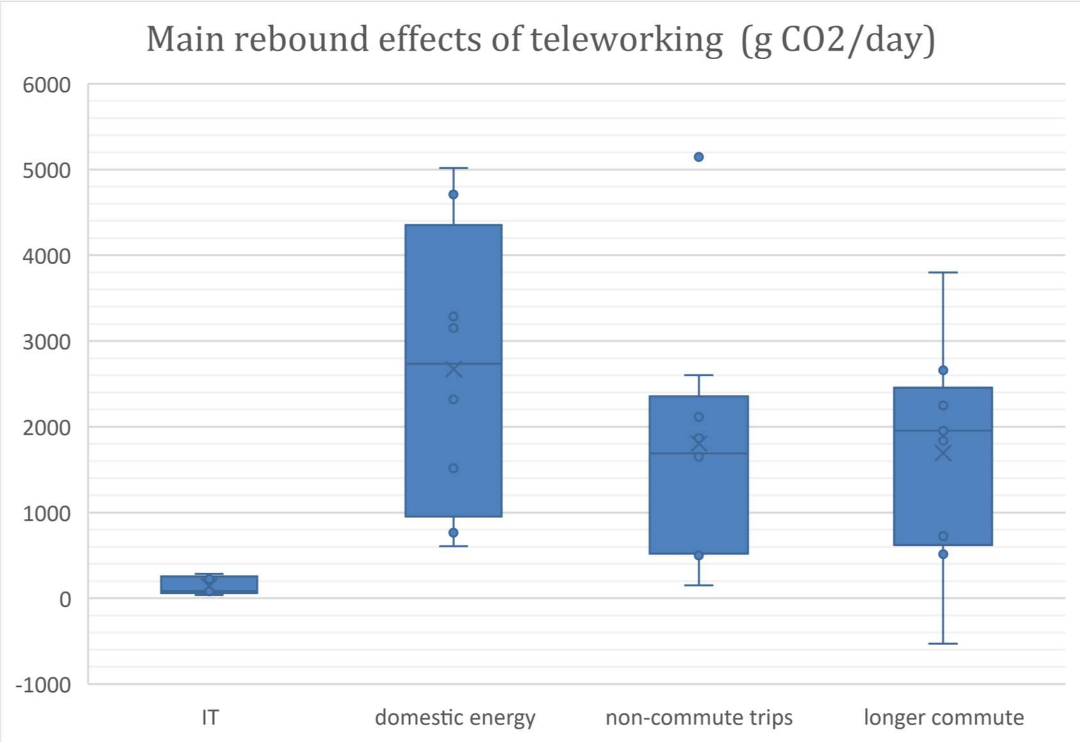

Figure 18 Daily GHG emissions generated by the 4 main types of rebound effects of teleworking, as detailed in Section 5.3. Analysis based on the literature that quantifies one or more of these effects, i.e., (H. Scott Matthews and Williams 2005; Helminen and Ristimäki 2007; Muhammad et al. 2007; Zhu 2012; S.-N. Kim, Mokhtarian, and Ahn 2012; Borggren et al. 2013; Zhu and Mason 2014; Perch-Nielsen et al. 2014; S.-N. Kim 2016; Larson and Zhao 2017; Melo and de Abreu e Silva 2017; Santos and Azhari 2022; Caldarola and Sorrell 2022; Shi, Sorrell, and Foxon 2023; Tao et al. 2023), as well as own calculations for the GHG emissions of the IT infrastructure additionally required for teleworking. Assumptions, transformations and calculations are transparently described below Figures 14 – 17.

Secondly, all studies that did consider them, found evidence for both mobility-related rebound effects. There is clear evidence for both an increase in non-commute trips compensating for the (no longer existing) multipurposeness of trips to work, and for less frequent but longer commutes for those frequently teleworking. For the latter, however, there is not yet evidence for a causality. While the correlation between teleworking and increased distance to work is statistically significant at $p < 0.001$ (Ravalet and Rérat 2019), it is not yet proven whether people live farther away because the ability to telework enables them to do so, or whether they telework because they lived farther away in the first place. There are, nevertheless, arguments suggesting that in the long run the ability to telework might indeed motivate – on average – people to live farther from their workplace: “Teleworking could, for example, be seen as an incentive (1) to choose a home that is remote from the workplace; (2) not to relocate; or (3) to accept or keep a job far away from home” (Ravalet and Rérat 2019).

Thirdly, and unsurprisingly, the impact of increased mobility is of course highly dependent on the means of transportation used. Most of the literature summarised in Figure 16 yields a relatively similar increase in non-commute trips for teleworkers of 4.5 – 7.5 km / day on average. Yet the impacts are substantially different: in Switzerland, with its highly developed public transportation system as well as in Korea, where the greater Seoul area is equally well connected, the induce GHG emissions are half a kilogram of CO_2 per teleworking day or even substantially less (Perch-Nielsen et al. 2014; S.-N. Kim 2016). Meanwhile, in the US or the UK, a similar induced additional distance leads to about 2 kg of CO_2 per teleworking day, perhaps more (Zhu 2012; Zhu and Mason 2014; Caldarola and Sorrell 2022; Shi, Sorrell, and Foxon 2022; Tao et al. 2023).

The rebound in additionally required domestic energy for teleworking, on the other hand, while also displaying variation, is always higher. The lowest number from those summarised in Figure 15 is 606 g CO_2 per teleworking day and the first quartile is already about 1kg of CO_2 / day. The explanation lies most likely in the more homogeneous character of home heating as compared to transportation.

5.5 Further possible reason for teleworking rebound: Continued consumption in offices despite teleworking

As argued in Section 5.2, next to a possible reduction in travel-related impact, the second environmental promise of telework is the energy reduction in office buildings. If less office space is required, this would have beneficial environmental consequences for both the construction and the operation of offices. To ensure a beneficial overall office-space-related impact (i.e., the balance between the additional domestic energy demand addressed in the last section and the potentially saved office impact), one should "strive to insure that consumption in office buildings falls sufficiently to at least balance out increases in residential consumption" (Eric D. Williams 2003).

It turns out, however, that the potential for space reduction crucially depends on the frequency of telecommute. Relatively seldom telecommuting, combined with a rigid workspace structure, could barely bring about any energy savings in office buildings: "once or twice per week may not lead to any change in commercial energy use at all. This is because the office layout remains the same and as nearly all the space is communal, the absence of a few workers will probably not affect energy use" (H. Scott Matthews and Williams 2005). This low energy consumption elasticity of large office spaces has been addressed early-on: "decreases in office energy use are expected to be small, given that the use of heating, air conditioning, and in some cases lights in the main office will not generally decline just because some employees are telecommuting" (Mokhtarian, Handy, and Salomon 1995). It is also vividly shown in an illustrative example of a more recent work: "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" (O'Brien and Aliabadi 2020).

This effect could be perceived both as a source of rebound or, and perhaps conceptually more correct, as not realised savings due to teleworking. While academically interesting, on a practical level this distinction is less relevant for the net environmental effect of teleworking; the contribution is the same whether it is considered a missed saving or an induced consumption. We have not attempted to quantify it not only because it is rather not a rebound effect (and thus out-of-scope for our analysis), but mainly because the literature has not thoroughly attempted to quantify this effect.

6 Discussion

Sections 0 and 5 discussed the rebound effects of e-commerce and teleworking, respectively. Both effects were analysed qualitatively as well as – to the extent possible and with inherent variations and uncertainties – quantitatively. The current section now discusses the results and further relevant aspects as follows: Section 6.1 juxtaposes the rebound effects of e-commerce and teleworking, presenting their commonalities and differences. Section 6.2 then discusses mitigation options for the rebound effects of both domains, showing also which of these unwanted consequences are harder to address. Section 6.3 reviews the literature for the two domains in Switzerland, which is very limited for e-commerce but more substantial for teleworking. Finally, Section 6.4 sets the numerical results in context of the Swiss overall per-capita GHG emissions, addressing also the most worrying aspects and the largest uncertainties.

6.1 Commonalities and differences between the rebound effects of e-commerce and telework

Figure 19 compares the rebound effects of e-commerce and teleworking, as presented in Sections 0 and 5, respectively. The two are of course not strictly comparable, as they are measured relative to different bases – per delivery (i.e., per shopping process) and per day of teleworking, respectively. The two bases, however, are not entirely dissimilar in terms of their annual frequency: For most who take advantage of them, both online shopping and teleworking probably occur dozens of time per year, albeit e-commerce might also be rarer (i.e., only a few times per year), while the upper limit for teleworking equals the number of working days in a year, which is above 200 – teleworking thus most likely occurs more frequently than e-commerce for most.

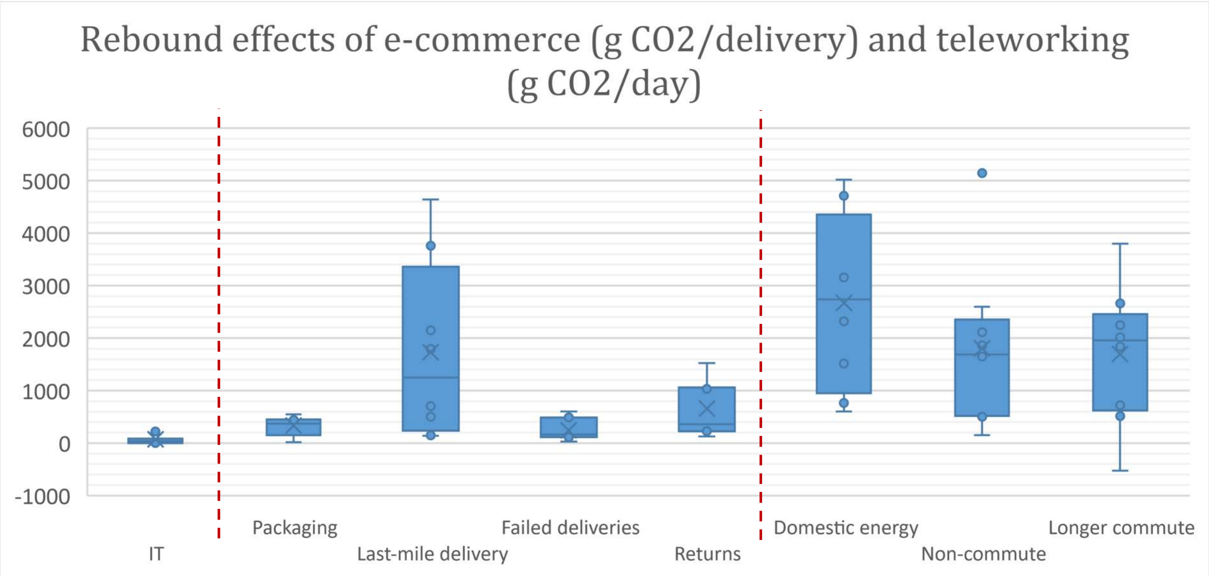

Figure 19 Juxtaposition of the rebound effects of e-commerce and teleworking, as presented in Sections 0 and 5, respectively. The (negligible) rebound effects triggered by additionally needed IT infrastructure of the two cases have been combined. Despite being relative to different bases (per e-commerce process and teleworking day, respectively), these bases are not that dissimilar in terms of their frequency of occurrence. It is thus interesting that the rebound effects are also of similar magnitude.

Because the bases of allocation are in the same ballpark (generously speaking) and not orders of magnitude apart, it is interesting that the rebound effects of the two processes are also of similar magnitude. In most instances, they will be in the order of a few kilograms of CO_2 (per e-commerce process and teleworking day, respectively). As the rebound effects stem mostly from induced additional traffic in both cases, this similarity is perhaps not surprising. A further commonality is that the ICT infrastructure additionally required for e-commerce and teleworking is a small and mostly negligible source of rebound in both cases. There are small differences though: Teleworking typically requires the usage of the additional IT infrastructure for a couple of hours per day; its effects, while substantially smaller than those of all other sources, are thus at least noticeable. For e-commerce, on the other hand, the effects are so tiny that they are barely noticeable and not worth any second thought. Despite this distinction, for most practical purposes, however, the impact of the IT infrastructure can be ignored for teleworking as well.

The good news about rebound effects that are mainly generated through additional traffic, is that their mitigation is relatively straightforward: As Section 6.2 below discusses, substituting transportation means for more environmentally friendly ones (i.e., public or low-impact private transportation such as bicycles, for teleworking; electric vehicles or cargo bicycles for e-commerce deliveries) helps mitigating the rebound effects for both cases to a substantial degree.

The rebound due to increased domestic energy consumption caused by working from home, however, is more difficult to tackle. While there is some wiggle room when it comes to the types, efficiencies and fuel types used for heating (or more generally, for heating, ventilation, and air conditioning – i.e., HVAC, systems) there is no silver bullet, no substantial paradigm shift that would reduce HVAC energy by orders of magnitude. The domestic energy consumption required for home office, combined with the continued usage of energy in understaffed offices, as discussed in Section 5.5, seems a rebound effect of more fundamental nature, difficult to address.

At a first, fairly superficial understanding, the last paragraph might indicate that the rebound effect of teleworking could be in principle harder to tackle than that of e-commerce. On the other hand, however, the sources of rebound for teleworking are quite well defined and straightforward. Other than the long-term effect of possibly moving further away from work (and which is conceptually well understood and for which measurements also exist, despite causality not being established yet), there is little evidence – and indeed seemingly little potential – for very subtle, intricated and hard to grasp indirect rebound effects. As a comparison of Sections 4.5 and 5.5 shows, however, e-commerce has several such sources that are even qualitatively hard to figure, and much more so quantitatively. The most worrisome among them seem to be two causes: i) the market tendency away from traditional e-commerce distribution pathways and towards longer, less efficient delivery directly from overseas, and ii) the fact that unlike work, there is no clear and well-defined boundary for consumption.

While none of them has been thoroughly assessed so far in literature, they both might induce unwanted and potentially substantial rebound effects: The tendency towards longer distribution pathways makes not only deliveries much more energy-intensive, but also returns. It also increases the chances of overproduction of cheap but environmentally damaging goods, which end up either underutilised or returned and then destroyed. The convenience of online shopping, which can be performed at any hour and from anywhere (e.g., late at night from the couch, from the train while travelling, or while attending a boring family reunion), makes prices comparisons and quality assessments so much easier than for traditional retail, and in general reduces transaction costs, is also likely to increase overall consumption. This, too, can lead to overconsumption (of then underutilised or returned and eventually destroyed goods), thus to overproduction, and a macroeconomic waste of resources and energy.

6.2 Mitigating the rebound effects of e-commerce and teleworking

As discussed in Section 6.1 above, the rebound effects of teleworking are both clearer defined and more limited in nature than those of e-commerce. In the first subsection (Section 6.2.1), we thus discuss here a few ways of mitigating the rebounds of teleworking. Mitigation options for the various types of rebound effects of e-commerce are then discussed in much more detail in Sections 6.2.2 – 6.2.6. The newest trends with typically far-reaching and hard-to-grasp rebound effects from Section 4.5 will be addressed in

6.2.1 Mitigating the rebound effects of teleworking

The rebound effects of teleworking have been discussed throughout Section 5 and schematically represented in Figure 12 and Figure 13. There are 4 main effects: additional IT infrastructure, additional domestic energy demand, induced non-commute trips, and longer commute due to relocation further away from work.[14] Among these 4 sources of rebound, the additionally required ICT infrastructure has fairly negligible impact, as discussed at various points throughout this study and summarised in Figure 19. As it is also crucially required as enabler for teleworking, it is not worth discussing its mitigation.

The magnitude of the rebound effects (expressed in GHGs) of newly induced trips as well as longer commutes, crucially depends on the length of these novel trips. The choice of travel mode, however, is also highly relevant for the overall environmental impact. Mitigating these two sources of rebound thus boils down to either aiming to reduce their length, or to maximise the usage of sustainable transportation modes.

The length of trips, unfortunately, seems to be fairly constant between teleworkers and non-teleworkers. In one of the few large-scale survey available, and building on the very thorough "Mobility and Transport Microcensus" (MTMC) carried out every 5 years in Switzerland, which consists of interviewing tens of thousands of households about their mobility behaviour, (Ravalet and Rérat 2019) show that Swiss teleworkers travel slightly more every week than non-teleworkers. This happens – presumably due to these two rebound effects combined, and the discrepancy of the two groups seemed to be growing from 2010 to 2015, the years of the two assessments.

As for the choice of transportation modes, Section 5.3.4 discussed that moving further away from an urban workplace and into suburban or rural areas can be correlated not only to longer commute distances, but also to a less sustainable choice of transportation modes for those distances. Two causes seem to at play here: the longer distances make emission-free transportation such as walking or cycling less likely, and the fact that suburban and rural areas are typically less well covered by public transportation. By contrast, in Switzerland the opposite seems to be the case. Referring to the longer commute distances of teleworkers, (Ravalet and Rérat 2019) observe that these are "mainly travelled using public transport, especially by train."

It would thus seem that the two levers (i.e., length of trips and modal choice) that determine the magnitude of these two rebound effects (i.e., induced non-work trips and longer commute) are either very rigid or deeply locked into the current socio-economic system – or the "socio-cultural regime", using the terminology from Frank Geels' multi-level perspective on technological transitions (Geels 2011): While the distance travelled might be relatively constant, the choice of modes appears largely dependent on the local transportation infrastructure and culture. If this is correct, then the former is impossible to mitigate (i.e., decrease), while the latter is changeable, but only over long periods of time and substantial financial efforts and societal resolve. A tendency towards more sustainable transportation modes also outside urban areas is a desirable societal goal far beyond the additional transportation induced by teleworking (and indeed by e-commerce), and it does not need to be addressed here.

The magnitude of the last identified rebound effect of teleworking (i.e., additional domestic energy consumption), also depends to some extent on factors that are either immutable or less changeable in the short term, such as geographic and climatic attributes (weather, amount of solar radiation), features of the property (its size, insulation, and heating technology) or of the infrastructure (the local electricity mix). Arguably the most important factor, however, is largely behaviour-dependent and thus changeable in the short term. It turns out that the additional domestic energy consumption induced by teleworking largely depends on whether only one room (i.e., the home office) of the dwelling will be heated in winter and cooled in summer, or the entire property. In their far-reaching analysis based on a large dataset, (Shi, Sorrell, and Foxon 2023) devise a factor of about 2.55 in additional heating energy if the entire property is heated for teleworking instead of a single room, thus highlighting the importance of reducing the heating area: "if a full-time teleworker only heats one room at home, he/she will have 16–85% higher

[14] Additionally, Section 5.5 also discussed the possibly unchanged (or only marginally changed) continued office energy consumption despite the introduction of teleworking; this effect, however, is probably better conceptualised as not realised savings.

energy demand and carbon emissions than a non-teleworker, depending upon the choices made for heating time and required temperature. However, if he/she heats the whole property, this figure increases to 58–117%" (Shi, Sorrell, and Foxon 2023).

6.2.2 Reducing or eliminating additional packaging

Giving up last-mile additional packaging altogether is arguably the lowest hanging fruit in dealing with the rebound effects of e-commerce. It requires some logistics' adaptation but does not seem to require major adaptations for last-mile transportation logistics, nor substantial loss of quality of service on customer side. The environmental benefits can even work in favour of the corresponding e-commerce platform and/or delivery service used. Several delivery services started over the last years to renounce additional packaging and are partly used by important mainstream e-commerce platforms. Figure 20 presents one such example for Switzerland.

Same Day Lieferservice
Blitzlieferung in Originalverpackung

Publiziert am 08.08.2023

Bis zum Herbst 2023 können rund 60 Prozent der Schweizer Haushalte von der Same Day Lieferung bei [redacted] profitieren. Möglich macht dies die innovative Post-Tochter [redacted] Ein grosses Plus dabei: Die gelieferten Produkte kommen ganz ohne zusätzliches Verpackungsmaterial aus.

Figure 20 August 2023 article announcing that 60% of Swiss population were already covered by a delivery service that deploys no additional packaging: This delivery service, a subsidiary company of the Swiss Postal service, is used by the largest Swiss e-commerce platform for consumer electronics and consumer goods.[15]

From both personal experience with this delivery service and its delivery disclaimers, the only potential drawbacks on customer side seem to be twofold: First, as no additional packaging protects the deliveries, the original product wrapping may arrive slightly affected, dirty or soaked (the latter if the delivery takes place in pouring rain). Secondly, the delivered products are usually visible for everyone, e.g. for neighbours when the recipient is not at home and the package left in common areas of the building – for some customers and/or some types of deliveries (which, for example, might reveal specific preferences or available budget), this might represent a breach of privacy. The company openly announces this in a disclaimer during the online order process, as shown in Figure 21.

Achtung!
Aus Umweltgründen kommt dieses Produkt ohne zusätzliches Verpackungsmaterial. Der Inhalt ist wahrscheinlich sichtbar.

Figure 21 German-speaking disclaimer being sent along the delivery notification from the service addressed in Figure 20, and which reads: "For environmental reasons, the product will be delivered without additional packaging. The content is probably visible".

[15] See https://www.logistikpunkt.ch/de/pages/logistik/2023/blitzlieferung-in-originalverpackung.

6.2.3 Reducing the returned products rate

Reducing the rate of returns is a meaningful measure to reduce various types of e-commerce rebound effects: to minimise traffic due to traditional short-distance e-commerce returns as discussed in Section 4.3.5, but also to minimise the more recent, subtle, and hard to quantify long-distance returns as discussed in Section 4.5.3 as well as the possibly associated higher rate of destroyed new goods as discussed in Section 4.5.4.

The rate of returns, and thus the rebound effects it triggers, is highly dependent on the product type: It is typically low for large expensive items such as furniture or large household appliances, very low for food (Allen et al. 2018), but high to very high for clothing (Edwards, McKinnon, and Cullinane 2010; Wiese, Toporowski, and Zielke 2012; Allen et al. 2018; Buldeo Rai, Touami, and Dablanc 2023) and consumer electronics (Van Loon et al. 2015). Unfortunately, garments and consumer electronics are also the goods most likely to quickly become out of fashion or technologically obsolete, and thus destroyed without ever having been used, as argued in Section 4.5.4.

For these two categories of goods, it is thus particularly important to reduce the rates of returns. Possible measures include changed return policies (for both) or technical measures that could guarantee a better fit (for clothing). According to (Allen et al. 2018), in 50% – 75% of cases, returns are free for consumers and paid for by the online retailer. Such policies not only increase returns (and thus rebound effects and detrimental environmental consequences), but are generally also economically not worthwhile for the retailer – the costs of free returns tend to be higher than the additional benefits due to the increased turnover supported by free returns (Patel et al. 2021). Being less generous with return policies might thus be desirable both from an environmental and economic perspective.

For clothing specifically, technical measures (such as smartphone pictures combined with machine-learning-based automatic sizing) or logistic ones, such as garment delivery to a “try and buy” neighbourhood store, where customers need to visit and decide upon the right fit (Allen et al. 2018), can ensure a better fit for garments purchased online, and thus hopefully also less returns.

6.2.4 Optimising last-mile delivery distance: Reducing return distance, failed delivery rates, and using longer delivery intervals

After reducing the return rate, the mileage generated by remaining product returns could also be minimised. This can be achieved, for example, by planning the collection of returned items as part of the regular delivery rounds (Edwards, McKinnon, and Cullinane 2010), in which the same van that delivers new parcels picks up returns instead of performing extra trips.

Reducing failed delivery rates (and thus the need for re-deliveries) is another beneficial strategy. Failed delivery rates depend on several factors. One of the most important is the deliverer’s policy when not encountering the recipients at home. If the delivery policy is to leave the parcel with neighbours or even on the porch, garden shed or other relatively unsafe places, failed deliveries are much lower than when the delivery company requires a proof-of-delivery signature (Edwards, McKinnon, and Cullinane 2010).

Such policy, of course, may increase the rate of theft and unjustified complaints (customers who dishonestly claim to not have received the package). Its feasibility depends on various socio-cultural factors, but can be encouraged by the customer specifically indicating whether – and where – the parcel is to be delivered in case of absence. If the rate of theft and dishonest complaints can be kept low enough, dealing with parcel deliveries more liberally when recipients are not at home might also make sense economically, and not only environmentally.

Finally, another measure to optimise last-mile delivery is to allow for longer delivery intervals, which enables a better route optimisation for the delivery service (Manerba, Mansini, and Zanotti 2018). There is a trade-off, however, between the route optimisation brought about by this measure and the convenience for customers and the thus-related failed delivery rate. A way out of this dilemma, which is being deployed by some delivery companies, is to allow customers to choose themselves if they require a tight delivery window or are more flexible and can allow for a larger window in the interest of more efficient deliveries.

6.2.5 Alternative last mile delivery vehicles: electric, automated, and cargo bicycles

For a given last-mile delivery distance, one further strategy to reduce the rebound effects of last-mile deliveries is to minimise their per-kilometre energy consumption (and thus also GHG and pollutant emissions). This can be achieved mainly in two way: through lighter vehicles and through electrified ones. Lighter vehicles can be e.g. mini-vans or even cargo-bicycles as substitutes for regular vans. All sizes of delivery vehicles can additionally be electrified, whether regular-sized vans, mini-vans or cargo bicycles. Figure 22 shows the example of such efficient delivery vehicle deployed for groceries in Zurich, Switzerland.

Figure 22 Grocery delivery in Zurich, Switzerland using an electric min-van; October 2023.

While the two heuristics mentioned above (i.e., light and electric vehicles), are certainly by and large correct, existing comparisons of last-mile delivery GHGs have to be taken with a grain of salt. They are subject to a large variability in the carbon intensity of electricity for the location of their respective case studies. This can skew results and make them difficult to compare between regions of differing electricity mixes. It can also make savings appear huge when only operation is considered, and not the production, while the electricity mix is nearly carbon-free. Assessing various electric delivery options such as electric vans, road automated delivery robots (RADRs) or sidewalk automated delivery robots (SADRs), (Figliozzi 2020) finds GHG savings of between 97.5 – 99.2% as compared to a traditional ICE delivery van. Even quite inefficient aerial drones save in this analysis 94.2 – 98.6 % as compared to the ICE van. Most of these savings are due to the very low-carbon electricity under scrutiny.

While the electrification of transportation (as well as heating) combined with the decarbonisation of electricity is indeed one of the important paths to combat the climate crisis, the decarbonisation of the electricity system will take decades in the most optimistic scenario (MacKay 2009). The smaller the overall amount of energy consumption, the easier it becomes to be delivered from low-carbon sources (i.e., renewables and nuclear).

Reducing the overall energy consumption of transportation is thus arguably at least as important as electrifying it. Comparing the energy consumption (and not the GHG emissions) of different last-mile scenarios, (Moore 2019) puts forward more realistic savings of 40 – 77% for the terrestrial electrified scenarios when compared to the ICE baseline, and just 13% savings for aerial drones. Generally, it seems that the more exotic alternative delivery vehicles are not a benefit from the environmental perspective, as automated delivery robots for either the last metres (from a human-driven vehicle) and an entirely automated last-mile delivery worsened the GHG emissions in (Li et al. 2021).

Considering the entire life cycle – which also includes the production of delivery vehicles – is certainly the better modelling, which reflects reality closer. Replacing diesel vans with electric vehicles (EVs) for the last mile delivery can improve transportation-related GHG emissions (from a life cycle perspective) between 17 – 54% (C. Siragusa et al. 2022) or 15 – 48% and even 69% for a low carbon intensity of the electricity mix (Lal et al. 2023). The amount of savings correlates positively with the daily driven distance (C. Siragusa et al. 2022), as the production impact, similar between the two, becomes relatively less important with increasing distance. As expected, it correlates negatively with the carbon intensity of the grid mix – the lower the carbon intensity of electricity, the larger the savings. These GHG savings are computed for relatively low-carbon electricity mixes; when looking at energy savings from a life-cycle perspective, it is likely that they would be more modest.

Unsurprisingly, cargo bicycles (whether purely mechanical or electric) perform best as last-mile delivery vehicles. Previous work has studied various flavours of such vehicles, such as: human-powered tricycles in central Beijing (Zacharias and Zhang 2015), human-powered cargo bikes (Ballare and Lin 2020), and electric cargo bikes (Shahmohammadi et al. 2020) – their GHG reduction potential lies indeed at 99% or more when compared to ICE-powered delivery vans.

Finally, electric last-miles delivery vehicles are beneficial not only for reducing GHG emissions but also other negative externalities of road traffic, such as air pollution or noise, or improving road safety – they have, for example, be proven to substantially decreasing local emissions of particulate matter (PM) and nitrogen oxides (NO_x) (Iwan et al. 2021).

6.2.6 Self-collection at pickup points and lockers

A final option to optimise last-mile deliveries is the usage of neighbourhood pickup locations, which can be pickup points or lockers. The former are typically operated by humans and can be, for example, post offices, newspaper stands, neighbourhood grocery stores, and alike, where customers can pick their parcels up during opening times. Lockers are directly operated by customers, for which they typically receive an access code (or a variation thereof, such as an QR code), and are sometimes also called “automated parcel station” (APS) (Ballare and Lin 2020). Lockers can be indoors (such as shopping centres, convenience stores or gas stations) or streetside, and can thus be operated during opening hours or 24/7, respectively. In both cases, couriers do no longer need to bring the deliveries to individual households but to a central location in the neighbourhood. This substantially reduces last-mile delivery through the couriers but induces new customer trips to the pickup points or lockers.

These trips are not unlike the shopping trips to physical shops saved by e-commerce and delivery in the first place. However, they might save energy and emissions when compared not only to traditional shopping but also to home deliveries of e-commerce for several reasons: i) pickup points and lockers are typically (much) closer to customers than the shops, ii) due to this closeness and as deliveries (other than groceries) typically consist of individual or few products, they can rather be picked up on foot or bicycle, and iii) pickup can often be performed on the way to or from home, thus not inducing a new trip, but enhancing the (environmentally beneficial) multimodality of trips (E.D. Williams 2002). To maximise this last effect, it is important that pickup points or lockers are locations that consumers already visit regularly, such as a neighbourhood grocery or convenience store (Junbeum et al. 2008) or at the entrance of cul-de-sac neighbourhoods (Moore 2019).

Lockers can induce energy savings of 48% as compared to home deliveries, and of 88% when also combined with electric vans (Moore 2019).

6.2.7 Addressing the subtler rebound effects due to long-term behavioural changes

Section 4.5 presented several further sources of rebound effects for e-commerce, which rely on more profound changes in behavioural patterns or business practices. Some are very new developments (i.e., the direct cross-border deliveries from Section 4.5.3), some are not that new but their increased importance due to e-commerce has recently been recognised (i.e., the scrapping of returned items, whether new or used, discussed in Section 4.5.4), and others rely on recently conceptualised behavioural patterns (i.e., the fact that online shopping does not fully substitute physical shopping activities, but often merely complements it, see Section 4.5.1, and the additional consumption induced through both direct and indirect rebound effects by the comparative affordability and convenience of e-commerce, see Section 4.5.2).

Two of these effects seem to be tightly intertwined with the new possibilities of the digital economy and thus difficult to mitigate: Referring to the merely partial substitution of online for traditional shopping (Section 4.5.1), it is not obvious which economic, fiscal or regulatory measures (or which awareness campaigns, for that matter) could be successfully deployed to encourage customers to fully replace their former physical shopping through e-commerce. Nor is it clear whether such measures would be ethical (and not perhaps too much of an infringement of personal freedoms such as freedom of movement). Finally, it also does not seem too important: As argued in Section 4.5.1, the physical trips to stores are likely to result in purchases of far fewer items than in the counterfactual of a world without e-commerce, and thus be more likely combined with other trips and suitable for more sustainable transportation modes.

Likewise, the additional consumption induced through direct and indirect rebound effects of e-commerce (Section 4.5.2) appears deeply entangled with the new possibilities and thus hard to counteract. It would, however, be important to do so. By contrast to the last category, the magnitude of these rebound effects can be substantial. Online retailers understandably want to maximise their turnover and are in a fierce competition with tight margins; it would thus not be realistic to expect them to fight these sources of rebound. Centralised government measures seem possible, whether awareness campaigns or nudging against consumerism or fiscal measures (such as a ubiquitous carbon tax that would implicitly discourage overconsumption). However, caution is required here as well, as such measures also aim at limiting individual freedoms such as economic freedom or freedom of choice.

The long-haul, cross-border deliveries (Section 4.5.3) as well as the increased likelihood for scrapping returned items (Section 4.5.4), on the other hand, are both conceptually more straightforward to address and ethically less controversial. They can both be addressed legislation and regulatory measures, and to some extent also by company-level policy measures and awareness campaigns. These measures are presented among the recommendations in Section 7.2 of the Conclusions below.

6.3 The literature on environmental effects of teleworking in Switzerland

The literature review found only one study examining the environmental effects of e-commerce in Switzerland. And this one study additionally has quite a narrow scope, only considering trips to the store for traditional shopping versus additional packaging and last-mile delivery for online shopping; but without considering any possible last-mile delivery rebounds (Hischier 2018). For e-commerce, it is thus impossible to discuss any Swiss particularities based on the literature.

By contrast, the literature searches and snowballing discussed in Section 3 revealed five Swiss studies that investigate the environmental effects of teleworking. Table 3 summarises them, together with the indicators used, a short presentation of the main results, and the extent to which rebound effects are considered. All are quite far-reaching and of high quality, but not all are within scope of our analysis: (Giovanis 2018) is out of scope as it does not focus on energy or GHGs but pollutants; it also does not discuss rebound effects. (Hostettler Macias, Ravalet, and Rérat 2022) is a systematic review of the literature on mobility-related rebound effects of teleworking that aims at revealing research gaps and proposing a research agenda; it thus performs its review conceptually, not quantitatively. Finally, (Ohnmacht, Z'rotz, and Dang 2020) examines a different remote work flavour that was relatively more important before the Covid pandemic: work from (and thus travel to) co-working spaces. As it also only considers one source of rebound (i.e., the longer commute of co-workers when they do commute to their company offices), it is also relatively out of scope for us.

Very much within our scope, and with a consideration of rebound effects at their very core, are the remaining two studies: (Ravalet and Rérat 2019) and the study commissioned one decade ago by the BFE, (Perch-Nielsen et al. 2014). The former considers both of the travel-related sources of rebound, i.e. longer commute and induced non-work trips, and finds evidence for both. The indicator, however, is travelled distance, not energy or GHGs. Due to the various transportation modes used, it is difficult to make assumptions and transform the distance-related rebound effects into energy or GHG rebounds. However, as the distance travelled weekly by teleworkers was both in 2010 and 2015 higher than that travelled by non-teleworkers, and the modal split is relatively similar, it is fair to assume that the rebound effects lead to backfire, i.e., a rebound effect larger than 100% (see Section 2.1.2).

In a partial overlap, the BFE-commissioned study (Perch-Nielsen et al. 2014) considers two sources of rebound: increased domestic energy consumption, and induced non-work trips. It does not measure the rebound effects directly, but assesses them in two scenarios: one of mild and one of strong rebound. For traffic, both scenarios yield fairly mild rebound effects, of 7% and 23%, respectively. For the domestic energy, however, even the conservative assumption of 4 square metres required working space at home per teleworker yields a backfire (rebound of about 114%). For the more realistic assumption of additionally heated 12 square metres per teleworker, the rebound is about 355% (approximately 199 GWh for savings of 56 GWh), turning the overall net energy effect of traffic and office energy cumulated into the negative.

Table 3 Swiss studies on the environmental effects of teleworking. (Giovanis 2018) does not focus on energy or GHGs but pollutants, and does not discuss rebound effects. (Hostettler Macias, Ravalet, and Rérat 2022) is a systematic review of the literature on mobility-related rebound effects of teleworking; but a conceptual one, not a quantitative one. (Ohnmacht, Z'rotz, and Dang 2020) examines travel to co-working spaces and considers one source of rebound, the longer commute of co-workers when they do commute to their company offices. (Ravalet and Rérat 2019) consider both of the travel-related sources of rebound, i.e. longer commute and induced non-work trips, and find evidence for both. Their indicator, however, is travelled distance, not energy or GHGs. The BFE-commissioned study (Perch-Nielsen et al. 2014) considers two sources of rebound: increased domestic energy consumption, and induced non-work trips.

Study	Indicators	Main results	Consideration of rebound
(Perch-Nielsen et al. 2014)	Energy [GWh]	0.9% of work performed remotely, -1% traffic. - 56 GWh from desk sharing, - 70 GWh from less traffic through homeworking, - 12 GWh from other forms of mobile work.	Yes, two types: i) from additional domestic energy demand and ii) from induced non-work trips. Two scenarios of mild and strong rebound effects. In the latter, overcompensations of savings due to massively increased energy usage at home.
(Giovanis 2018)	Various pollutants	Population teleworking (TW) partially (2013): 8.4% → -1.9% traffic, -3.6% NO_2, -3.5% CO, -3.3% PM_{10}, - 2.3% O_3, - 2.1% SO_2	No. Paper out of scope for our study.
(Ravalet and Rérat 2019)	Distance travelled [km]	16.5% TW occasionally, 4.6% intensely in 2010; 18.2% and 6.1% in 2015, respectively. On office days, TWs commute longer than non-TWs (20 vs 15.7 km on average in 2010, 24.6 vs. 16.1 km in 2015). Higher weekly overall travel for TWs: 243 vs. 227 km in 2010, 244 vs. 210 km in 2015. No important modal shifts though.	Yes, both important travel-related sources of rebound: longer commute and induced non-work trips.

(Ohnmacht, Z'rotz, and Dang 2020)	GHGs [CO_2]	Compares commute-related GHG emissions of co-working spaces (both urban and rural) with those of traditional office work. Co-workers have on average lower yearly commute-related emissions than non-co-workers, 554 kg vs. 797 kg CO_2.	One source of rebound is implicit in the data: the longer distances that co-workers have to travel when they do commute not to the co-working place but to their company's offices. Non-commute trips, on the other hand, are not covered by the study. And other sources of rebound effects such as domestic heating, are out of scope.
(Hostettler Macias, Ravalet, and Rérat 2022)	None	Swiss-based authors, but not a Switzerland-specific study, nor one that put forward any quantifications. It is instead a systematic review of the mobility-related rebound effects of teleworking.	Yes, the main focus of the article lies on rebound effects, albeit not quantitatively, but conceptually/taxonomically in order to propose a research agenda.

6.4 Putting the rebound effects of the two domains into an overall Swiss perspective

Based on the reviewed literature, Figure 19 presented the magnitudes of the rebound effects for both e-commerce and teleworking. Adding the five individual sources together results in a median rebound effect for e-commerce of **2,151 g CO_2 per online shopping** instance (with a first and third quartile of **732 g CO_2 and 5,392 g CO_2**, respectively).

What does this mean as compared to a person's overall carbon footprint, for example in Switzerland? In the following analysis, we will consider two perspectives on the country-wide (and thus also on the average individual's) emissions: production-based and consumption-based emissions. Production-based emission accounting is the default one used in international treaties such as the 1997 Kyoto Protocol or the 2015 Paris Agreement: It estimates the emissions produced within a country's borders. By contrast, consumption-based accounting attributes the emissions generated in the production of goods and services (often referred to as "grey emissions") to their country of consumption.[16]

To change from the production to the production perspective, the grey emissions of imported goods need to be added, and those of exported goods to be subtracted in a country's assessment. For rich countries such as Switzerland, which typically import substantially more carbon-intensive goods than they export, this perspective change typically leads to a substantial increase of the (overall and thus also per-capita) emissions. For Switzerland, for example, the average GHG emissions per Swiss inhabitant amount to about 5 t CO_2eq./year from a production perspective and about 13 t CO_2eq./year from a consumption perspective.[17]

At the same time, according to the survey performed by a shipping company in May 2024, Swiss online shoppers received an amount of 5.2 parcels per month (i.e., 62.4 per year).[18] The exact semantics of "Swiss online shoppers" is not defined, but we presume it refers to "Swiss households which order online". The reason is that according to various sources, the Swiss e-commerce market is currently about 15 billion CHF per year.[19] If these 62.4 orders per year had been per average Swiss online shopper (over 5 million), the resulting 310 million yearly orders would have had an average value of just below 50 CHF; far lower than the actual average order value of 220-300 CHF for smartphone and laptop orders, respectively.[20] By considering the 62.4 statistical orders per household (and not per individual

[16] See, e.g., https://www.myclimate.org/en/information/faq/faq-detail/who-produces-co2/.
[17] See https://www.bafu.admin.ch/bafu/en/home/topics/climate/in-brief.html.
[18] See https://www.dpd.com/ch/en/news/e-shopper/.
[19] See, e.g., https://www.mordorintelligence.com/industry-reports/switzerland-ecommerce-market, or https://www.gfk.com/de/presse/ch-onlinehandel-2024.
[20] See https://www.swissinfo.ch/eng/life-aging/online-spend-increasing-in-switzerland/73447357.

e-commerce user), the numbers are more compatible, albeit still not a perfect fit. For such a household, then, these 62.4 statistical shopping instances amount to a median of 134 kg CO_2/year rebound effects of online shopping (with an interquartile range of 45 – 336 kg CO_2/year).

In Switzerland, there are about 4 million households with an average household size of 2.18 persons,[21] of which 83% shop online.[22] Given the 5 t CO_2eq. (production-based) and 13 t CO_2eq. (consumption-based) annual per-capita emissions, the average household of 2.18 persons is thus responsible for about 10,900 kg CO_2/year from a production perspective and much more substantial 28,340 kg CO_2/year from a consumption perspective.

To account for the 83% of households that are shopping online, we scale down the 134 (45 – 336) kg CO_2/year rebound effects of online shopping per household by a factor of 0.83, yielding **111 (37 - 279) kg CO_2/year** rebound effects of online shopping per average Swiss household, accounting also for the 17% of households that do not shop online.

1) *Putting this into the context of the overall average Swiss per-household GHG footprint, yields the following percentages (which can be interpreted as per-household, per-capita or for all of Switzerland, as the allocation for any of these bases of calculation changes both parts of the fraction and does not affect the percentage):*
   - **1.02% (0.41% – 3.08%)** of the Swiss GHG footprint from a production perspective, and
   - **0.39% (0.16% – 1.19%)** of the Swiss GHG footprint from a consumption perspective.

Performing a similar analysis for teleworking and adding the individual rebound sources represented in Figure 19 together, yields a **median rebound effect per teleworking day of 6,463 g CO_2**, with an interquartile range from **4,007 g CO_2 – 9,417 g CO_2**. To compute a yearly aggregation, we assume an average of 2 teleworking days per week (which is in line with the assumptions and averages used throughout Section 5). From the 236 working days per year (consistent with the assumptions in Section 5 and accounting for holidays and sick leave), the 40% average teleworking days amount to 94.4 average teleworking days are then responsible for a rebound effect of **610 (378 – 889) kg CO_2** per year.

To put this into the perspective of the per-capita GHG emissions of Switzerland (which is computed for the entire population), it needs again to be scaled down to the share of teleworkers among the entire population. This can also be computed as share of teleworkers among the working population times the share of the working population among the total population. As the Swiss working population is currently about 5.3 million[23] from the country's total resident population of roughly 9 million[24], of which 26% can at least partially work from home,[25] a factor of 0.26 * 0.59 = 0.15 needs to be applied, yielding an average of **91 (57 - 133) kg CO_2** of rebound effects due to teleworking per year and Swiss resident, whether (tele)working or not.

2) *Relating these numbers to the average per-capita Swiss GHG emissions (this time using not the per-household emissions as above, but the individual emissions of 5t from a production and 13t from a consumption perspective, as we are considering residents not households) yields*
   - **1.82% (1.14% – 2.66%)** of the average Swiss per-capita GHG footprint from a production perspective, and
   - **0.7% (0.44% – 1.02%)** of the average Swiss per-capita GHG footprint from a consumption perspective.

[21] See https://www.bfs.admin.ch/bfs/en/home/statistics/population/families/households.html.
[22] See https://www.s-ge.com/en/system/files?file=event/downloads/Presentazioni%20Foodtech%20Ecosistema%20Svizzera-Italia%2018.06.2024%20-%20Parte%202_0.pdf&ct.
[23] See https://www.bfs.admin.ch/bfs/en/home/statistics/work-income/employment-working-hours/economically-active-population/labour-market-status.html.
[24] See https://www.bfs.admin.ch/bfs/en/home/statistics/population.html.
[25] See https://ux-tauri.unisg.ch/RePEc/usg/econwp/EWP-2213.pdf.

For the teleworkers themselves, these numbers are of course much more substantial, as the scaling down with the factor of 0.15 must not be performed and the full 610 (378 – 889) kg CO_2 per year need to be put in relation to their overall yearly GHG footprint.

3) *It is questionable whether these numbers can be related to the Swiss per-capita average of 5t / 13t CO_2 per year, as the footprint of the working population, and of teleworkers in particular, is arguably substantially above the average. But if under these relatively simplistic assumptions, it would yield per teleworker:*

- **12.2% (7.56% – 17.78%)** of the average Swiss per-capita GHG footprint from a production perspective, and
- **4.69% (2.90% – 6.84%)** of the average Swiss per-capita GHG footprint from a consumption perspective.

Comparing the estimates (1) and (2) for the two domains, teleworking has the higher impact but lower variability and less uncertainty (it also does not have the subtle and potentially far-reaching rebound effects of e-commerce that are not well understood nor yet quantified, as presented in Section 4.5 and discussed in Section 6.1). This rebound of teleworking can also grow substantially towards the results from (3), if a larger share of the population will start teleworking and the average share of telework also increases from our 40% assumption.

The 7.56 – 17.78% range from (3) is perhaps surprisingly high. But it becomes less surprising when considering that the main rebound effects of teleworking occur as additional traffic and additional domestic energy demand. These are the two domains responsible for the majority of Switzerland's GHG emissions, with 33% due to transport (of people and goods alike) and 23% in buildings (homes as well as offices).[26] It is thus hardly surprising that they also represent the lion's share in everyone's personal GHG footprint, and that a profound paradigm shift of the mobility and house heating patterns can have substantial impacts in anyone's individual footprint.

Crucially, this range does not represent the net effect of teleworking (computed as savings – rebound). Our study focused on the rebound effects of the two domains and did not aim to quantify the savings as well or to compute the net effects. In both domains, and for teleworking in particular, however, there are also substantial savings, as has been highlighted from the outset of this study. Even if for regular teleworkers, the rebound effects of teleworking represents 7, or 12, or 17 percent of their individual GHG footprint, this does not mean that the net effect is as high; on the contrary, it will typically be much lower. What it does mean, however, is that after the savings induced by teleworking, there is quite a substantial counteracting rebound effect – and an important opportunity to truly realise the environmental potential of digital services such as teleworking, if their rebound effects can be mitigated.

[26] See https://www.bafu.admin.ch/bafu/en/home/topics/climate/in-brief.html.

7 Conclusions

The increasing digitalisation of our societies and economies brings about three types of environmental effects: direct effects (i.e., the footprint), beneficial indirect effects, and detrimental indirect effects. Environmentally beneficial indirect effects lead to less energy and resource use, emitted GHG and pollution through mechanisms such as efficiency gains or dematerialisation. Meanwhile, environmentally detrimental indirect effects yield more consumption, emissions and pollution through several mechanisms, chief among which various forms of rebound effects (Coroamă et al. 2020; Bremer et al. 2023).

Digital services often enable new socio-economic paradigms, which also yield indirect environmental effects. Both the positive and the negative ones tend to be much more important than the direct footprint of the ICT devices enabling them (Coroamă and Mattern 2019). Indirect effects can thus be important levers both to mitigate, but also to worsen the multiple environmental crises of today. It is thus paramount to conceptualise them, be able to reasonably quantify them and understand their orders of magnitude, and to explore ways to foster the beneficial effects and limit the detrimental ones.

7.1 New forms of working and shopping, and their energy and climate effects

In this context and reflecting their outstanding importance, this study investigated the indirect energy and GHG effects induced by digitalisation in two societal domains that recently underwent substantial metamorphoses: shopping and work. In these two fields, enabled by technological means and changed societal habits and norms, the paradigm shifts towards online shopping / e-commerce and teleworking, respectively, gain increasing traction. While they are both decade-old concepts that could be accomplished with the technologies of – say – the 1980s as well (online shopping using the French Minitel system, for example, and teleworking via telephone and fax machines, respectively), they have only really matured over the last 15-25 years thanks to various enabling technologies that have themselves appeared or matured. Large and easy to navigate online shops and high-quality videoconferencing platforms, respectively, require a variety of underlying technologies such as widespread, fast and reliable Internet connectivity, ubiquitous quality webcams, safe and easy to use online payments, or co-evolving logistics of the physical delivery services.

Whilst the technological maturity enabled them to steadily grow, the real boost for these two domains came with the Covid-19 pandemic: With societal life abruptly coming to a halt and the need to have as large a share of the population as possible self-isolating, it was all of a sudden discovered that e-commerce and teleworking had been up for grabs the entire time, and could be swiftly deployed to continue these crucial societal and economic activities while minimising social contact.

These new forms of shopping and working bring about potential energy and environmental benefits, mainly from less travel to stores and work commute. They both, however, also harbour the potential for substantial rebound effects. The possible benefits have often been highlighted, the potential drawbacks less so. This study has thus examined both qualitatively but also (to the extent possible) quantitatively the rebound effects induced by e-commerce and teleworking.

For each of the domains, it has shown the main sources for rebound effects. Based on a systematic literature review, it further presented and summarised existing quantifications for each of these sources, revealing where the main perils lie. For e-commerce in particular, the study further presented further subtler sources of rebound, which are harder to grasp, and several of which are very recent developments. To conclude the study, we now present a couple of recommendations drawn from our analysis and possible avenues of further research that we deem important.

7.2 Recommendations

As discussed in Section 6.1, among the two domains considered in this study, the rebound effects of e-commerce are more worrisome: they are more varied, potentially substantially larger, without clearly distinguishable upper limits, and certainly harder to grasp. Fortunately, however, they are also more straightforward to address, as the business models triggering them do not seem at the core of our societal or economic life. Nor do potential measures for their mitigation seem to put any fundamental freedoms at risk. By contrast, the rebound effects of teleworking seem more intimately interwoven with new societal norms of working and thus the current socio-cultural regime (Geels 2011). Possible measures towards their mitigation are ethically questionable since they might touch upon fundamental freedoms such as the freedom of establishment or movement (see Section 6.2.7).

Given that the rebound of e-commerce is potentially more dangerous and at the same time it can be addressed easier and with less ethical concerns than the rebound of teleworking, most recommendations focus on the former domain. While focusing below on the example of clothing and the fast fashion phenomenon, the discussion and the recommendations can be applied almost unchanged to other types of products such as electronics.

Four categories of stakeholders can generally undertake actions against environmentally detrimental developments: i) Policymakers, ii) the industry, iii) retailers, and iv) consumers (Niinimäki et al. 2020). While we address most categories below, most recommendations aim at policymakers.

7.2.1 General measures against overconsumption

One worrying tendency of e-commerce is its propensity to induce additional consumption both through direct rebound (due to lower costs) and indirect rebound (due to increased convenience, lowered transaction costs, and newly available marketing channels), as discussed in Section 4.5.2. For clothing in particular, this can contribute to accelerating the tendency towards fast fashion; it is acknowledged that “fast fashion requires fast marketing” (Sheridan, Moore, and Nobbs 2006).

For these reasons, e-commerce seems bound to exacerbate the trend towards overconsumption.[27] General strategies that address overconsumption are hence likely to also address to some extent the additional amount of overconsumption induced by e-commerce. Such strategies can be regulatory (restricting access to resources or the amount of pollution or emissions one can be responsible for), fiscal (increasing the costs for resource use, pollution, and emissions through environmentally-based taxation), consumer-oriented (awareness campaigns and appeals), or consumer-initiated such as boycotts (Brown and Cameron 2000).

7.2.2 Measures subjecting large online sales platforms to inland legislation and regulation

The advent of much more decentralised e-commerce ecosystems, in which large online platforms connect overseas vendors directly to customers, risks to further speed up the trend towards fast fashion, leading to what has been called “ultra fast fashion”.[28] Beyond further accelerating overconsumption, such platforms can also substantially worsen the environmental performance of deliveries and returns (see Section 4.5.3) and, because of how quickly fast fashion grows out of fashion, increase the likelihood of returned clothing items (of which there are many in online shopping) be scrapped (see Section 4.5.4). Addressing these platforms specifically could thus be meaningful, especially since the manufacturers (category ii of stakeholders) of the goods they trade are typically overseas, and thus outside the influence of inland legislation and regulations.

The online platforms connecting overseas manufacturers with inland customers are typically also registered overseas. One promising public policy, however, is to legally “internalise” these overseas retailer platforms. This is what the European Commission has recently undertaken with the online retail platform

[27] The term ‘overconsumption’ has two meanings: defined as social criticism of an overly consumeristic society, where the focus is to challenge the notion that increased consumption of material goods leads to more happiness. From an environmental perspective, the question shifts towards the appropriate use of natural resources (Brown and Cameron 2000), pollution and emissions. We discuss here exclusively the environmental perspective, although there is some correlation between the two.
[28] See https://www.mdr.de/mdr-thueringen/audio-service-ultra-fast-fashion-100.html.

addressed in Section 4.5.3: By designating it as a “Very Large Online Platform” under the European Digital Services Act,[29] it brought it on equal footing with European counterparts, and thus subject to European legal, customer protection, safety, and environmental regulations.

7.2.3 Extended carbon border adjustment mechanisms (CBAMs)

As discussed by several of the sources listed in Section 4.5.3, the success of large online sales platforms is due to the attractiveness of the extremely low prices they largely put forward. These prices are partly justified by the pressure on local manufacturers and consequent poor working conditions, partly by dumping prices used to gain market share.[30] This then leads to all the negative environmental externalities discussed so far: overconsumption, fast fashion, long delivery routes, and the destruction of unused goods.

As the manufacturers, their working conditions, and pricing are largely outside the influence of inland policies, one way to counter the extremely low prices at the root of this negative environmental (and often also social) spiral would be carbon border adjustments mechanisms (CBAMs), which represent “a policy that charges a fee for imported goods based on how much climate pollution was created making them” (Wolfram and Krol 2023). The EU was the first to introduce such a mechanism for a few domains (i.e., cement, iron & steel, aluminium, fertilisers, electricity and hydrogen).[31] Extending CBAMs to a large variety of products would increase the prices of the goods traded over online platforms to a certain minimum value irrespective of potential dumping prices.

If CBAMs would cover the GHGs embodied during transportation as well, they would additionally be an effective deterrent against flight-based transport. Finally, if fiscal measures against overconsumption are adopted (as advised in Section 7.2.1), adjusting imported products for carbon would be a necessary levelling of the playing field.

7.2.4 Measures against the destruction of unused goods

The reasons behind the destruction of unused goods are multifaceted. As listed in (Roberts et al. 2023), they can be economic (in particular for low-cost items, the costs of storage and handling can be higher than the value of the item, so it makes economic sense to rather destroy it), due to counterproductive fiscal reasons (in Germany, for example, the donation of unused items is subject to VAT on its original price, while the destruction is not[32]) or legal (for fear of being held liable for products whose quality can no longer be assured). As discussed in Section 4.5.4, returned goods are at higher risk of being scrapped, and the rate of returns in e-commerce (in particular for garments and electronics) is much higher than in traditional retail.

Beyond the measures to reduce the return rates in e-commerce addressed in Section 6.2.3, general measures to mitigate the destruction of goods would thus also address this specific rebound effect of e-commerce. Several European countries undertook steps in this direction such as eliminating the VAT on donated goods (Belgium) or the ban on destruction of unsold goods that need to be donated or recycled. While probably helpful, such measures can bring about negative side-effects, such as “waste dumping” abroad under the pretext of donations or the impossibility of recycling for many goods. These measures have also been criticised for not addressing overproduction or the high volumes of unsold/returned goods (Roberts et al. 2023).

Various further policy measures have been proposed, which can be categorised along two dimensions: their type (regulatory, market-based, and informative) and whether they aim upstream or downstream

[29] See https://digital-strategy.ec.europa.eu/en/news/commission-designates-temu-very-large-online-platform-under-digital-services-act.
[30] See https://www.srf.ch/play/tv/kassensturz/video/temu-im-fokus---gefaehrliche-produkte-und-miese-arbeitsbedingungen?urn=urn:srf:video:f4475f67-cc61-49b2-b72b-352208de273d.
[31] See https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.
[32] See https://www.tagesschau.de/wirtschaft/unternehmen/textilien-wegwerfen-101.html.

of the unsold goods or customer returns (Roberts et al. 2023). Without presenting the details here, but to give a flavour of the types of measures that have been proposed, they include: a tax on returned items (to force companies to no longer have too generous return policies), mandatory reporting of unsold stocks and returns (to incentivise companies to reduce them in order to avoid a negative image), a minimum 5-year warranty on consumer products (to generally improve the quality of products, but also to make them more expensive and thus decrease scrapping likelihood as well as minimising overall consumption), education regarding the environmental cost of returns and destruction of goods (to change norms at a cultural level).

7.3 Future research

Next to the recommendations presented in Section 7.2 above, and which aimed rather at policymakers, along the course of this study, a couple of topics were identified that require further research. These topics, aimed rather at the academic and research community, are listed in this final section of the report.

7.3.1 Causality of increased home-workplace distance for teleworkers

As discussed at length in Section 5.3.4, teleworkers live on average further away from their workplace than their non-teleworking counterparts, leading to a substantial rebound effect. While the correlation is undisputed, including in Switzerland (Ravalet and Rérat 2019), the causality is not yet understood: "do people telework to avoid a long commute, or do they choose to live further away from the workplace because their job enables them to telework?" (Caldarola and Sorrell 2022). To understand the mechanisms behind this phenomenon, and thus also possible mitigating methods, more research into the causality is needed.

In Switzerland, a currently ongoing research project at the University of Lausanne is exploring precisely this causality: "We will study the role teleworking plays in the choice of both residential and work places, the trips that are avoided and/or made possible by teleworking and the overall balance of greenhouse gas emissions of both teleworkers and non-teleworkers".[33] Next to quantitative methods, the SNF-funded project plans to deploy also qualitative methods to explore the decision-making process underlying the choice of residence. At the time of writing (June 2024), the project had published a first qualitative, systematic review of mobility-related rebound effects of teleworking (Hostettler Macias, Ravalet, and Rérat 2022).

7.3.2 Conceptual uncertainties surrounding indirect effects, including rebound

Among the numerous rebound effects of e-commerce, many are within the ability (and arguably the responsibility) of the online sales platforms and/or delivery services themselves; see Sections 6.2.2 – 6.2.6. Others can be addressed through policy measures; see Section 7.2 above. The new consumption-inducing mechanisms of e-commerce, however, are not yet sufficiently understood, in particular those triggered by indirect rebound effects. As briefly discussed in Sections 4.5.2 and 7.2.1, digital platforms enable entirely new and subtle marketing channels, lower various types of transactions costs, and increase the convenience and flexibility of shopping. Better understanding these various sources of indirect rebound effects seems key in better targeting their effects.

Related to this point, but both more conceptual and of a more general relevance which goes far beyond the domains of e-commerce or teleworking discussed in this study, are the questions on the causality, attribution, and limits of indirect effects of digitalisation, including its rebound. These are easiest discussed alongside two dimensions: time and causality, as sketched in Figure 23.

Along the time dimension, indirect effects can by definition not start earlier than the moment when the corresponding technology or service is first introduced. The question is whether they should be considered for all eternity as indirect effects (including rebound) of digitalisation or whether a point arrives in

[33] See https://data.snf.ch/grants/grant/192304.

which they should just be considered an integral part of the fabric of society. In the same way as we do not discuss today about the rebound effects of the invention of electricity, for example. Drawing from the work of (Geels 2011), (Coroamă et al. 2020) suggest that when a technology or service becomes part of the "socio-technical regime", its former indirect effects should no longer be considered as such; however, more research is required.

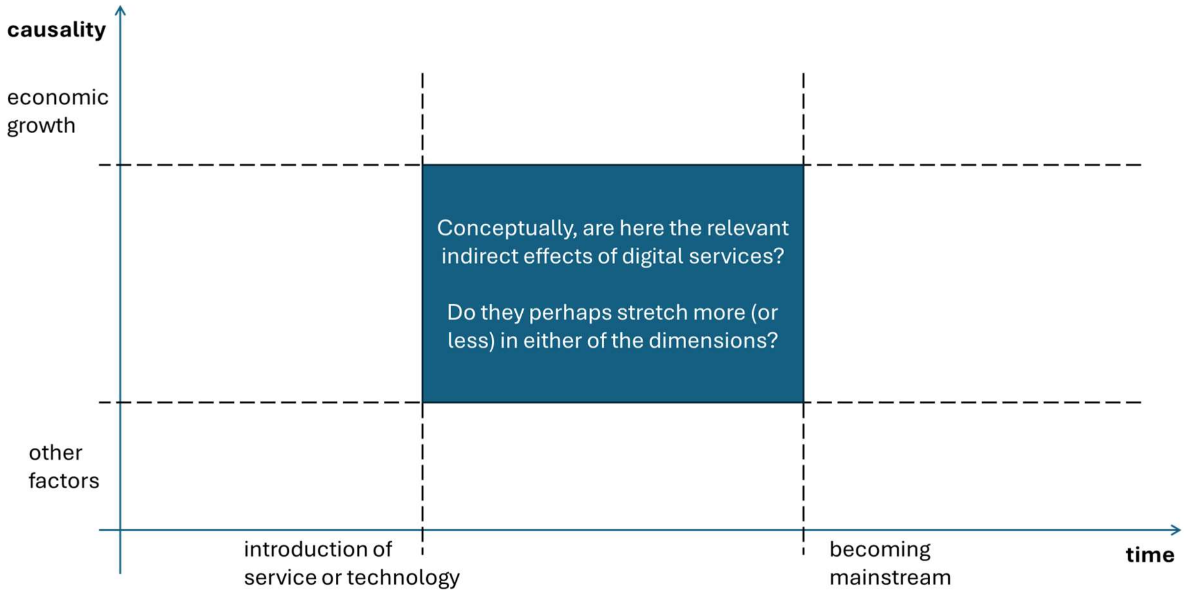

Figure 23 Schematic representation of the two dimensions that underline the conceptual uncertainty of indirect effects of digitalisation (crucially including rebound effects as well): time and causality. In time, the main question is whether there is an expiry date for effects to be considered indirect effects of digitalisation: Do they at some point just become part of the fabric of society? Along the causality dimension (which is of course not even an ordinal dimension, just a collection of possible causes), the indirect effects of digitalisation must be extracted from all the other possible causes, represented low on the axis. For rebound effects in particular, it is an open (yet crucial) question whether they must also be distinguished from economic growth, i.e., is there a point where rebound stops being rebound and starts being economic growth, or are they just two sides of the same coin?

The causality dimension is of course not a cardinal dimension such as time, and not even an ordinal one. Methodologically not entirely accurate, it is meant to represent the poly-causality of indirect effects. Obviously, digitalisation does not happen in a vacuum; further technologies, the political and economic contexts, possible policy, legal and fiscal measures, consumer behaviour, and more factors influence the environmental effects of a digital system or technology. A challenge in this context is to isolate the influence of the digital sector in domains such as e-commerce or telework. Arguably even more challenging, however, is the delimitation towards economic growth: The rebound effects brought about by various types of efficiencies (of energy, materials, time, transaction costs, etc) are an obvious engine for economic growth. But are they two different phenomena or two sides of the same coin? Or two distinct phenomena that should be distinguished, as Figure 23 suggests? In other words, and more provocatively: can we desire economic growth but work against rebound effects – generally, or those of digitalisation specifically?

7.3.3 Need for new assessment methodologies of the environmental effects of digitalisation and AI

Irrespective of the conceptual uncertainties surrounding them discussed above, the indirect effects of digitalisation are substantial and growing, as discussed from the outset of this study. Yet methodologies for their assessment are still lacking. Challenges include the definition of system boundaries (in space and, as discussed above, in time), the identification of effects, the definition of counterfactuals, and the attribution among various causes (Bieser and Hilty 2018; Coroamă et al. 2020).

With the advent of artificial intelligence (AI), these effects are bound to grow, including the various rebound effects of AI (Coroamă and Pargman 2020). And while the direct impacts of digitalisation were typically negligible compared to its indirect effects, as argued throughout this study, the direct footprint of various AI systems may be substantial. Novel holistic methods for the assessment of the direct and indirect impacts are thus necessary, both for the assessment of digital systems in general, and of AI in particular.

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