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A time-use approach to assess indirect environmental effects of information and communication technology: Time rebound effects of telecommuting

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The Faculty of Business, Economics and Informatics of the University of Zurich hereby authorizes the printing of this dissertation, without indicating an opinion of the views expressed in the work.

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The Chairman of the Doctoral Board: Prof. Dr. Thomas Fritz

For my parents, Elvira and Ludwig.

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Abstract

Impacts of digitalization on the environment

Digitalization, the process of societal change driven by the increasing use of information and communication technology (ICT), is fundamentally changing existing structures and processes in all economic and social systems, with substantial consequences for the environment. Digitalization impacts the environment in two ways:

— Direct effects refer to the environmental impacts caused throughout the lifecycle of ICT hardware: its production requires resources and energy, it is powered with electricity during use, and it must be disposed of after the use phase.
— Indirect effects refer to the impacts of applying or using ICT, which change existing patterns of production and consumption (e.g. through intelligent heating) and their environmental consequences (e.g. lower energy consumption).

There is a consensus that ICT applications (via indirect effects) have the potential to contribute to environmental protection; however, assessments of indirect environmental effects of ICT and the actions required to exploit those potentials involve substantial uncertainty. For example, results of industry studies often indicate that ICT applications have the potential to avoid more greenhouse gas (GHG) emissions (indirect effect) than the ICT sector causes itself (direct effect). Results of other studies, mostly in the academic field, agree that the increasing effects of ICT on GHG emissions outweigh the reducing effects to date, and that they cancel each other out at best. Such diverging results, driven by inconsistencies in methodological assessment approaches, make it difficult for decision makers to correctly interpret the results and take the environmental impact into account in ICT investment or policy decisions.

A time-use perspective for assessing indirect environmental effects of ICT

A systematic literature review reveals that most assessments of indirect effects focus on ICT impacts on patterns of production (e.g. GHG emissions associated with the production of paper-based books vs. e-book readers). However, ICT also changes patterns of consumption. In particular, ICT use affects how individuals use their time, with manifold consequences for the environment. For example, ICT can reduce transport through virtual mobility or increase transport by creating the desire to travel to places seen on the Internet. Analyzing the indirect environmental effects of ICT from a time-use perspective has significant potential to improve our understanding of these phenomena for several reasons.

First, individual time use, the pattern of activities individuals perform during a day, is crucial for the environmental impacts associated with lifestyles (e.g. taking a walk in the woods requires no electricity, streaming a movie does). At the same time, ICT relaxes time and space constraints of activities (e.g. e-commerce allows consumers to shop for goods from almost anywhere at any time) and thus changes time allocation and the environmental impacts associated with time use. Second, time is a limited resource for everyone due to the hard 24-hour time budget constraint per day. This phenomenon makes time a central link between different activities and their environmental impacts which can be used to model interaction among activities and among ICT use cases impacting time allocation. For example, if a researcher finds that working from home saves 20 minutes of commute time per day, he or she must also answer the question how the time saved is spent. If we add further ICT use cases (e.g. e-commerce, e-banking,) to the assessment, they again change the rules of the game in which all activities compete for the same, naturally limited resource—time. Modeling interaction among ICT use cases is key to investigating systemic ICT impacts such as fundamental changes to lifestyles driven by

increasing ICT use. Third, the time-use perspective allows researchers to analyze time rebound effects, which occur when increases in time efficiency lead to an increase in environmental loads (e.g. if time not spent on commuting when working from home is spent on other GHG-intensive activities).

Recognizing these characteristics of the time-use perspective, I develop a conceptual framework for systematically assessing the impact of ICT on time use and environmental impacts using energy use as an exemplary environmental impact category. The core of this framework is that it categorizes ICT impacts on time use into two types:

- ICT impacts on activity planning and execution: for example, *parallelization* of activities when working while traveling on a train, *avoidance* of commuting when working from home, or *substitution* of physical shopping with online shopping.
- Systemic impacts of ICT on time use: effects which only occur through the relationships between variables in the broader system in which the ICT use case takes place. For example, the possibility to work remotely from home can influence families' decisions regarding where to live because longer commuting distances become more acceptable (because people do not commute as often), which can lead to changes in settlement structures and as well as individual time use, e.g. for leisure or travel.

Changes in time use affect direct energy requirements through the energy used while performing activities (e.g. in the form of electricity for cooking or fuels for transport). Indirect energy requirements, the energy embedded in goods and services used to perform activities, only change if production of goods and services can be avoided (e.g. if working from home leads to fewer cars being purchased or less office space being built). From a time-use perspective, the energy impacts of ICT use depend on the direct and indirect energy requirements of the activities before and after adoption of an ICT use case.

Demonstrating the time-use approach with the ICT use case telecommuting

I demonstrate the time-use approach by showing how time-use data can be analyzed and linked with data on the energy requirements of activities to assess the energy impacts of a change in time allocation using the example use case telecommuting. Telecommuting means substituting physical presence in the employer's office with virtual presence and remote access to data, e.g. by working from home or from a local co-working space and thereby reducing commute time and the related energy consumption. Telecommuting is subject to time rebound effects. That is, reducing commuting allows telecommuters to spend the commute time saved on travel for other purposes and non-travel activities such as leisure, which are associated with their own energy requirements.

I apply the time-use approach using time-use and travel data collected in an actual co-working living laboratory in Stockholm, Sweden. I find that people spend the commute time they saved mainly on non-travel activities (e.g. leisure or chores) and only to a small extent on 'private travel'. This substitution can lead to a reduction in net energy requirements because travel (especially individual motorized travel) is associated with higher energy requirements than most non-travel activities.

However, the size of the time rebound effect of telecommuting depends on the marginal energy requirements of the substitute activities, i.e. the energy impacts of a change in time use, which are difficult to predict. For example, spending more time on car travel directly increases fuel consumption; however, spending more time on house cleaning only increases direct energy requirements if energy-consuming appliances are used longer (e.g. vacuum cleaners, stoves). Plus, the time rebound effects of telecommuting depend on the transport modes because transport modes differ significantly in their energy requirements. For example, car commuters can realize high energy savings through

telecommuting because car travel is highly energy-intensive. In contrast, for bikers or pedestrians, the direct energy requirements of travel (and telecommuting-induced energy savings) are zero, and thus the effect of any additional energy required for substitute activities is to increase net direct energy requirements.

A second case study of the co-working living lab in Stockholm broadens the scope by investigating environmental impacts of telecommuting beyond impacts due to changes in time allocation. It shows that besides time rebound effects, telecommuting can cause further environmental effects. For example, working from a co-working space can lead to an increase in office space (e.g. due to the co-working space in addition to the employer's office space) and energy required for heating, cooling, and lighting the space.

Whether telecommuting brings about energy savings depends largely on telecommuting-induced changes to:

(1) telecommuters' time spent in transport and use of transport modes,
(2) space requirements at all work locations (employer office, co-working space, and home office space),
(3) substitute travel and non-travel activities, goods, and services and their energy impacts (time and income rebound effects).

Thus, telecommuting does not necessarily lead to energy savings, but should be accompanied by additional energy savings measures. Organizations adopting telecommuting or providing telecommuting services (in particular co-working space providers) should advise telecommuters concerning their preferences regarding work location and transport modes. All stakeholders should work together to find strategies to reduce the total office space required. If all actors adopt such measures, telecommuting can be a viable ICT application to reduce the environmental impacts of work, relieve pressure on transport systems, and increase the well-being of workers. However, if organizations and telecommuters do not address these energy-saving measures, additional energy required for space heating and cooling, a possible change in transport modes used, and time and income rebound effects can compensate or even overcompensate for commute-related energy savings. The fact that a large number of employees can work from home during the COVID-19 pandemic is an impressive example of the social benefits of flexible work models.

This dissertation shows that the time-use approach is a useful—if not key—element of methods for assessing the environmental effects of ICT (using energy impacts of telecommuting as an example). I encourage researchers and ICT companies to apply the time-use approach in combination with other production- and consumption-focused approaches to shed light on indirect environmental effects of ICT from various perspectives and to identify pathways for aligning digitalization with environmental protection.

Zusammenfassung

Auswirkungen der Digitalisierung auf die Umwelt

Die Digitalisierung, d.h. der gesellschaftliche Wandel, der durch den zunehmenden Einsatz von Informations- und Kommunikationstechnologien (IKT) vorangetrieben wird, verändert bestehende Strukturen und Prozesse in allen Wirtschafts- und Sozialsystemen und hat erhebliche Folgen für die Umwelt. Die Digitalisierung wirkt sich auf zwei Arten auf die Umwelt aus:

- Direkte Effekte sind die Umweltauswirkungen während des Lebenszyklus von IKT-Hardware, welche in der Herstellung Ressourcen und Energie benötigt, mit Elektrizität betrieben und schliesslich entsorgt wird.
- Indirekte Effekte sind die Auswirkungen der Anwendung oder Nutzung von IKT, wodurch sich bestehende Produktions- und Verbrauchsmuster ändern (z.B. intelligentes Heizen) und auch deren Umweltfolgen (z.B. reduzierter Energieverbrauch).

Es besteht Konsens darüber, dass die indirekten Effekte von IKT-Anwendungen das Potenzial haben, zum Umweltschutz beizutragen. Es besteht jedoch grosse Unsicherheit hinsichtlich der Bewertung der indirekten Umweltauswirkungen und der erforderlichen Massnahmen, um die Potenziale auszuschöpfen. Zum Beispiel zeigen Ergebnisse von Industriestudien häufig, dass IKT-Anwendungen mehr Treibausgas-(THG-)Emissionen vermeiden können (indirekter Effekt) als der IKT-Sektor selbst verursacht (direkter Effekt). Ergebnisse anderer Studien, hauptsächlich im akademischen Bereich, zeigen, dass Effekte, die zu einer Erhöhung von THG-Emissionen führen, bisher überwiegen und emissionssenkende Effekte diese im besten Fall kompensieren. Unterschiedliche Ergebnisse, die auf inkonsistenten Methoden der Abschätzung beruhen, erschweren es Entscheidungsträgern, die Ergebnisse richtig zu interpretieren und bei IKT-Investitionen oder -Richtlinien die Umweltauswirkungen zu berücksichtigen.

Der Zeitnutzungsansatz zur Bewertung der indirekten Umweltauswirkungen von IKT

Eine systematische Literaturanalyse zeigt, dass sich die meisten Bewertungen indirekter Auswirkungen auf Veränderungen von Produktionsprozessen konzentrieren (z. B. Vergleich der THG-Emissionen aus der Produktion von Papierbüchern und E-Book-Readern). Der Einsatz von IKT wirkt sich jedoch auch auf Konsummuster aus, insbesondere auf die Zeitnutzung von Einzelpersonen, was vielfältige Folgen für die Umwelt hat. Beispielsweise kann IKT durch virtuelle Mobilität Verkehr verringern oder aber ihn erhöhen, indem der Wunsch erzeugt wird, zu Orten zu reisen, die im Internet zu sehen sind. Eine Bewertung indirekter Umweltauswirkungen der IKT aus einer Zeitnutzungsperspektive bietet aus mehreren Gründen Potenzial, das Verständnis dieser Effekte zu verbessern.

Erstens ist die individuelle Zeitnutzung (die Aktivitäten, die Einzelpersonen an einem bestimmten Tag ausführen) entscheidend für die Umweltauswirkungen von Lebensstilen (z. B. erfordert das Streamen eines Films Strom, ein Spaziergang im Freien jedoch nicht). Gleichzeitig hebt der Einsatz von IKT zeitliche und räumliche Restriktionen von Aktivitäten auf (z. B. ermöglicht E-Commerce es, Waren von nahezu jedem Ort zu jeder Zeit einzukaufen) und ändert somit die Zeitnutzung und deren Umweltauswirkungen. Zweitens ist Zeit aufgrund der harten 24-Stunden-Beschränkung des Zeitbudgets pro Tag für alle eine begrenzte Ressource. Dies macht die Zeit zu einem zentralen Bindeglied zwischen verschiedenen Aktivitäten und ihren Umweltauswirkungen, welches zur Untersuchung der Interaktion zwischen Aktivitäten und zwischen zeitnutzungsverändernden IKT-Anwendungen genutzt werden kann. Wenn man beispielsweise feststellt, dass das Arbeiten von zu Hause aus 20 Minuten Pendelzeit pro Tag spart, muss man auch die Frage beantworten, für welche

Aktivitäten die eingesparte Zeit aufgewendet wird. Wenn nun weitere IKT-Anwendungen (z. B. E-Commerce, E-Banking) berücksichtigt werden, ändern sie erneut die Rahmenbedingungen, unter denen alle Aktivitäten um dieselbe, natürlicherweise begrenzte Ressource konkurrieren—Zeit. Die Modellierung der Interaktion zwischen IKT-Anwendungen ist essenziell zur Untersuchung systemischer Auswirkungen der IKT, etwa grundlegende Veränderungen von Lebensstilen durch die zunehmende Nutzung von IKT. Drittens ermöglicht es der Ansatz, Zeitnutzungs-Rebound-Effekte zu untersuchen, die auftreten, wenn eine Erhöhung der Zeiteffizienz zu einer Erhöhung der Umweltbelastung führt (z. B. wenn gesparte Reisezeit für andere THG-intensive Aktivitäten aufgewendet wird).

Unter Berücksichtigung dieser Eigenschaften des Zeitnutzungsansatzes entwickle ich einen konzeptionellen Rahmen für die systematische Bewertung der Auswirkungen von IKT auf Zeitnutzung und die Umwelt am Beispiel Energieverbrauch. Dieser unterscheidet zwei Arten von Auswirkungen der IKT auf Zeitnutzung:

— IKT-Auswirkungen auf die Planung und Durchführung von Aktivitäten: Zum Beispiel *Parallelisierung* von Aktivitäten durch Arbeiten während Zugreisen, *Vermeidung* des Pendelns durch Arbeiten von zu Hause aus oder *Ersetzen* des physischen Einkaufens durch Online-Shopping.
— Systemische Auswirkungen von IKT auf die Zeitnutzung: Auswirkungen, die nur durch die Beziehungen zwischen Variablen auf einer höheren Systemebene auftreten, in dem der IKT-Anwendungsfall stattfindet. Beispielweise, wenn durch die Möglichkeit, auch von zu Hause aus zu arbeiten, längere Pendelstrecken akzeptabler werden (da sie seltener zurückgelegt werden) was Wohnorts-Entscheidungen von Familien und somit Siedlungsstrukturen beeinflussen kann, und dadurch wiederum Zeitnutzungsmuster, z.B. für Freizeit und Transport, verändert.

Änderungen in der Zeitnutzung wirken sich auf den direkten Energieverbrauch aus, der bei der Durchführung von Aktivitäten verursacht wird (z. B. in Form von Elektrizität für das Kochen oder Treibstoffe für Transport). Der indirekte Energiebedarf—die graue Energie, welche für die Herstellung von Waren notwendig ist, die für Aktivitäten verwendet werden—ändert sich nur, wenn die Produktion von Waren vermieden werden kann, z. B. wenn Telearbeit dazu führt, dass weniger Autos gekauft werden oder weniger Büroraum gebaut wird. Aus Sicht der Zeitnutzung hängen die Energieeffekte des IKT-Einsatzes vom direkten und indirekten Energiebedarf der Aktivitäten mit und ohne Anwendung von IKT ab.

Veranschaulichung des Zeitnutzungsansatzes anhand der IKT-Anwendung Telearbeit

Um den Ansatz zu veranschaulichen, zeige ich am Beispiel des Anwendungsfalls Telearbeit, wie Zeitnutzungsdaten analysiert und mit Daten zum Energiebedarf von Aktivitäten verknüpft werden können, um die Energieeffekte einer Veränderung der Zeitnutzung zu untersuchen. Telearbeit ist der Ersatz von physischer Anwesenheit im Büro durch virtuelle Präsenz und Fernzugriff auf Daten, indem beispielsweise von zu Hause aus oder in einem lokalen Co-Working-Space gearbeitet wird. Hierdurch verringern sich Pendelverkehr und -zeit und die damit verbundenen Energieverbräuche und THG-Emissionen. Zeitnutzungs-Rebound-Effekte von Telearbeit treten dann auf, wenn die gesparte Pendelzeit für andere Aktivitäten (Reisen für andere Zwecke, Freizeit, Hausarbeit) eingesetzt wird, die ebenfalls Energieverbräuche verursachen.

Anhand von Zeitnutzungs- und Reisedaten, die in einem tatsächlich Co-Working *Living Laboratory* in Stockholm gesammelt wurden, wende ich den Zeitnutzungsansatz an. Die Auswertung zeigt, dass die eingesparte Pendelzeit hauptsächlich für andere Aktivitäten (z.B. Freizeit, Hausarbeit) und nur zu einem kleinen Teil für «private Wege» aufgewendet wird. Dies kann den Nettoenergiebedarf senken, da Reisen (insbesondere mit dem motorisierten Individualverkehr) mit einem höheren Energiebedarf verbunden ist als die meisten anderen Aktivitäten.

Die Größe des Zeitnutzungs-Rebound-Effekts von Telearbeit hängt allerdings vom Grenzenergiebedarf der Ersatzaktivitäten ab, also den Auswirkungen einer Veränderung in der Zeitnutzung auf den Energiebedarf von Aktivitäten, welcher schwer zu bestimmen ist. Beispielsweise erhöht längeres Autofahren direkt den Kraftstoffverbrauch. Der Energiebedarf von Hausarbeit erhöht sich allerdings nur, wenn energieverbrauchende Geräte länger verwendet werden (z. B. Staubsauger, Backöfen). Außerdem hängt der Zeitnutzungs-Rebound-Effekt von Telearbeit von den genutzten Verkehrsmitteln ab, da diese sich in ihrem Energiebedarf erheblich unterscheiden. Zum Beispiel können Personen, die mit dem Auto pendeln, durch Heimarbeit hohe Energieeinsparungen erzielen, da Autofahrten sehr energieintensiv sind. Im Gegensatz dazu ist für Personen, die den Weg zur Arbeit zu Fuss oder mit dem Fahrrad zurücklegen, der direkte Energiebedarf dafür (und die Energieeinsparung durch Telearbeit) gleich Null. In diesem Fall führen zusätzliche Energieverbräuche für andere Aktivitäten direkt zu einer Erhöhung des Nettoenergiebedarfs.

Eine zweite Fallstudie des Co-Working *Living Laboratory* in Stockholm erweitert den Blick auf weitere Umweltauswirkungen von Telearbeit über die Auswirkungen aufgrund von Zeitnutzungsveränderungen hinaus. Sie zeigt, dass Telearbeit neben den Zeitnutzungs-Rebound-Effekten weitere wesentliche Umweltauswirkungen verursacht. Beispielsweise kann das Arbeiten von einem Co-Working Space zu einer Vergrösserung der Bürofläche (z. B. aufgrund des Co-Working Spaces zusätzlich zu den Büroflächen des Arbeitgebers) und damit zur Steigerung der zum Heizen, Kühlen und Beleuchten der Fläche erforderlichen Energiemenge führen. Ob Telearbeit zu Energieeinsparungen führt, hängt daher in hohem Masse von Veränderungen in folgenden Bereichen ab:

(1) Die Reisezeit der Telearbeitenden und die von ihnen genutzten Verkehrsmittel
(2) Der Flächenbedarf an allen Arbeitsorten (in Büros der Arbeitgebenden, in Co-Working-Spaces und zu Hause)
(3) Der Energiebedarf der Reiseaktivitäten und von anderen Aktivitäten, Gütern und Dienstleistungen, die anstatt des Pendelns durchgeführt bzw. konsumiert werden (Zeitnutzungs- und Einkommens-Rebound-Effekte).

Daher sollten aktuelle und zukünftige Anbietende von Telearbeitsdienstleistungen und Arbeitgebende, die Telearbeit einsetzen, Telearbeitende bei der Wahl ihres Arbeitsortes (vorzugsweise in der Nähe des Wohnortes) und ihrer Verkehrsmittel beraten und Strategien zur Reduzierung der Gesamt-Bürofläche finden. Wenn alle Beteiligten diese Massnahmen ergreifen, kann Telearbeit eine vielversprechende IKT-Anwendung sein, um die Umweltauswirkungen der Arbeit und die Belastung von Verkehrssystemen zu verringern und das Wohlbefinden von Arbeitnehmenden zu steigern. Wenn Unternehmen und Telearbeitende diese Energiesparmassnahmen nicht angehen, können der zusätzliche Energiebedarf zum Heizen und Kühlen von Flächen, eine vermehrte Nutzung energieintensiver Verkehrsmittel sowie Zeitnutzungs- und Einkommens-Rebound-Effekte die pendelbezogenen Energieeinsparungen aufwiegen oder sogar überkompensieren. Die Tatsache, dass während der COVID-19-Pandemie eine Vielzahl an Arbeitnehmenden von zu Hause aus ihrer beruflichen Tätigkeit nachgeht, ist ein eindrucksvolles Beispiel der gesellschaftlichen Vorteile von flexiblen Arbeitsmodellen.

Diese Dissertation zeigt am Beispiel der Auswirkungen der Telearbeit auf den Energieverbrauch, dass der Zeitnutzungsansatz zur Bewertung der indirekten IKT-Umweltauswirkungen geeignet ist. Sowohl Forschende als auch IKT-Unternehmen sollten den Zeitnutzungsansatz in Kombination mit anderen produktions- und konsumorientierten Ansätzen anwenden, um indirekte Umwelteinflüsse der IKT aus verschiedenen Perspektiven zu beleuchten und Wege zu finden, um die Digitalisierung mit dem Umweltschutz in Einklang zu bringen.

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List of abbreviations

BT	*British Telecom*
CW	*Co-working*
CO_2	*Carbon dioxide*
CO_{2e}	*Carbon dioxide equivalent*
EnviroInfo	*Environmental Informatics*
EoL	*End-of-life*
GeSI	*Global e-Sustainability Initiative*
GHG	*Greenhouse gas*
ICT	*Information and communication technology*
ICT4S	*ICT for Sustainability*
IPCC	*Intergovernmental Panel on Climate Change*
IPTS	*Institute for Prospective Technological Studies*
LCA	*Life cycle assessment*
LCI	*Life cycle inventory*
MTUS	*Multinational Time Use Study*
Phf care	*Personal, household and family care*
RQ	*Research question*
SDG	*Sustainable Development Goal*
SoSA	*Software Sustainability Assessment method*
TC	*Telecommuting*
U.S.	*United States*
UN	*United Nations*
VMT	*Vehicle-miles traveled*
WWF	*World Wildlife Fund*

SYNOPSIS

1 Introduction

1.1. Motivation

Global warming is one of the major challenges of sustainable development, threatening habitats and biodiversity around the world.

In September 2015, the United Nations (UN) adopted the Sustainable Development Goals (SDGs), consisting of 17 goals to “end poverty, protect the planet, and ensure prosperity for all” (United Nations, n.d.-c, p. 1). As of February 2020, 189 member states have ratified the Paris Agreement, which “aims to strengthen the global response to the threat of climate change” by reducing the amount of greenhouse gases (GHGs) emitted (Paris Agreement, 2015, p. 2; United Nations, n.d.-b).

Yet GHG emissions continue to increase. Figure 1 shows the development of the atmospheric concentration of three GHGs since the year 0 until today and the (reconstructed) development of global temperature since the year 1000 until today. The SDG Report 2019 showed that in 2017, atmospheric CO2 concentrations reached a new peak (146% of pre-industrial levels) and that “in order to limit global warming to 1.5 °C […] carbon emissions need to fall by a staggering 45 per cent by 2030 from 2010 levels and continue at a steep decline to achieve net zero emissions by 2050” (United Nations, 2019, p. 48). The fires in the Australian summer of 2019/2020, in which over 32 humans and 1.25 billion animals died and over 12 million hectares land burned, were an alarming example of the potential consequences of global warming for habitats and biodiversity around the world (WWF Australia, 2020).

The fact that the SDGs address various environmental aspects, also beyond climate protection, shows that environmental protection is a central condition for sustainable development. For example, SDG 6 addresses clean water and sanitation, SDG 7 affordable and clean energy, SDG 14 life below water and SDG 15 life on land (United Nations, n.d.-c).

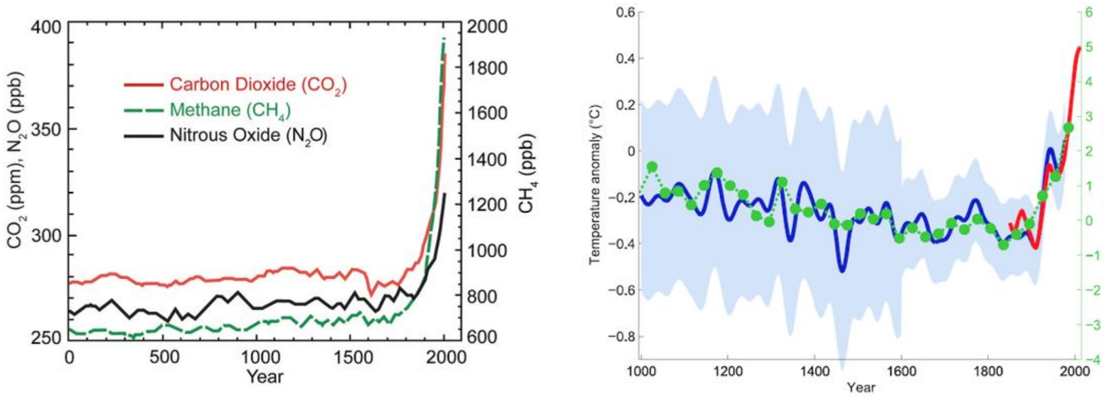

Figure 1: Atmospheric concentration of three GHGs from 0 to 2000 (left) (Melillo et al., 2014) and global average temperature from 1000 to 2000 (“hockey stick diagram”, right) (Spratt, 2015). The blue line, green dots and the light blue area in the right figure show the reconstruction and uncertainty of temperatures based on Page2K reconstruction and Mann, Bradley and Hughes (1999), whereas the red curve shows the global average temperature based on actually measured temperature data from 1850 onwards (Morice et al., 2012).

Digitalization can play a crucial role in environmental protection, in particular in reducing GHG emissions. Yet the uncertainties about the actual impacts of digitalization on the environment and about the actions required to unfold its environmental protection potential is high.

Digitalization, the process of societal change driven by increasing use of information and communication technologies (ICTs), fundamentally changes existing structures and processes in all economic and social systems, with substantial consequences for the environment (Brennen & Kreiss, 2014; WBGU, 2019). Digitalization impacts the environment in two ways (Berkhout & Hertin, 2001; Hilty & Aebischer, 2015):

— An increasing amount of ICT hardware is produced, powered with electricity while being used, and disposed of after the use phase—a system of processes which requires resources and causes emissions to the environment (direct effects).
— The application of ICT changes existing patterns of production and consumption, with manifold environmental consequences (indirect effects). For example, ICT allows some workers to work from home and have virtual meetings, thus avoiding travel-related GHG emissions.

In recent years, many industry studies have been conducted to quantify direct and indirect environmental effects of ICT, specifically on GHG emissions. These studies usually conclude that indirect effects are desirable for climate protection (i.e., reducing GHG emissions) and clearly larger than direct effects, hence leading to a significant total reduction of GHG emissions (GeSI & Deloitte, 2019; Malmodin & Bergmark, 2015). For example, the Global e-Sustainability Initiative (GeSI), an ICT industry association for sustainability, claims that, on a global scale, ICT applications could avoid up to 20% of annual GHG emissions in 2030 (indirect effect), while the ICT sector will cause roughly 2% of global GHG emissions (direct effect) (GeSI & Accenture Strategy, 2015).

On the basis of such results, the scientific community and the ICT sector have increasingly focused their attention on assessing indirect effects of ICT on GHG emissions. Telecommunication network operators started estimating the indirect impact of their products and services on GHG emissions. For example, British Telecom (BT) estimated that, by 2020, their customers could avoid three times more GHG emissions by using BT products and services than BT causes itself (British Telecom, 2017). Swisscom estimated a factor of two by 2020 and AT&T a factor of ten by 2025 (AT&T, 2019; Swisscom AG, 2017). A System Dynamics model developed in a project commissioned by the Institute for Prospective Technological Studies of the European Commission (IPTS) on "The future impact of ICT on environmental sustainability" in the EU yielded a different net effect of ICT on GHG emissions. The simulation results, recently validated with new data, suggest that by 2020, positive and negative effects of ICT on GHG emissions tend to cancel each other out across application domains. The authors conclude that a set of policies is necessary to specifically unfold the positive potential of ICT while inhibiting negative effects (Achachlouei & Hilty, 2015; Hilty et al., 2004; Hilty, Arnfalk, et al., 2006).

The diverging results can be explained by a difference in approaches: The IPTS study was based on a dynamic socio-economic model, whereas the newer studies tried to assess the potentials using a simple static approach. Such inconsistencies in methodological approaches make it difficult for decision makers to interpret the results and take into account the environmental impact in ICT investment or policy decisions (Bieser & Hilty, 2018c).

Improving the assessment of environmental effects of increasing ICT use is vital for unfolding the potential of digitalization for environmental protection.

Improving such assessments and showing pathways for aligning digitalization with environmental protection is the overarching goal of this dissertation, for the following reasons:

- There is a consensus that digital solutions have the potential to significantly contribute to environmental protection; however, there is high uncertainty about the magnitude of this potential.
- The overall potential has to be broken down to specific potentials of ICT application domains or use cases to be systematically explored. Targeted action to exploit these potentials is required.
- Many researchers agree that so far unfavorable effects outweigh favorable affects, and at best cancel each other out (Hilty, Arnfalk, et al., 2006; Hilty & Bieser, 2017).

Analyzing how ICT changes individual time use and the environmental consequences of this change has significant potential to improve the understanding of indirect environmental effects of ICT.

The main focus of most assessments is how ICT changes our patterns of production (e.g. GHG emissions associated with production of paper-based books vs. e-book readers) (Bieser & Hilty, 2018b; Pohl, Hilty, et al., 2019). However, ICT use also affects how individuals allocate time to activities—with manifold consequences for the environment. For example: on the one hand, ICT can help us save time and GHG emissions by replacing physical business trips with virtual mobility (e.g. videoconferencing) (Warland & Hilty, 2016). On the other hand, ICT can increase time spent in transport and associated environmental impacts by making "information about people and activities much more accessible" and therefore create the "desire to travel to participate in those activities and interact with those people" (Mokhtarian, 1990, p. 235). Thus, understanding the relationships between ICT, time use, and environmental impacts is essential to promote its desired environmental impacts and prevent unfavorable (unsustainable) ones. Investigating indirect environmental effects of ICT from a time-use perspective is promising for the following reasons:

First, individual time use, the pattern of activities individuals perform during a day, is crucial for the environmental impacts associated with lifestyles (e.g. taking a walk outside requires no electricity, streaming a movie does) (Jalas, 2002). At the same time, ICT relaxes time and space constraints of activities (e.g. e-commerce allows you to shop goods from almost anywhere at any time) and thus changes time allocation and environmental impacts associated with time use (Røpke & Christensen, 2012). Second, time is a limited resource for everyone due to the hard 24-hour time budget constraint (Bieser & Hilty, 2018a; Druckman et al., 2012). This phenomenon makes time a central link between different activities and their environmental impacts, which can be used to model interaction among activities and among ICT use cases which impact time allocation. Modeling interaction among ICT use cases is key to investigating systemic ICT impacts such as fundamental changes to lifestyles driven by increasing ICT use. Third, the time-use perspective allows researchers to analyze time rebound effects, which occur when increases in time efficiency lead to an increase in energy use (e.g. time not spent on commuting when working from home is spent on other energy-intensive activities) (Sorrell & Dimitropoulos, 2008).

Some applications of the time-use approach in the field of indirect environmental effects of ICT exist. For example, Wang and Law (2007) assess impacts of ICT use on time use and travel behavior in Hong Kong. Widdicks et al. (2018) use a time-use approach to assess the impact of the availability or absence of an Internet connection on time use of individuals. Røpke and Christensen (2012) discuss energy impacts of ICT from an everyday life perspective. Most of these studies focus on specific ICT applications or specific types of ICT impacts on time use and the environment. A systematic and comprehensive analysis of ICT impacts on time use and the environment does not exist yet. Hence, there is significant potential to improve the understanding of such effects by analyzing them from a time-use perspective. In this dissertation, I systematically develop a comprehensive framework of ICT impacts on time use and environmental impacts and apply it to the example use case telecommuting (TC). I mainly use energy use as an example environmental impact category, because TC has the potential to avoid energy consumption associated with commuting, because most environmental assessments of time use focus on energy use and because energy use is closely linked to global warming as the global energy supply is still based on fossil energy sources to a large extent.

1.2. Terminology

This section provides definitions of important terms and concepts used in this dissertation.

Information and communication technology (ICT)

ICT is the entirety of technologies used to store, process and transmit information (Hilty & Bieser, 2017). Mankind has always been striving for technologies to store, process and transmit information, but these have historically developed separately (e.g. cuneiform writing, abacus, smoke signals). What makes our age special is that these three types of technologies have all become electronic and digital, a development that has made it possible to merge them into one technology, now called (digital) ICT. Anything that can be stored can also be transmitted, and vice versa. And because everything is stored and transmitted in digital form, it can also be processed using algorithms.

ICT sector

All activities related to producing, operating and disposing of ICT products and services. This includes ICT end-user devices (e.g. laptop computers, smartphones), telecommunication networks (e.g. 4G mobile networks), data centers and the companies producing and providing ICT products and services (e.g. telecommunication network operators, data center operators, search engine providers).

Digitization and digitalization

I follow the definition of Brennen and Kreiss (2014, p. 1), who define digitization as “the material process of converting individual analogue streams of information into digital bits” (e.g. transforming a paper-based book into an e-book) and digitalization as “the way in which many domains of social life are restructured around digital communication and media infrastructures”. Thus, digitalization is the transformation of social and economic processes in all domains driven by increasing use of ICT. The term ‘digital transformation’ is often used to describe the transformative changes achieved through digitalization.

ICT application domain and ICT use case

An application domain is a specific and definable field in which ICTs are deployed (e.g. ‘smart transport’, ‘virtual mobility’ or ‘smart buildings’). Each application domain consists of various ICT use cases (e.g. the use case ‘traffic control and optimization’ in the domain ‘smart transport’, ‘video conferencing’ in ‘virtual mobility’ or ‘intelligent heating’ in ‘smart buildings’).

Environmental impact assessment

Various definitions for this term exist. The Convention on Biological Diversity states that “Environmental Impact Assessment […] is a process of evaluating the likely environmental impacts of a proposed project or development, taking into account inter-related socio-economic, cultural and human-health impacts, both beneficial and adverse" (Convention on Biological Diversity, 2018, p. 1). For more definitions see section 11.2.

Environmental impact categories

Various environmental impact categories exist (Pelletier et al., 2007). In this dissertation, I focus on the impact categories 'energy use' and occasionally 'global warming potential'. Energy use is measured in multiples of watt-hours (e.g. kilowatt hour, kWh) or joule (e.g. megajoule, MJ). Global warming potential is measured in multiples of kilograms (e.g. metric tons, t) of CO_2e (carbon dioxide equivalents). CO_2e is the amount of CO_2 with the same global warming potential as a given mixture of GHGs. For example, the global warming potential of methane is 21 times higher than the global warming potential of CO_2 in a time horizon of 100 years (United Nations, n.d.-a).

Environmental effects of ICT

The environmental effects of ICT are the environmental consequences of producing, using and disposing of ICT. In 2001, Berkhout and Hertin (2001) introduced a conceptual framework distinguishing first, second and third order environmental effects of ICT. This framework has been further developed by various authors. Figure 2 shows a popular framework distinguishing direct, enabling and systemic effects of ICT use.

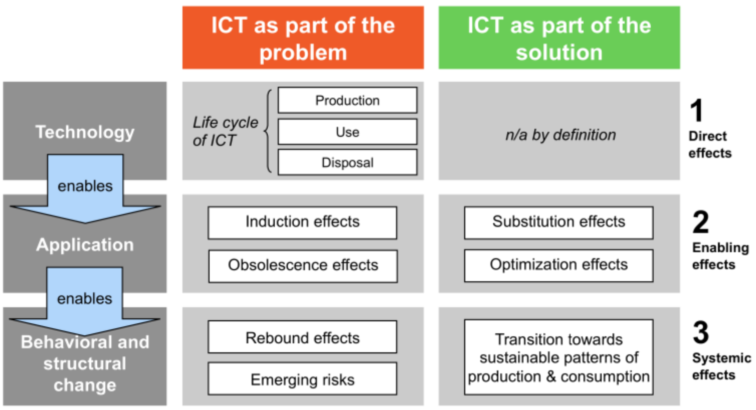

Figure 2: The three-levels model of ICT effects by Hilty and Aebischer (2015, p. 25).

Direct environmental effects of ICT are the environmental impacts caused by producing, using and disposing of ICT hardware. Such effects are usually assessed using the life cycle assessment (LCA) method, which is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006, p. 2).

Enabling effects are the environmental impacts of applying or using ICT. These can be environmentally favorable (e.g. if an environmental harmful activity is substituted with a less harmful activity, such as air travel with video conferencing) and/or environmentally unfavorable, e.g. if applying ICT induces other activities with environmental impacts, such as printers inducing paper consumption (Hilty & Aebischer, 2015).

Systemic effects refer to the "the long-term reaction of the dynamic socio-economic system to the availability of ICT services, including behavioral change (life styles) and economic structural change" (Hilty & Aebischer, 2015, p. 25). Again, this reaction can have positive and/or negative consequences for the environment.

Enabling effects and systemic effects (or second and third order effects) are often subsumed under the term 'indirect effects'. The assessment of indirect environmental effects of ICT is challenging because ICT applications are not independent systems, but interact with each other and with variables in the broader use case system. ICTs display "diverse and complex impact patterns", "exceptional dynamics of innovation and diffusion" and "cross-sector application" (Erdmann & Hilty, 2010, p. 826). Their actual impacts depend on the socio-economic context they are embedded in.

Rebound effects

One of the most intensively discussed unwanted effect of ICT use is the rebound effect. While many definitions of rebound effects exist, the term is often used as "an umbrella term for a variety of mechanisms that reduce the potential energy savings from improved energy efficiency" (Sorrell, 2009, p. 1457). For example, if the fuel economy of cars improves, people drive longer distances with the car because the costs per kilometer decrease. Greening et al. (2000) distinguish three types of rebound effects:

— Direct rebound effects: energy efficiency improvements and price reductions of an energy service leading to increased use of the same service (e.g. increased fuel economy of cars leading to more kilometers driven)
— Indirect rebound effects: energy efficiency improvements and price reductions of an energy service leading to increased use of other services (e.g. money saved on car fuel is now spent on additional air travel)
— Economy-wide rebound effects: adjustment of economy-wide supply and demand based on improvements of energy efficiency

Often, rebound effects are also calculated for other environmental impact indicators (e.g. GHG emissions). Also, various other classifications of rebound effects exist. For example, Santarius (2012) distinguishes financial, material, psychological and cross-factor rebound effects, Börjesson Rivera et al. (2014) distinguish direct, indirect, economy-wide, time and space rebound effects.

ICT solutions are subject to various types of rebound effects, which can compensate, if not overcompensate, for ICT-enabled reduction of environmental burdens (Coroamă & Mattern, 2019; Gossart, 2015; Hilty, Köhler, et al., 2006). There is high uncertainty about the actual magnitude of rebound effects, which also vary by socio-economic context. This dissertation deals specifically with time rebound effects, which occur when ICT-enabled increases in time efficiency lead to an increase in energy use (Sorrell & Dimitropoulos, 2008). For example, if navigation tools save travel time and fuel consumption, the travel time saved can be spent on other energy-intensive activities, which compensate for travel-related energy savings.

Assessment of indirect environmental effects of ICT

I define the "assessment of indirect environmental effects of ICT" as "the process of identifying the future environmental consequences of an ICT solution's capacity to change existing production and consumption patterns, taking into account interrelated socio-economic, cultural and human-health impacts, both beneficial and adverse, with the aim of informing decision-makers or the general public and mitigate unfavorable or promote favorable environmental consequences" (Bieser & Hilty, 2018a, p. 67). Examples can be the impacts of a real-time public transport information system on transport mode choice, travel distances and GHG emissions or the impacts of a new policy on the use of public parking space by car sharing service providers on private car ownership. For more details see section 11.2 of this dissertation.

Time-use pattern

A time-use pattern describes the pattern (e.g. sequence, duration) of activities individuals perform during a day.

Time-use approach

The time-use approach as introduced by Jalas (2002) is an approach for analyzing individual lifestyles based on the allocation of time to everyday activities (e.g. travel, leisure, work, sleep) and the environmental impacts associated with these activities. For example, car travel requires fuel and causes GHG emissions, working out at the gym requires energy for heating, lighting and providing the equipment.

Telecommuting (TC)

Mokhtarian (1991, p. 11) defines TC as "working at home or at an alternate location and communicating with the usual place of work using electronic or other means, instead of physically traveling to a more distant work site". Non-home-based TC is usually conducted at a TC center, which is "a site, other than the home, from which the employee works instead of traveling to a more distant central work location". These can be 'satellite work centers' in which employees from one company work or 'local or neighborhood work centers', which are shared by two or more employers.

Co-working (CW)

CW is a special case of TC and "describes any situation where two or more people are working in the same place together, but not for the same company" (DTZ, 2014, p. 3). CW spaces are "shared workplaces utilised by different sorts of knowledge professionals [..] working in various degrees of specialisation in the vast domain of the knowledge industry" (Gandini, 2015, p. 194).

Remarks

Over the course of this PhD project, which includes seven articles, I continuously refined the terminology. In this dissertation, I harmonized the terminology across articles. This explains the slight differences between the original articles published in journals and conference proceedings and the articles included in this dissertation:

— In this dissertation, I use the term 'time rebound effect' instead of 'time-use rebound effect', 'travel time' instead of 'traveling time' and ´transport mode' instead of ´travel mode´.
— In article 5, I use the activity category 'personal, household and family care (phf care)'. In article 6 and 7, I use the activity category 'everyday chores' to describe the same activities, because this term was used in the CW living laboratory in Stockholm.
— The SMARTer 2030 study was commissioned by GeSI and conducted by Accenture Strategy. Depending on the context, I refer to it as a 'GeSI study' or an 'Accenture study'.
— Other minor changes were also made (e.g. changing '141.0m' to '141.0 min').

2 Research questions (RQ)

2.1. Research question 1

The overarching goal of this dissertation is to improve the assessment of indirect environmental effects of ICT in order to find pathways for aligning digitalization with environmental protection. As this opens a very broad research field, the first part of this dissertation aims at identifying main potentials for improvement. Thus, I answer the following research question by answering three sub-questions.

RQ 1: What is the state of the art in assessing indirect environmental effects of ICT with respect to the assessment approaches applied, research gaps and methodological challenges?

- *RQ 1.1: What assessments of indirect environmental effects of ICT have already been conducted?*
- *RQ 1.2: What assessment methods have been used for the assessment of indirect environmental effects of ICT?*
- *RQ 1.3: What are the main research gaps and methodological challenges in assessments of indirect environmental effects of ICT?*

2.2. Research question 2

In order to close the research gaps identified by answering *RQ 1*, I apply the time-use approach to the field of indirect environmental effects of ICT. Used as a perspective to understand indirect environmental effects of ICT, the time-use approach emphasizes the impacts of ICT on patterns of consumption (a major research gap identified when answering *RQ 1*) and the environmental consequences. The time-use approach is common in the field of ecological economics; however, it has only rarely been applied to assess indirect environmental effects of ICT so far. *RQ 2* has two sub-questions:

RQ 2: Is the time-use approach suitable for assessing indirect environmental effects of ICT?

- *RQ 2.1: What are advantages and limitations of the time-use approach for assessing indirect environmental effects of ICT?*
- *RQ 2.2: What is the relationship between ICT use, time use and environmental impact?*

2.3. Research question 3

Finally, I demonstrate how the time-use approach can be used to assess indirect environmental effects of ICT. I use TC (specifically working from home or a local CW space) as an example use case and energy use as an exemplary environmental impact category because TC has high potential to avoid commute time and the related energy consumption. Plus, TC is subject to various types of rebound effects such as time and income rebound effects (time and money not spent on commuting will be spent on other activities) (Mokhtarian, 2009; Mokhtarian et al., 1995). *RQ 3* has three sub-questions:

RQ 3: What is a suitable operationalization of the time-use approach to assess indirect environmental effects of ICT and does it deliver results of practical relevance?

- *RQ 3.1: What data is required to assess indirect environmental effects of ICT from a time-use perspective and what is a suitable approach to analyze this data?*
- *RQ 3.2: To what extent do time rebound effects of telecommuting compensate for commute-related energy savings?*
- *RQ 3.3: Which measures are effective to maximize energy savings through telecommuting?*

3 Approach

3.1. A mixed method approach

The approach taken to answer the research questions is a mixed method approach, which is a study "in which the researcher incorporates both qualitative and quantitative methods of data collection and analysis in a single study" (Creswell, 1999, p. 455). It is especially useful for research whose results are to be used for policy making because "it enables a policy researcher to understand complex phenomena qualitatively as well as to explain the phenomena through numbers, charts and basic statistical analyses" (Creswell, 1999, p. 455). Mixed method approaches can "illuminate […] complexity through multiple lenses" (Rossman & Wilson, 1994, p. 324).

Such a research design is useful for answering the research questions for the following reasons:

— Identifying research gaps and methodological challenges in the assessment requires both qualitative and quantitative analysis of the existing literature.
— Qualitative understanding of the relationship between ICT use, time use and environmental impact is required to build an assessment approach for investigating indirect environmental effects of ICT from a time-use perspective.
— Demonstrating the approach and assessing time rebound effects of TC requires quantitative analysis of time and energy use impacts of TC.
— The results of the assessments done in response to *RQ 3* are to be used by policy makers and practitioners to develop TC strategies which reduce environmental impacts.

Figure 3 provides a graphical illustration of the research questions and methods used to answer them, which are described in some detail in the following three sections and in Table 1.

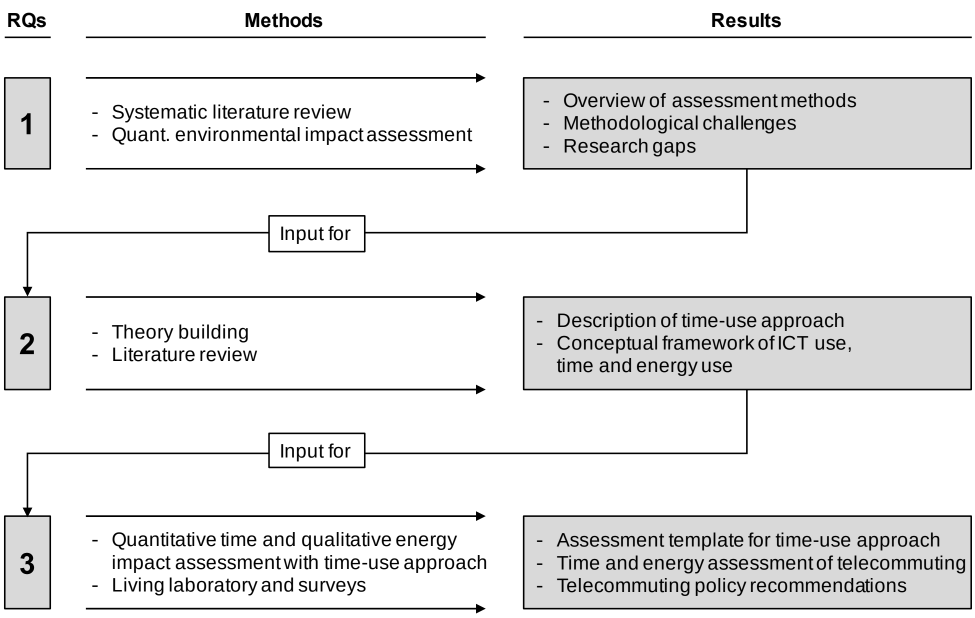

Figure 3: Graphical illustration of the dissertation's mixed-method approach including research questions, applied methods and results.

3.2. Part I: Determining the status quo

"Determining the status quo" is about providing an overview of existing assessments of indirect environmental effects of ICT and identifying research gaps and methodological challenges in the scientific literature and industry practice. Therefore, I follow two steps:

— A systematic literature review of assessments of indirect environmental effects of ICT to identify applied assessment methods, application domains and research gaps
— A quantitative assessment of indirect effects of ICT on GHG emissions using the ICT enablement method (an assessment method frequently used in the ICT industry) in order to identify and discuss methodological challenges in such assessments

The results of this part lay the foundation for developing a new assessment approach.

3.3. Part II: Developing a new assessment approach

This part is about systematically developing a new assessment approach (the time-use approach) which can close the main research gaps and overcome methodological challenges. This part is clustered into two sub-sections:

— Introduction of the time-use approach and systematic discussion how it addresses methodological challenges and research gaps identified in *RQ 1*
— Development of a conceptual framework of ICT impacts on time and energy use by systematically analyzing and clustering insights of existing literature on ICT impacts on time use and energy impacts of time use

3.4. Part III: Demonstrating the approach

This part is about actually using the time-use approach for assessing indirect environmental effects of ICT with the example use case TC and the example environmental impact category energy use. Thus, this section serves two purposes: providing a template for future assessments of indirect environmental effects of ICT from a time-use perspective and actually assessing energy impacts of TC and deriving policy recommendations for harnessing potential energy savings and mitigating risks. This part is clustered into three sub-sections:

— A demonstration how time-use data can be analyzed and linked with data on environmental impacts of activities to assess environmental consequences of a change in time allocation
— A case study of time, travel and energy impacts using data of an actual CW living laboratory in Stockholm
— A systematic analysis of environmental effects of CW beyond time use based on the CW living laboratory in Stockholm

#	Part	Activities	Outcome	Applied Method
1	Determining the status quo-	- Identifying existing assessments, assessment methods, application domains and use cases of indirect environmental effects of ICT	- Overview of assessment methods, application domains and use cases - List of research gaps	- Systematic Literature Review
		- Conducting an assessment of indirect effects of ICT on GHG emissions and identifying research gaps and methodological challenges in the assessment	- List and discussion of research gaps and methodological challenges	- Quantitative environmental impact assessment with ICT enablement method
2	Developing a new assessment approach	- Developing a new approach to assess indirect environmental effects of ICT—the time-use approach.	- Description of the time-use approach - Description of the relationship between ICT, time use and environmental impact	- Theory building
		- Identifying concrete ICT impacts on time and energy use - Qualitative assessment of time-use impacts of the ICT use case telecommuting (working from home)	- Conceptual framework of ICT impact on time and energy use	- Literature review - Theory building - Qualitative assessment of time-use impacts using the framework
3	Demonstrating the approach	- Demonstrating the time-use approach at the example of the ICT use case telecommuting using Dutch time-use data	- Template for assessments using a time-use approach - Advantages and disadvantages of time-use approach for environmental impact assessment of ICT use and identification of fields for further research	- Graphical time-use data analysis - Literature review and qualitative energy impact assessment using time-use approach
		- Applying the time-use approach to the ICT use case telecommuting (working from a co-working space) in a co-working living laboratory in Stockholm	- Time and energy assessment of telecommuting (working from a co-working space) - Policy recommendations for co-working	- Living laboratory approach and surveys - Quantitative time and qualitative energy impact assessment using time-use approach
		- Identifying environmental impacts of co-working beyond impacts due to changes in time allocation - Assessment of commute-related energy savings and energy required to operate a co-working space in a co-working living laboratory in Stockholm	- Conceptual framework of environmental impacts of co-working - Energy assessment of telecommuting (working from a co-working space) - Policy recommendations for co-working	- Living laboratory approach and surveys - Quantitative energy impact assessment

Table 1: Activities, outcomes and applied methods in each part of the dissertation.

3.5. Interdisciplinary approach

Research on sustainable development is inter- if not transdisciplinary in its very nature: Sustainable development is characterized by dilemmas, trade-offs and conflicting goals. Finding good solutions to overcome these conflicts always requires multiple perspectives and therefore a mix of methods and approaches from various academic disciplines. The research field ICT4S is interdisciplinary by definition, combining aspects of informatics and sustainability research. This interdisciplinarity is also at the core of this dissertation.

The research reported in this dissertation starts with a cross-disciplinary research method (systematic literature review) and a research method specific to the field of ICT4S, the ICT enablement (assessment) method. It then identifies and applies a new assessment approach (time-use approach) to assess indirect environmental effects of ICT which includes elements from informatics, economics, human geography and earth sciences. This dissertation also contributes to transportation research, as TC is discussed as an ICT use case in this discipline and the time-use approach has many similarities to transportation research approaches (e.g. activity-based modeling). The choice of journals and conferences emphasizes the interdisciplinarity (see 4.1).

The topic of this dissertation—ICT impacts on time use and the environment—also contributes to the strategy of the Department of Informatics of the University of Zurich (focus area People-oriented Computing) and various cross-faculty strategic fields of the University of Zurich such as the Digital Society Initiative.

4 Contributions

4.1. Articles comprising this dissertation

This dissertation is comprised of 7 articles (Table 2). Five articles have already been published at the time of submitting this dissertation and two are submitted to peer-reviewed journals. During my PhD studies, I co-authored further peer-reviewed articles which are related to this dissertation, but not directly included here (Table 3). Additionally, I co-organized a workshop on “(How) can our digitalized society operate within planetary boundaries?” at the conference ICT4S 2019.

4.2. Contributions to practice

The assessment of indirect environmental effects of ICT gained attention through the work by GeSI, an industry association for ICT and sustainability. In its SMARTer studies (GeSI et al., 2008; GeSI & Accenture Strategy, 2015; GeSI & BCG, 2012; GeSI & Deloitte, 2019), GeSI emphasized the potential for using digital solutions for climate protection. These studies have played an instrumental role in developing the field, although this dissertation takes a critical view of their approach.

A large part of this dissertation is based on cooperative research with private companies and public institutions. Part I is partly based on the research project “Opportunities and Risks of Digitalization for Climate Protection in Switzerland”, which was conducted together with Swisscom and WWF Switzerland (Hilty & Bieser, 2017). A study on the opportunities and risks of digitalization for climate protection in Germany, based on cooperative research with Bitkom, Germany’s largest association of the digital economy, and the Borderstep Institute for Innovation and Sustainability, was published in spring 2020 (Bieser, Hintemann, et al., 2020).

The third part of this dissertation is partly based on an actual living laboratory CW space in Stockholm, Sweden, which is part of the Mistra SAMS Sustainable Accessibility and Mobility Services project by KTH Royal Institute of Technology and VTI Swedish National Road and Transport Research Institute. Employees from various medium-sized and large companies in Sweden are part of the CW living laboratory.

Further studies with industry partners in this field started during the final phase of this dissertation. I presented results of completed studies at several practitioner events. Table 4 shows the most important reports, articles and presentations.

Parts of the results of this dissertation specify conditions for environmentally friendly telecommuting. Knowing about these conditions can support policy makers in developing policies which encourage environmentally friendly travel and work patterns, organizations in developing strategies to reduce environmental impacts associated with commuting and use of office space and individuals in reflecting on the environmental impacts of their work-related and private activities.

Part	Article	Publication type	Status
Part I: Determining the status quo	Bieser, J., & Hilty, L. (2018b). Assessing indirect environmental effects of information and communication technology (ICT): A systematic literature review. Sustainability, 10(8), 2662. https://doi.org/10.3390/su10082662	Journal article	Published
	Bieser, J., & Hilty, L. (2018c). Indirect effects of the digital transformation on environmental sustainability: Methodological challenges in assessing the greenhouse gas abatement potential of ICT. In: Penzenstadler, B., Easterbrook, S., Venters, C. & Ahmed, S. I. (editors). ICT4S2018. 5th International Conference on Information and Communication Technology for Sustainability, vol 52, pages 68-81. https://doi.org/10.29007/lx7q	Contribution to conference proceedings	Published
Part II: Developing a new assessment approach	Bieser, J., & Hilty, L. (2018a). An approach to assess indirect environmental effects of digitalization based on a time-use perspective. In: Bungartz, H.-J., Kranzlmüller, D., Weinberg, V., Weismüller, J. & Wohlgemuth, V. (editors). Advances and New Trends in Environmental Informatics. Progress in IS. Springer, Cham, pages 67-78. https://doi.org/10.1007/978-3-319-99654-7_5	Contribution to conference proceedings (EnviroInfo 2018)	Published
	Bieser, J., & Hilty, L. (2020). Conceptualizing the impact of information and communication technology on individual time and energy use. Telematics and Informatics, 101375. https://doi.org/10.1016/j.tele.2020.101375	Journal article	Published
Part III: Demonstrating the approach	Bieser, J., Höjer, M., Kramers, A., & Hilty, L. (2020). Toward a method for assessing the energy impacts of telecommuting based on time-use data. Travel Behaviour and Society. Submitted for publication.	Journal article	Submitted for publication
	Bieser, J., Vaddadi, B., Kramers, A., Höjer, M., & Hilty, L. (2020). Impacts of telecommuting on time use, travel and energy: A case study of co-working in Stockholm. Travel Behaviour and Society. Submitted for publication.	Journal article	Under revision
	Vaddadi, B., Bieser, J., & Pohl, J., Kramers, A. (2020). Towards a conceptual framework of direct and indirect environmental effects of co-working. In: ICT4S 2020. 7th International Conference on ICT for Sustainability. ACM, Virtual Conference, pages 27-35. https://doi.org/10.1145/3401335.3401619	Contribution to conference proceedings	Published

Table 2: Articles included in this dissertation.

Article	Publication type	Status
Bieser, J. & Coroama, V. (2020). Direkte und indirekte Umwelteffekte der Informations- und Kommunikationstechnologie. NachhaltigkeitsManagement Forum (2020). https://doi.org/10.1007/s00550-020-00502-4	Journal article	Published
Bieser, J., Haas, D., & Hilty, L. (2019). VETUS—Visual exploration of time-use data to support environmental assessment of lifestyles. In: ICT4S 2019. 6th International Conference on Information and Communication Technology for Sustainability. https://doi.org/10.5167/uzh-171387	Contribution to conference proceedings	Published

Table 3: Further related articles.

Type	Contribution	Journal, conference or project partner
Technical reports	Bieser, J., Hintemann, R., Beucker, S., Schramm, S., & Hilty, L. (2020). Klimaschutz durch digitale Technologien: Chancen und Risiken. Bitkom. https://doi.org/10.5167/uzh-190091	Bitkom, Borderstep Institute for Innovation and Sustainability
	Bieser, J. & Hilty, L. (2019). Kurzstudie zum Elektrizitätsbedarf von Rechenzentren in der Schweiz.	Swisscom
	Hilty, L., & Bieser, J. (2017). Opportunities and Risks of Digitalization for Climate Protection in Switzerland. University of Zurich. https://doi.org/10.5167/uzh-141128	Swisscom & WWF Switzerland
Articles	Bieser, J. (2018c). Digitalisierung bietet Chancen für den Klimaschutz. Swiss IT Magazine, 201811. https://doi.org/10.5167/uzh-171389	Swiss IT Magazine
Presentations	Bieser, J. (2020a). Environmental impacts of co-working.	RemoteCon
	Bieser, J. (2020b). Chancen und Risiken der Digitalisierung für den Umweltschutz.	BFH Workshop. Die digitale Welt nachhaltig gestalten
	Bieser, J. (2019). Indirect effects of digitalization on the environment.	LCA Discussion Forum
	Bieser, J. (2018b). Chancen und Risiken der Digitalisierung für den Klimaschutz.	"Mehr Effizienz in Rechenzentren und Serverräumen". Conference by asut and EnergieSchweiz.
	Bieser J. (2018a). Chancen und Risiken der Digitalisierung für den Klimaschutz.	Swiss Green Economy Symposium 2018
	Bieser J. (2018a). Chancen und Risiken der Digitalisierung für den Klimaschutz.	Green IT Special Interest Group
	Bieser J. (2017). Digitalisierung und Klimaschutz.	Swiss Green Economy Symposium 2017

Table 4: Contributions to practice.

5 Outline of the articles included in this dissertation

The following sections outline the articles included in this dissertation and show how they relate to each other.

5.1. Part I: Determining the status quo

5.1.1 Article 1: Assessing indirect environmental effects of information and communication technology (ICT): A systematic literature review

Existing assessments of indirect environmental effects of ICT focus on 7 main application domains using 15 different assessment approaches.

The systematic literature review provides a state-of-the-art overview of the methods used in the research field as well as research gaps and is intended to support researchers in designing sound assessments which yield significant results. We identified 54 studies in 7 main application domains using 15 different assessment approaches. The most common application domains are virtual mobility (e.g. TC), virtual goods (e.g. digital media), and smart transport (e.g. route optimization) (Figure 4).

Most assessments focus on ICT-induced changes in production patterns. The consumption side is underexplored.

The main finding is that most assessments focus on ICT-induced changes in production patterns and only few assessments specifically focus on changes to consumption patterns (Figure 4). Assessing ICT impacts on production is useful for understanding the environmental consequences of (roughly) functionally equivalent product systems with and without the application of ICT (e.g. differences in energy consumption between providing a movie on DVD and via online streaming platforms). Understanding ICT impacts on consumption patterns is essential for understanding ICT's impact on individuals' behavior, society as a whole, and the environmental consequences of these changes. For example, flat-rate based online movie streaming platforms provide access to a large selection of digitally stored movies and decrease the cost per movie for the end consumer, who now can afford to watch more movies. This again increases online data traffic (especially in the case of high-resolution movies) and the energy required to operate the data centers and networks required.

The consumption-centered assessments use methods such as interviews or surveys to ask consumers about their consumption behavior and potential changes. The environmental consequences are then estimated by comparing the environmental impact of the goods and services that are consumed by individuals before and after the ICT-induced change. For example, Røpke and Christensen (2012) assess how ICT changes the activities that are performed by individuals throughout one day and the energy consumption that is associated with these activities.

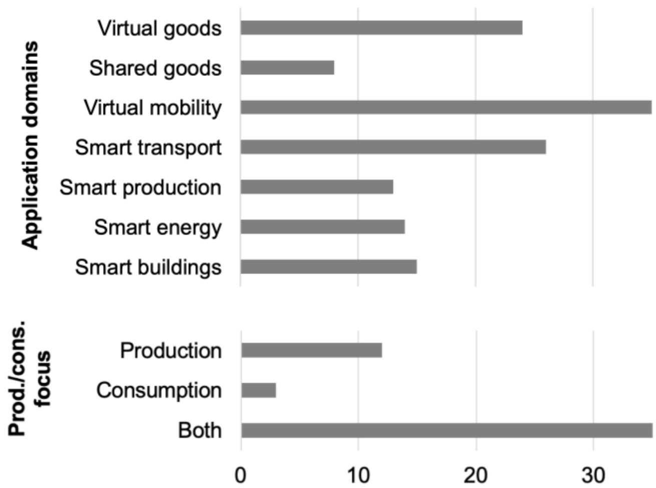

Figure 4: Number of studies by application domain and production vs. consumption focus. One study can cover more than one application domain. Most of the studies which have, both, a production and a consumption focus, mainly focus on changes to production patterns and address changes to consumption patterns only to a small extent.

5.1.2 Article 2: Indirect effects of the digital transformation on environmental sustainability: Methodological challenges in assessing the greenhouse gas abatement potential of ICT

ICT use has the potential to avoid GHG emissions in Switzerland, especially in the building, transport and energy domains. Targeted actions to exploit these potentials are required.

The article presents an assessment of the potential of frequently discussed ICT use cases to avoid GHG emissions ('GHG abatement potential') in Switzerland. In order to identify the main methodological challenges of such assessments, we analyzed the estimation approach of a heavily discussed study by

GeSI (2015) on the global GHG abatement potential of ICT (SMARTer 2030) and reassessed the main assumptions in their estimation.

The results confirm that ICT has the potential to reduce GHG emissions in Switzerland, especially in the building (e.g. through intelligent heating), transport (e.g. through traffic control and optimization as well as logistics sharing) and energy domains (e.g. through demand side management). However, the results also suggest that the SMARTer 2030 study may be too optimistic and that the potential is smaller than projected there. The main risk of overoptimistic studies is that they convey the notion that GHG emissions can be avoided simply through diffusion of ICT in the relevant domains. However, ICTs are embedded in complex socio-economic systems, and their actual impact depends on interaction with variables in the broader use case system; thus, targeted action to exploit these potentials is required.

Assessments of indirect environmental effects of ICT face various methodological challenges which need to be addressed to increase the validity of results.

Besides the quantification of GHG abatement potentials, the main result of this study is a list of methodological challenges I encountered during the assessment and which commonly occur in such studies (Table 5). How a study deals with these challenges has a crucial influence on its results.

Methodological challenge	**Description**
Selection of use cases	Defining the set of use cases is a general problem in the assessment of the overarching indirect effect of ICT on GHG emissions since it is impossible in principle to analyze ″all″ future ICT applications that are potentially relevant. The SMARTer 2030 study focused on ICT use cases with the potential to avoid GHG emissions; thus, it systematically excluded ICT use cases which increase GHG emissions (e.g. printers inducing the use of paper).
Allocation	The significance of the ICT application as an enabler of the use case varies highly across use cases. The assessment of ICT-induced GHG savings raises allocation issues as "ICT typically does not induce efficiency on its own, but only in a suitable technological, political or organizational context" (Coroamă, Schien, et al., 2015, p. 2). Allocating all GHG abatements to ICT must be questioned especially if the GHG abatement potential is put into relation to the GHG footprint of the ICT sector.
Baseline	Assessments of indirect effects of ICT on GHG emissions need to identify baseline emissions, i.e., the emissions that would be expected if the ICT use case under study were not adopted (Hilty et al., 2014). Isolating the adoption of specific ICT use cases from a baseline scenario can be difficult since ICT has widely penetrated society. This problem is even larger for prospective studies, since "the baseline scenario, […] as it expands into the future, is inherently speculative" (Coroamă, Schien, et al., 2015, p. 2).
Impact	Studies of GHG abatement potentials need to estimate the actual impact of the use cases on baseline GHG emissions (e.g. to what extent smart meters reduce household energy consumption). However, estimating the actual impact is tricky because ICT's "theoretical potentials materialize only under specific conditions" (Hilty et al., 2014, p. 1).
Adoption	Prospective studies need to estimate the future adoption of all ICT use cases. Future estimations always involve uncertainty, and reliable forecast data is often unavailable.
Rebound effect	"ICT are subject to important rebound effects of all kinds (energy, time, knowledge-related) […]" (Gossart, 2015, p. 445). From an economic point of view, rebound effects are based on demand elasticities, which are difficult to predict, especially in the long term.
Interaction	ICT use cases can interact with other ICT use cases (e.g. ′e-health′ can enable users to avoid travel, which impacts the fuel saving potential of ′route optimization′) and with variables in the broader use case system (e.g. the acceptance of videoconferencing depends on cultural aspects in the country). Including interaction in an assessment is challenging and requires dynamic modelling and simulation approaches.
Extrapolation	Extrapolating results from specific regions (e.g. individual countries) to a larger scale (e.g. globally) introduces a lot of uncertainty, as case study results may not be representative (Malmodin & Coroamă, 2016).

Table 5: Methodological challenges in assessments of indirect environmental effects of ICT.

5.2. Part II: Developing a new assessment approach

5.2.1 Article 3: An approach to assess indirect environmental effects of digitalization based on a time-use perspective

The time-use approach is a promising approach to address the main research gaps and methodological challenges in assessments of indirect environmental effects of ICT.

Based on the results of part I, this article recognizes that three main challenges or research gaps in the assessment of indirect environment effects of ICT exist:

- Only few assessments take ICT-induced changes in consumption patterns and associated environmental impacts into account.
- Most assessments do not consider interaction among use cases. For example, the use case TC by itself can avoid travel-related GHG emissions. In combination with other use cases (e.g. e-commerce, e-health) it can more fundamentally change individual lifestyles, which may only be visible using a more comprehensive, systemic perspective.
- ICT solutions are subject to various types of rebound effects, which can compensate, if not overcompensate, for ICT-enabled reduction of environmental burdens. There is high uncertainty about the actual magnitude of rebound effects, which also vary by socio-economic context.

The time-use approach is promising to address these challenges. First, it takes a consumption-oriented perspective: How do individuals spend their time?

Second, the time-use approach can also capture interaction among use cases because (1) time is a limited resource for everyone, a fact which makes time budget constraints a central link between different activities and (2) many ICT use cases relax individuals' time and space constraints, thus changing time allocation. For example, if the researcher finds that TC saves 20 minutes of commute time per day on average, he or she must also answer the question how the time saved is spent. If we add further ICT use cases to the assessment, they again change the rules of the game in which all activities compete for the same, naturally limited resource—time.

Third, the time-use approach is suitable to investigate one important type of rebound effect: the time rebound effect.

There are strong links between ICT use, time use and environmental impact which can be used to investigate environmental effects of increasing ICT use.

The final result of this article is an overarching framework based on the time-use approach which describes the interconnection between ICT use, time-use patterns and environmental impact (Figure 5). ICT use changes individual time-use (e.g. avoiding travel). How individuals use their time impacts the use of infrastructures, e.g. for transport, working and living. Construction, use and maintenance of infrastructure (especially transport and building infrastructure) causes large environmental impacts. ICT can also directly impact infrastructure utilization (e.g. automated driving can increase the number of cars on streets) and infrastructure utilization can also impact time-use (e.g. if people work from home because they expect the commuter trains to be overcrowded).

To summarize, a strong link between ICT use, time-use patterns and environmental impacts exists, and taking such a time-use perspective can help overcome several main challenges in the assessment of indirect environmental effects of ICT.

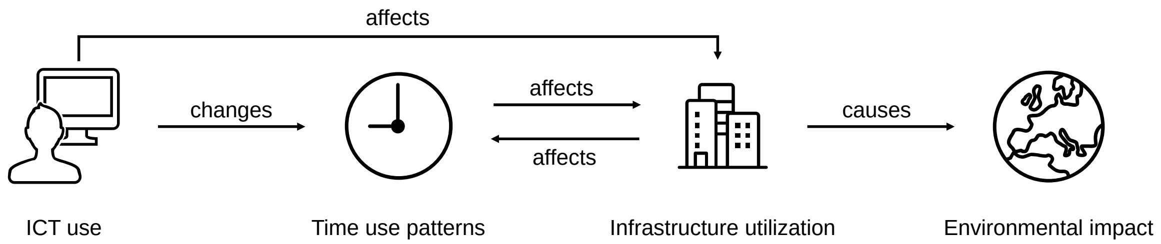

Figure 5: Relationships between ICT use, time-use patterns, infrastructure utilization and environmental impact.

5.2.2 Article 4: Conceptualizing the impact of information and communication technology on individual time and energy use

ICT impacts planning and execution of activities, which causes systemic effects in a broader systems perspective. The systemic effects are characterized by feedback loops and can cause delayed changes in time use patterns.

Based on the overarching framework of the time-use approach, this article presents a detailed conceptual framework of ICT impacts on time and energy. Because ICT impacts on time and energy use are diverse (e.g. ICT can reduce transport time through virtual mobility or increase transport time by creating the desire to travel to places seen on the Internet), it is essential to gain a deeper understanding of the fundamental impact patterns by means of this framework.

The first part of the framework is a description of ICT impact patterns on activities, which are derived from the existing literature on ICT impacts on leisure, maintenance, work and transport activities. The framework distinguishes between immediate impacts of ICT on planning and execution of activities (Table 6) and systemic effects with consequences for time use.

Phase	Aspect	Guiding question(s)	ICT impact pattern
Activity planning	Activity selection	Which activities will I perform?	- Substituting activities - Avoiding activities - Delegating activities - Creating additional activities
	Activity scheduling	When will I perform activities? Where will I perform activities?	- Relaxation of time constraints - Relaxation of space constraints - Parallelization
	Planning horizon, duration and frequency	How long do I plan in advance? How much time do I spend on planning? How often do I plan activities?	- Shorter/longer planning horizon - Less/more time spent on planning - More frequent replanning
Activity execution	Activity manner	How do I perform an activity?	- Impact highly activity-specific - E.g. decreasing/increasing complexity of the activity
	Activity duration	How long does an activity take?	- Shorter/longer activity duration
	Activity fragmentation	Do I complete an activity once I started it?	- Interrupting activities - Increasing focus on activities

Table 6: ICT impact patterns on activity planning and execution.

The systemic effects of ICT on time use are effects which only occur through the relationships between variables in the broader socio-economic system in which the ICT use takes place. ICT impacts on time use can trigger causal chains which form feedback loops and change time use with some delay. For example, TC mitigates the need to live close to the employer's office (Salomon, 1986). If this results in, for example, living in a rural instead of an urban area, this feeds back on individual time use patterns, e.g. regarding time spent on traveling for groceries, the preferred mode of travel, or the type of leisure activities chosen.

From a time-use perspective, the energy impacts of ICT use depend on the direct and indirect energy requirements of the activities before and after adoption of an ICT use case.

The second part of the framework is a description of energy impacts of time use, based on Jalas' time-use approach (Jalas, 2002), which distinguishes direct and indirect energy requirements of activities. Energy use is an exemplary environmental impact category and could in principle be replaced with other environmental impact categories (e.g. global warming potential).

Direct energy requirements represent the direct consumption of energy carriers during the performance of an activity. These include fuel consumption of transport vehicles, fuel or electricity consumption for heating and cooling buildings (e.g. oil, gas, electricity), and electricity consumption of electrical and electronic appliances (e.g. stoves, lights, TV sets). Indirect energy requirements are embedded energy, i.e. the "energy use of producing the goods and services that are needed in the activity" (e.g. production of a car) (Jalas, 2002, p. 114).

From a time-use perspective, net energy impacts of ICT depend on the energy requirements of the activities performed before and after adoption of an ICT use case. In other words, net energy impacts of ICT depend on the marginal energy requirements of activities, the impacts of a change in time allocation on energy requirements of activities.

5.3. Part III: Demonstrating the approach

5.3.1 Article 5: Toward a method for assessing the energy impacts of telecommuting based on time-use data.

Interrelations between time spent on commuting and on other travel and non-travel activities can be assessed with time-use data.

This article demonstrates how the time-use approach can be operationalized with actual time-use data. TC is used as an example ICT use case because it is subject to time rebound effects. That is, reducing commuting allows telecommuters to spend the time saved on commuting on travel for other purposes and on non-travel activities such as 'leisure', which are associated with their own environmental impacts. Most existing TC studies focus on travel impacts and do not consider changes in time spent on non-travel activities.

To demonstrate the approach, I assess interrelations between changes in commute time and time spent on travel and non-travel activities using Dutch time-use data from 2005 aggregated by the Multinational Time Use Study (MTUS) (Gershuny & Fisher, 2013). To do so, I conduct a graphical data analysis by plotting the average time spent on activities by time spent on commuting (clustered in 'commute' classes) on a line chart (Figure 6). It shows that interrelations between time spent on commuting and on other activities exist and that time-use data can be used to investigate these interrelations. For example, less time spent on commuting on a workday seems to be associated with more time spent on 'sleep and rest', 'leisure', 'phf care', 'private travel' and 'eating and drinking'. In contrast, work shows a different pattern: greater daily commute time tends to be associated with greater 'work' time. However, people work less on days when their commute is very long.

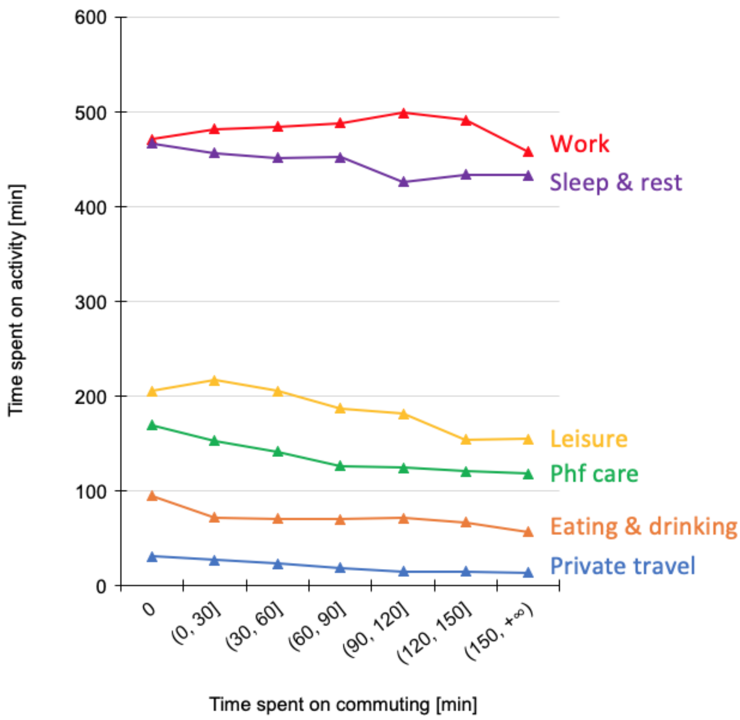

Figure 6: Average time spent on an activity on a workday by 'commute' class.

There is unexploited potential to use time-use data for assessing travel and environmental impacts of TC and other ICT use cases that affect time allocation.

Environmental assessments of TC can benefit from time-use data for several reasons. For example, with time-use data, impacts of TC on travel and on non-travel activities can be included in the assessment. Also, if time-use data covers weekly time-use patterns, possible interactions in time use between weekdays and weekends can be assessed. However, using time-use data for environmental assessment of TC also entails some challenges. For example, most time-use studies collect cross-sectional data and do not capture information on TC behavior explicitly. Such data does not allow researchers to make causal inferences concerning the impacts of time spent on commuting (or even TC) on time use for other activities. Also, time-use assessments of TC need to control for various other factors (e.g. doctor's appointments, picking up children from school) and demographic and socio-economic variables (e.g. 'having a child' or 'cohabiting' can impact time spent on 'phf care'), which can impact individuals' time use. While many time-use surveys collect data on diarists' demographic and socio-economic characteristics, various relevant factors impacting time use (e.g. having a doctor's appointment) are usually not included in such studies. Still, this analysis shows that there is unexploited potential to use time-use data for assessing travel and environmental impacts of TC and other ICT use cases that affect time allocation.

Conducting quantitative energy assessments of TC from a time-use perspective requires data on the marginal energy requirements of activities—energy impacts of changes in time use.

Time-use data can be linked with data on energy requirements of activities to assess the energy impacts of changes in time allocation. Conducting comprehensive, and specifically quantitative, energy assessments of TC from a time-use perspective necessitates data on the marginal energy requirements of activities—the energy impacts of changes in time use (e.g. due to TC). These depend specifically on the relationship between the time spent on a given type of activity and the use and purchase of (energy-consuming) goods and services. For example, in the case of travel, the direct energy requirements are mostly proportional to the time spent on the activity (e.g. driving a car longer directly increases fuel consumption). But the direct energy consumption of non-travel activities only increases if energy-consuming appliances are used longer (e.g. vacuum cleaning longer increases energy consumption, tidying up longer does not). Changes in time allocation only impact indirect energy requirements if they trigger additional production or avoid production (e.g. not purchasing a car because of TC). With respect to infrastructure use, if ICT-based solutions lead to a long-term change in demand for infrastructures, changes in the processes of building and operating them can be expected.

These impacts have been out-of-scope in most energy assessments of activities and need further investigation. Gathering this data and drawing robust conclusions is challenging as the behavioral response due to changes in time use can be very different for different activity types (e.g. a change in commute time can have different consequences than a change in housework time), for individuals with different demographic and socio-economic characteristics (e.g. individuals with and without children), and also depends on individual preferences and needs.

5.3.2 Article 6: Impacts of telecommuting on time use, travel and energy: A case study of co-working in Stockholm

Working from a local CW space and from home instead of a more distant employer office can reduce workday travel time and increase time spent on leisure and everyday chores.

A special case of TC is working from a CW space closer to home. This article presents an analysis of differences in time use, travel patterns, and energy impacts of TC using the data from a CW living lab in Stockholm. As the analysis considers travel and non-travel activities, it is an operationalization of the time-use approach.

The CW living lab is a CW space in Tullinge, south of Stockholm, which offers 14 workplaces plus conferencing facilities. From September to November 2019, 20 employees of an IT company with headquarters north of Stockholm filled out time-use diaries for three weeks (resulting in a maximum of 21 diary days). Figure 7 shows the average daily time spent on four types of activities by work location on that day. It shows that when diarists worked from the local CW space or from home, total daily travel time was significantly lower than on days when they worked from the more distant employer office. This is because telecommuters did not compensate commute time saved with travel for private purposes; instead, they spent it on other activities, such as ‘leisure’ or ‘everyday chores’.

Some diarists used the same commute transport modes or switched to less energy-intensive ones (e.g. from car to biking or walking). There is no indication that CW led to a major shift to more energy-intensive transport modes (e.g. from public transport to car transport).

Figure 8 shows average daily travel time (‘commute’ + ‘private travel’) across transport modes. Time spent on public transport is greatest on employer office days, significantly lower on CW days, and almost zero on home office days. Car travel is also greatest on employer office days and lower on CW days. On home office days, car travel is greater than on CW days. Since there is no commute on home office days, car travel is for private purposes only. Time spent on ‘biking and walking’ is roughly equal on employer office and CW days and lower on home office days.

An additional analysis of commute transport modes shows that some diarists used the same commute transport modes or switched to less energy-intensive ones (e.g. from car to biking or walking) on CW days. The possibility to switch from other transport modes to biking and walking is a feasible option only because the CW space is located in the neighborhood of the diarists’ homes. There is no indication that CW led to a major shift to more energy-intensive commute transport modes (e.g. from public transport to car transport).

Still, we have to consider that the analysis is based on cross-sectional data and covers weekdays only. Thus, we cannot compare time use before and after adopting CW or interactions between time use on weekdays and weekends. For example, people could shift activities which induce car travel from weekends to weekdays (e.g. going shopping). This would reduce the car use on weekends, but total car use per week would not change.

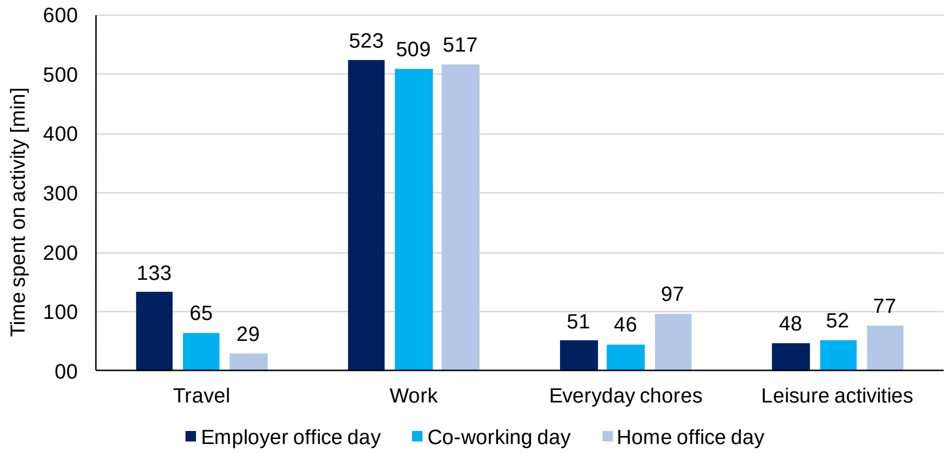

Figure 7: Average daily time spent on an activity by work location on that day. The sum of time spent on all activities differs on employer office, co-working and home office days because time-use diarists often did not fill out diaries completely.

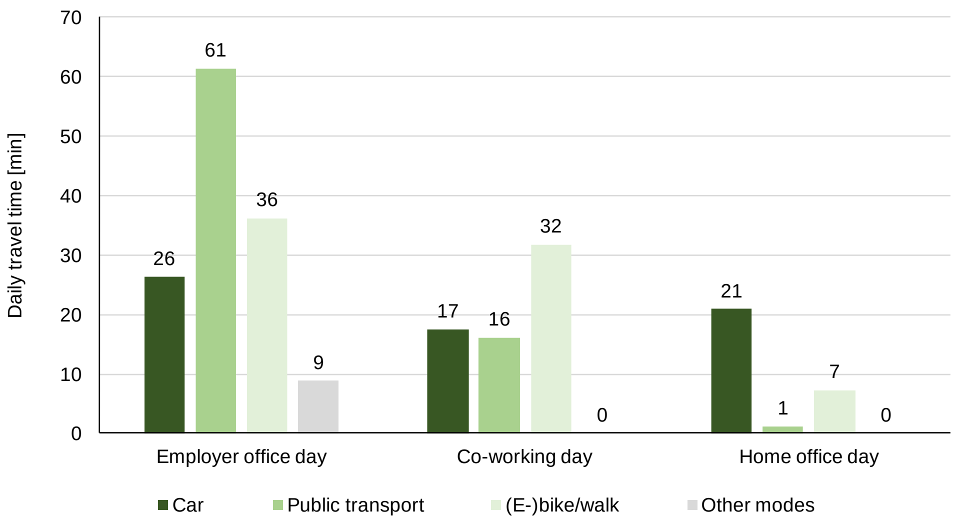

Figure 8: Daily travel time per workday across transport modes by work location.

Working from a local CW space or home has the potential to realize net energy savings because commute time saved is mainly spent on non-travel activities, which are associated with lower energy requirements than travel. However, the energy impacts depend on the transport modes used and the marginal energy requirements of non-travel activities.

Since various studies have shown that the direct energy requirements of most non-travel activities are lower than those of travel activities (Aall, 2011; De Lauretis et al., 2017; Jalas & Juntunen, 2015), there seems to be a potential for net energy savings through working from the CW space or from home. However, the actual impacts depend on the marginal energy requirements of activities, which are difficult to quantify.

Plus, the energy impacts of TC also depend on the transport modes because their energy requirements differ. For people who exclusively commute by car, the direct energy savings due to reduced commuting are higher than for public transport commuters, as car travel is associated with higher direct energy requirements. For bikers and pedestrians, the travel-related energy savings due to working from home or the CW space would be zero, as the direct energy requirements of this transport mode are zero. Thus, any increase in direct energy requirements due to more time spent on other activities would lead to a net increase in direct energy requirements. Therefore, TC strategies should aim at reducing motorized transport and encourage telecommuters to switch to non-motorized transport modes (as some diarists in this case study did).

5.3.3 Article 7: Toward a conceptual framework of direct and indirect environmental effects of co-working

Working from a local CW space causes direct environmental effects through the infrastructure required to operate CW spaces, indirect environmental effects due to individual co-workers or organizations adopting CW, and systemic environmental effects through a system transformation toward CW.

This article takes a broader view of environmental impacts of ICT use by presenting a framework of possible environmental effects of CW beyond the environmental impacts due to changes in time use (Figure 9). It emphasizes that the time-use approach should be complemented with other methods to shed light on the environmental effects of ICT from various perspectives.

The framework of environmental impacts of CW distinguishes effects on three layers. The first layer, 'Technology: Co-working infrastructure', describes the environmental effects of building, operating, and maintaining infrastructures required for CW (e.g. CW space, video conferencing systems, parking, etc.). The second layer, 'Application: Working at a co-working space', describes the environmental effects due to individual workers or organizations adopting CW. This directly affects the use of space, transport infrastructure, and ICT equipment. Time and income rebound effects are also included in this layer because co-workers will spend money and time not spent on commuting on other activities that are in turn associated with their own environmental impacts (Bieser & Hilty, 2020; Sorrell & Dimitropoulos, 2008). The third layer, 'Structural change: Large-scale adoption of co-working', describes the environmental effects of system transformation toward CW. It leaves the level of individual co-workers or organizations and focuses on the environmental consequences of a transformation toward a society-wide CW culture. Such a transformation includes changes to working cultures, ways of communication, lifestyles, and land use patterns, which only occur if a critical mass of society switches from conventional working habits to CW.

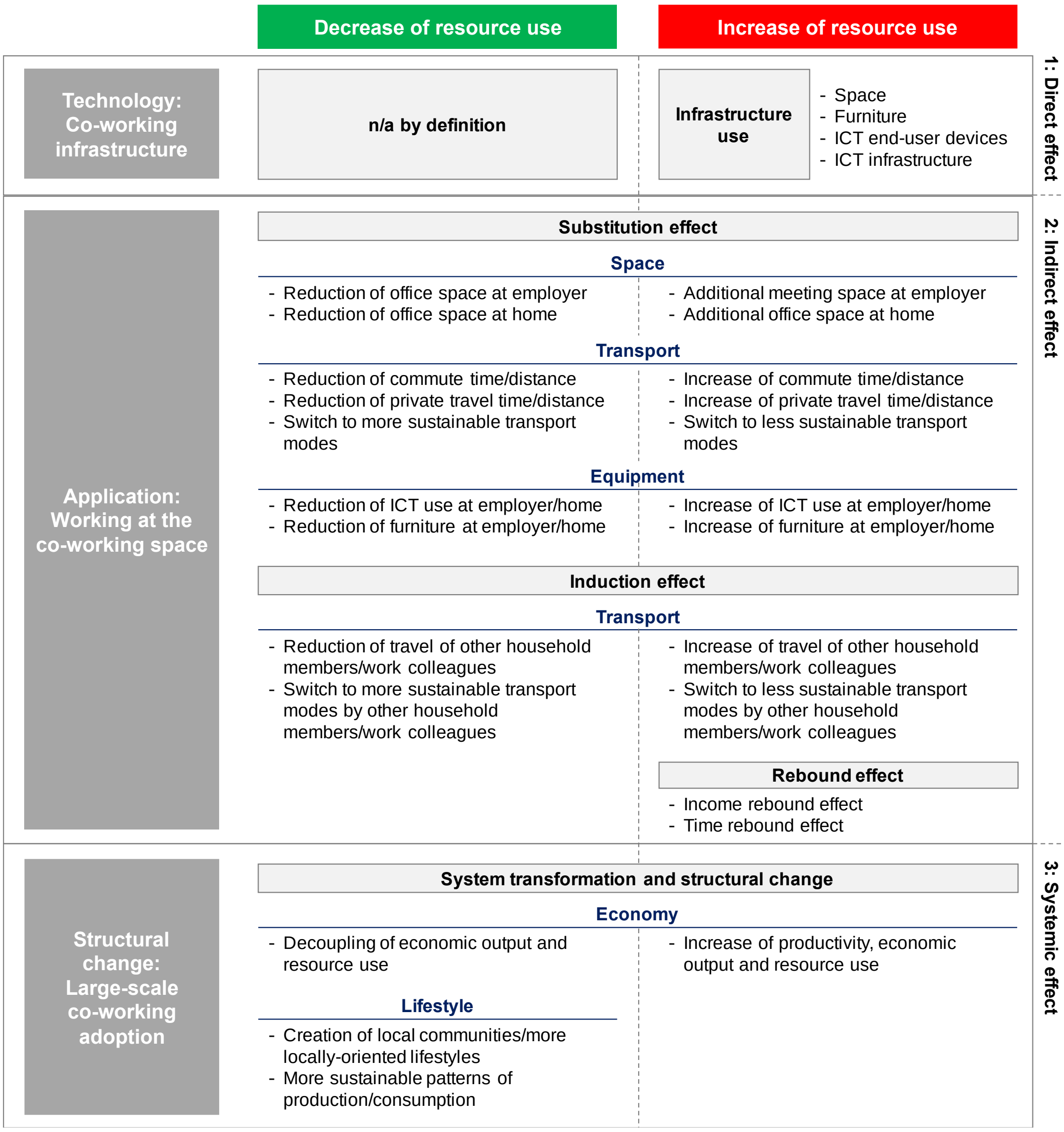

Figure 9: Framework of environmental effects of co-working.

The energy required to operate the CW space can offset travel-related energy savings.

The relevance of energy impacts of changes in space requirements due to CW is demonstrated based on data from the CW living lab in Stockholm. Figure 10 shows the direct energy requirements of providing the CW space in Stockholm (broken down per person and workday) and the direct travel-related energy impacts of working in the CW space instead of the employer office (left) and of working in the CW space instead of home (right) for one day. It shows that the direct energy consumption of providing the CW space is mainly caused by heating, cooling, and lighting the CW space. Compared to employer office days, the reduction in travel on CW days leads to a reduction of travel-related direct energy requirements because long commutes are avoided. These savings roughly equal the direct energy required to provide the CW space; thus, the direct energy required to provide the CW space roughly offsets the travel-related energy savings.

Home office and CW days have almost the same travel-related direct energy requirements: although travel time is higher on CW days, more energy-intensive transport modes are used on home office days (cars are used for private purposes; for more information on the modal split, see 5.3.2). Yet providing the CW space still involves energy consumption. Thus, working at CW spaces instead of home can increase energy consumption overall.

When interpreting the results, we have to consider that we did not take changes in energy requirements at the employer's office or at home into account in this calculation. For example, CW could enable employer's to reduce their office space and associated energy consumption for heating, cooling and lighting the space. Plus, working from home can increase residential energy consumption (e.g. for cooking, heating or cooling). Mokhtarian et al. (1995) summarize early studies which consider household energy impacts of TC and conclude that increases in residential energy consumption account for 11-25% of travel energy savings. Such effects have to be considered in comprehensive energy assessments of TC.

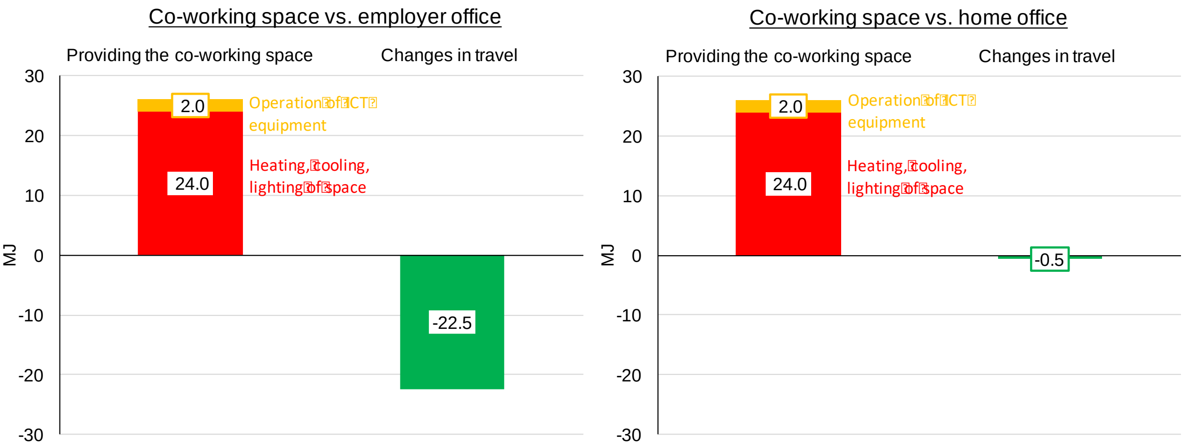

Figure 10: Difference in average energy requirements on a co-working day compared to a workday at the employer's office (left) or at home (right) across co-workers.

As the number of CW days rises, net energy savings increase as well because of the increasing number of avoided commutes.

The total energy required for heating, cooling, and lighting the CW space does not increase proportionally with increasing utilization of the CW space. This is because buildings do not require much more heating energy if occupancy increases. However, the number of avoided employer office days (long commute) is proportional to total commute-related direct energy savings, specifically for car commuters (e.g. one CW or home office day avoids one long commute, two CW or home office days avoid two long commutes, …). Thus, substituting additional employer office days with CW or home office days seems to be a good strategy to increase net energy savings, provided other energy requirements associated with TC do not change.

Organizations adopting TC or providing TC services (e.g. CW space providers) should advise telecommuters on their preferences regarding work location (most often preferably close to home) and transport modes and find strategies to reduce total office space.

CW does not lead to energy savings per se, but should be accompanied by additional energy saving measures. Whether or not CW results in energy savings depends to a major extent on CW-induced changes to telecommuters' time spent in transport and use of transport modes, space use at all work locations (employer office, CW space, and telecommuters' homes), and substitute activities, goods, and services and their energy impacts (time and income rebound effects).

Future research should take an even broader perspective and also include potential structural effects of TC in the assessment. This research could reveal under which conditions TC at a larger scale can be a viable model to reduce work- and travel-related environmental impacts, take pressure off transport systems, and increase the well-being of workers.

6 Discussion, limitations and future work

In the following, I summarize and discuss some overarching findings and limitations of this dissertation. They are also intended to provide inspiration for future work.

6.1. Closing the research gaps by applying the time-use approach

In this dissertation, I introduced and applied the time-use approach to assess indirect environmental effects of ICT. Understanding how ICT, in our case TC, changes consumption patterns is relevant for estimating its environmental impact, but also interesting for drawing conclusions on social impacts of ICT. For example, time-use analysis showed that TC can increase time spent on chores or leisure, which can contribute to deceleration of lifestyles. Still, other consumption perspectives besides time use exist and can be useful for investigating environmental effects of ICT. For example, investigating ICT impacts on household expenditure and associated environmental impacts would help to estimate income rebound effects. The principal assessment approach applied in this study (first, estimating ICT impacts on time use, and second, the consequences for the environment) could also be applied here, but with money instead of time.

The time-use approach is also useful for investigating ICT time rebound effects. To do so direct and indirect energy requirements of activities performed before and after adopting an ICT use case have to be assessed. However, other rebound effects besides time use exist as well (e.g. direct rebound, economy-wide rebound) and have to be kept in mind.

One research gap that I was not able to investigate due to time limitations was interaction among use cases because I focused on a single use case: TC. Still, the time-use approach seems to be useful for modeling interaction among use cases and other variables, using time as an interaction mechanism. Modeling interaction is also required to investigate systemic effects of ICT use. Most assessments do not consider systemic effects, because including several use cases along with their interdependencies in one assessment increases complexity and the number of unknown parameters. However, investigations of such systemic effects are urgently required if we want to unfold the potential of ICT for environmental protection. Applying the time-use approach with dynamic modeling and simulation methods would allow researchers to observe interaction and systemic behavior over time, keeping complexity at a manageable level.

To summarize, the time-use approach is a key element for investigating indirect environmental effects of ICT. In order to holistically understand such effects, we need to shed light on these effects from various perspectives; thus, the time-use approach needs to be complemented with other methods: I propose a combination of the following:

- LCA to compare product systems before and after the adoption of ICT (production perspective),
- time-use and other consumption-oriented perspectives to investigate ICT impacts on lifestyles and its social and environmental consequences,
- dynamic modeling and simulation methods to investigate interaction between use cases and between use cases and other system variables and to identify systemic effects of ICT adoption.

For example, the results of the time-use assessment (how do individuals reallocate their time due to ICT use) could be used as input parameters for an agent-based model which allows researchers to model large quantities of individuals, simulate their time allocation behavior over time and observe the impact of more widespread adoption of TC on macroeconomic indicators. This approach is also promising for investigating how changes on the micro level of an ICT solution (e.g. different solution design, different policies) impact the aggregate outcome on the macro level.

6.2. Data availability and analysis

Time-use data

The time-use data used in this study was collected in a CW living lab for the purpose of observing impacts of TC on time use and travel. In many cases, such data will not be available. Another approach is to use data from time-use studies which have already been conducted. Time-use data is often collected on behalf of federal statistical offices to investigate various issues of social or environmental concern (e.g. gender equality). Thus, a significant amount of data selection and preparation effort is required to fit the data to a specific research question. For example, in the study presented in article 6, I also use data from a countrywide Swedish time use surveys to investigate TC impacts on time use by comparing time allocation on days with higher and lower amounts of time spent on commuting. This allowed me to compare time allocation behavior by work location of participants in the CW living lab with associations between time spent on commuting and other activities of a large, representative sample of the Swedish population. Still, it is important to consider that the countrywide Swedish time-use data was not collected for investigating impacts of a change in commute time on time spent on other activities (as done in the CW living lab).

This data and the data collected in the CW living lab is cross-sectional data. It can be used to compare travel and time-use behavior of individuals across days or weeks with different commute times (within-person differences) or to compare differences across individuals with different TC patterns (between-person differences). However, such data does not allow researchers to make causal inferences about impacts of time spent on commuting (or even TC) on time use for other activities. Whether TC actually leads to a reduction in travel can only be investigated with the time-series data by comparing travel behavior of individuals before and after the adoption of TC.

Other factors (e.g. doctor's appointments, picking up children from school) and demographic and socio-economic variables (e.g. having a child, cohabiting) affect diarists' time use and should be included in comprehensive assessments of TC or other ICT use cases which affect time allocation. While many time-use surveys collect data on demographic and socio-economic characteristics of diarists, various relevant factors impacting time use (e.g. having a doctor's appointment) are usually not included in such studies.

Still, this dissertation shows that time-use data can be used to investigate time-use impacts of increasing ICT use. It shows that there is unexploited potential to use time-use data for assessing travel and environmental impacts of TC and other ICT use cases that affect time allocation.

Environmental data

One of the main challenges in this dissertation was estimating the environmental impacts of activities.

First, I focused mainly on the environmental impact category energy use. Further impact categories exist, need to be investigated, and weighted against each other (e.g. land use change, global warming potential).

Second, in many cases data from the regions and time periods under study is not available in sufficient detail.

Third, most assessments of energy impacts of activities allocate data on purchase and use of energy-consuming goods and services to an average time allocation pattern at a specific point in time. In contrast, in this dissertation, I am interested in the energy impacts of a change in time allocation (marginal energy requirements of activities). Estimating marginal energy requirements of activities is challenging, as a change in time allocation does not necessarily induce a change in energy requirements. For example, spending more time on eating or household care does not necessarily imply additional use of energy-consuming household appliances. This is even more challenging for indirect (embedded) energy requirements as indirect energy requirements only change if production, operation, or maintenance of goods, services, or infrastructure is avoided.

If future research explores these relationships, the time-use approach can not only be a key element in assessing energy impacts of TC considering travel and non-travel impacts, but can also be used for energy assessments of various other ICT applications which impact individual time allocation.

6.3. Energy impacts of telecommuting

The results of the case study of the CW living lab in Stockholm presented in article 6 indicate that TC has the potential to reduce transport demand and the associated energy impacts because saved commute time is mostly spent on non-travel activities which have lower energy requirements. The analysis was based on a small sample of workers from one company and living in the same area. For individuals with different time use, travel patterns, demographic or socio-economic backgrounds, the results may be different. However, the analysis of existing time-use data collected from a larger sample of Swedish citizens also indicated that lower daily commute times are associated with lower daily travel times.

The modal split is a central variable for net energy impacts of TC. For example, car commuters can realize high energy savings through TC because car travel is highly energy-intensive. For bikers or pedestrians, the direct energy requirements of travel (and TC-induced energy savings) are zero and thus the effect of any additional energy required for substitute activities is to increase net direct energy requirements.

Besides energy requirements of travel and non-travel activities, I also identified other energy impacts of TC, such as energy consumption for heating and cooling at CW spaces, at home and at the employer’s office, income rebound effects and systemic effects of TC adoption (e.g. telecommuters moving further away from their employers’ offices because longer commutes become more acceptable). Various studies have shown that these effects can also be significant (Kim et al., 2012; Vaddadi et al., 2020; Zhu, 2012).

To summarize, there is a potential for realizing energy savings through TC, however these depend on changes to time spent on travel and non-travel activities, marginal energy requirements of these activities and changes to space use due to TC and further, especially systemic effects, of TC adoption.

6.4. Future work

Based on the results, limitations and uncertainties of my work, I recommend the following directions for future research.

Assessment of indirect environmental effects of ICT

- Combination of the time-use approach with other environmental impact assessments approaches
- (Regionalized) Assessment of marginal energy requirements of activities with respect to time use
- Additional data analysis approaches for estimating ICT impacts on time use
- Consideration of different demographic and socio-economic characteristics of individuals and other factors impacting time use in time-use analysis
- Quantitative assessment of different types of rebound effects of ICT use (e.g. time, income, economy-wide rebound effect)
- Deeper analysis of interactions among ICT use cases and systemic effects of ICT use

Telecommuting case

- Long-term study on impacts of TC on individual behavior, transport systems and associated environmental impacts (months or years instead of days and weeks)
- Social and environmental impacts of large-scale adoption of TC (from individuals to society), especially for the case of working from CW spaces in residential neighborhoods
- Assessment of effects of TC on the environment beyond energy use and global warming potential

7 Answers to research questions

In the following, I summarize the answers to the research questions of this dissertation.

RQ 1: What is the state of the art in assessing indirect environmental effects of ICT with respect to the assessment approaches applied, research gaps and methodological challenges?

There are at least 54 studies in 7 main application domains using at least 15 assessment methods. LCA, the ICT enablement method, and partial footprint are by far the most frequently used assessment methods, whereas simulation methods and qualitative approaches are less often applied. The main research gap is that most assessments do not investigate ICT impacts on consumption patterns.

RQ 1.1: What assessments of indirect environmental effects of ICT have already been conducted?

There are at least 54 studies in 7 main application domains. The most common application domains are virtual mobility (e.g. TC), virtual goods (e.g. digital media), and smart transport (e.g. route optimization).

RQ 1.2: What assessment methods have been used for the assessment of indirect environmental effects of ICT?

There are at least 15 methods, namely agent-based modeling, System Dynamics, LCA, partial footprint, material input per service unit, the ICT enablement method, regression analysis, descriptive statistics, transport models, vehicle drivetrain models, scenario analysis, literature review, meta-analysis, interviews, and surveys. LCA, the ICT enablement method, and partial footprint are by far the most frequently used assessment methods, whereas simulation methods and qualitative approaches are less often applied.

The ICT enablement method is useful for rough comparative assessments of ICT application domains and use cases. LCA or a partial footprint, are more useful to assess the inherent complexities of specific ICT use cases in order to improve the design of an ICT solution or derive policies to mitigate unfavorable environmental impacts or promote favorable environmental impacts at the product level. Dynamic simulation methods, such as agent-based modeling or system dynamics, are also useful to develop such policies. While system dynamics is most useful for describing causal mechanisms at the socio-economic macro-level analysis, agent-based modeling is useful to explain macro-level phenomena with micro-level behavior.

RQ 1.3: What are the main research gaps and methodological challenges in assessments of indirect environmental effects of ICT?

The main research gap is that most assessments do not investigate ICT impacts on consumption patterns. However, both, production and consumption perspectives are required to understand how ICT changes economic processes and indirectly their environmental impact—what goods and services people consume, how they are produced, and how the overall product systems ("from cradle to grave") interact with the environment.

Methodological challenges exist with respect to degrees of freedom in the assessment methodology, selection of ICT use cases, allocation of impacts to ICT when ICT adoption is not the only change to the system under study, definition of the baseline against which the impact is measured, estimation of the environmental impact, prediction of the future adoption of use cases, estimation of rebound effects, interaction among use cases, and extrapolation from the individual use case to society-wide (systemic) impacts.

RQ 2: Is the time-use approach suitable for assessing indirect environmental effects of ICT?

The time-use approach is suitable for assessing indirect environmental effects of ICT because it focuses on ICT impacts on consumption patterns, allows to capture interaction among use cases and to consider time rebound effects.

RQ 2.1: What are advantages and limitations of the time-use approach for assessing indirect environmental effects of ICT?

The time-use approach is useful for the following reasons:

- Many ICT use cases relax time and space constraints of individual activities, thus changing individual time allocation.
- The time-use approach can be used to capture interaction among use cases because time is a limited resource for everyone, making time budget constraints a central link between ICT use cases. Modeling interaction among use cases is key to investigating systemic ICT impacts.
- It can be used to investigate one important type of rebound effect, namely time rebound effects.
- It allows to include travel and non-travel activities and associated environmental impacts in the assessment.
- It focuses on ICT impacts on consumption patterns instead of production patterns.

Thus, it is promising for addressing some of the main research gaps and methodological challenges identified in *RQ 1.3*. Especially investigations of systemic effects of ICT use are urgently required if we want to unfold the potential of ICT for environmental protection.

The main limitations of the time-use approach lie in the limited availability of the data required, challenges in inferring causality between ICT use and changes in time use, challenges in assessing the marginal energy requirements of activities, and the fact that the time-use approach focuses on just a single aspect of consumption, namely time use, and disregards other aspects of consumption such as income expenditure.

RQ 2.2: What is the relationship between ICT use, time use and environmental impact?

ICT use changes individual time allocation to activities (e.g. TC reduces commute time). Impacts of ICT on time use can be categorized into relaxation of time and space constraints to activities, parallelization, fragmentation, substitution, avoidance, and delegation of activities, changes to the duration and manner of activities, changes to the process of activity planning, and generation of new ICT-based activities. In a broader systems perspective, these effects also trigger causal chains which can form feedback loops and thus change time-use patterns with some delay (systemic effects).

The activities we perform cause direct and indirect environmental impacts. Direct impacts occur during the performance of an activity (e.g. emissions caused by driving a car). Indirect impacts are impacts "embedded" in the goods, services, and infrastructures used to perform activities (e.g. resources used to produce a car, energy used to build and maintain a highway). The impacts of changes in time use depend on the marginal environmental impacts of activities. They depend specifically on the relationship between time spent on a given type of activity and the use and purchase of (energy-consuming) goods and services. For some activities, the direct environmental impacts are proportional to the time spent on the activity (e.g. driving a car longer increases fuel consumption), while for other activities changes in time allocation have no impact on direct environmental impacts of the activity (e.g. taking a walk). Indirect environmental impacts only change if the production of goods and services also changes (e.g. if TC leads to fewer cars being purchased, and thus fewer cars being produced). With respect to infrastructure use, if ICT-based solutions lead to a long-term change in demand for infrastructures, changes in the processes of building and operating them can be expected.

The net environmental impact of a given ICT use case results from the sizes of direct and indirect environmental impacts of the activities performed before and after adoption of the use case.

RQ 3: What is a suitable operationalization of the time-use approach to assess indirect environmental effects of ICT and does it deliver results of practical relevance?

The time-use approach can be operationalized by comparing time use of individuals before and after the adoption of an ICT use case and the environmental impacts of the goods and services used to perform activities.

The approach can yield results of practical relevance. For example, assessing energy impacts of TC with the time-use approach showed that time rebound effects of TC depend largely on TC-induced changes to time spent in transport, use of transport modes before and after adopting TC and the marginal energy requirements of the substitute activities.

RQ 3.1: What data is required to assess indirect environmental effects of ICT from a time-use perspective, and what is a suitable approach to analyze this data?

Table 7 shows the main steps and data requirements.

#	Step of assessment	Data requirements
1	Estimating changes in time allocation due to ICT use cases	- Time-use data - Preferably time series data before and after the adoption of an ICT use case including data on other variables affecting time use (e.g. demographic characteristics of individuals)
2	Estimating environmental impacts due to changes in time allocation to activities (marginal environmental impacts of activities)	- Data on direct and indirect environmental impacts of goods and services used to perform activities, preferably throughout the whole life cycle (life cycle inventory, LCI, data) - Data on use of goods and services for activities - Data on impacts of change in time allocation on the use and purchase of goods and services
3	Estimating energy impacts of changes in time allocation due to ICT use cases	- Combination of data required in step 1 and 2

Table 7: Main steps and related data requirements for assessing indirect environmental effects of ICT from a time-use perspective.

It has to be noted that regionalized time use and environmental data is required for such kind of assessments because the behavioral response of individuals to the adoption of an ICT use case (e.g. TC) and the environmental impact of activities depends on the socio-economic context. Plus, the impact of ICT on time use and the environment depends on the policies in place at the specific location and time. In principle, ICT changes existing constraints placed on activities (e.g. working is not bound to employer offices anymore). If and how organizations and individuals change their existing patterns of production and consumption due to the availability a new ICT solution is a separate question. For example, the current COVID-19 pandemic shows that telecommuting at a larger scale was already possible since a longer time; however, only now, as targeted policies are put in place, adoption of telecommuting increases significantly.

RQ 3.2: To what extent do time rebound effects of telecommuting compensate for commute-related energy savings?

In the CW case study in Stockholm, telecommuters spend commute time saved on CW or home office days mainly on non-travel activities. Most studies have shown that non-travel activities are associated with lower energy requirements than travel activities. Thus, there seems to be potential for net energy savings through TC.

However, the size of the rebound effects of TC depend on the marginal energy requirements of commuting and of the substitute activities, respectively. If the marginal energy savings of avoided commuting are larger than the average of the marginal energy requirements of the substitute activities, TC leads to energy savings (time rebound effect < 100%). If the marginal energy savings of avoided commuting are lower than the average of the marginal energy requirements of the substitute activities, TC leads to an increase in energy consumption (time rebound effect > 100%).

In the case of travel, the direct energy requirements are mostly proportional to the time spent on the activity (e.g. driving a car longer directly increases fuel consumption). But the direct energy consumption of non-travel activities only increases if energy-consuming appliances are used longer (e.g. vacuum cleaning longer increases energy consumption, tidying up longer does not). Thus, the size of time rebound effects depends significantly on individuals' specific behavioral responses to TC adoption, which are difficult to predict and need further investigation.

Also, the time rebound effects of TC depend on the transport modes because their (marginal) energy requirements differ significantly. For example, car commuters can realize high energy savings through TC because car travel is highly energy-intensive. As most non-travel activities have lower energy requirements than car travel, this substitution can be expected to yield energy savings (lower time rebound effect). In contrast, for bikers or pedestrians, the direct energy requirements of travel (and thus the TC-induced energy savings) are zero, and thus the effect of any additional energy required for substitute activities is to increase net direct energy requirements.

RQ 3.3: Which measures are effective to maximize energy savings through telecommuting?

The highest energy savings through TC can be achieved if the following conditions are met:

- Total travel time is reduced.
- The number of TC days per telecommuter is increased (increasing the number of TC days increases the amount of commute-related energy and GHG savings).
- Total (heated and cooled) space is reduced—at employer offices, at CW spaces and at home.
- Telecommuters use energy-efficient transport modes on TC days and do not spend money and/or time saved on other energy-intensive activities, goods, and services.

If telecommuters and employers fail to fulfill these conditions, additional energy required for cooling and heating spaces as well as a change in transport modes used could compensate or even overcompensate for commute-related energy savings. Thus, current and future providers of TC services (e.g. CW space operators) and employers adopting TC should advise telecommuters in their choice of work location (most often preferably close to home) and transport modes and find strategies to reduce total space. This way, TC can be a viable ICT application to reduce the energy impacts of work, take pressure off transport systems, and increase the well-being of workers.

However, this analysis does not consider systemic effects of TC adoption which only become apparent in a broader systems perspective.

8 Conclusion

Digitalization provides an unprecedented opportunity to overcome some of the most critical societal challenges of the 21st century, such as global warming. Still, the potentials to contribute to effective solutions through digitalization are not being exploited systematically, mainly due to a lack of knowledge about the diverse impact patterns of digital technologies and the actions required.

The overarching goal of this dissertation was to improve the assessment of indirect environmental effects of increasing ICT use. After capturing the status quo in the research field and identifying important research gaps as well as methodological challenges, I developed and applied a time-use approach to assess such effects. I demonstrated that this approach is a useful element in assessments of indirect environmental effects of ICT. It is instrumental for overcoming some of the main research gaps and methodological challenges such as investigation of ICT impacts on consumption patterns or consideration of time rebound effects. Plus, the time-use approach can be used to capture interaction among use cases because time is a limited resource for everyone, making time budget constraints a central link between ICT use cases. Modeling interaction among use cases is key to investigating systemic impacts of increasing ICT use, which are often excluded in such assessments because including additional variables and their interactions increases the complexity of assessments considerably.

By applying the time-use approach in a case study of CW in Stockholm, I showed that CW has the potential to reduce energy requirements by reducing commute time and distance. Whether TC in general brings about energy savings depends largely on TC-induced changes to:

(1) telecommuters' time spent in transport and use of transport modes,
(2) space requirements at all work locations (employer office, CW, and home office),
(3) substitute activities, goods, and services and their energy impacts (time and income rebound effects).

TC does not lead to energy savings per se, but should be accompanied by additional energy saving measures. Thus, organizations adopting TC or providing TC services (in particular CW space providers) should advise telecommuters on their preferences regarding work location and transport modes. All stakeholders should work together to find strategies to reduce the total office space required. Otherwise, there is some risk that additional infrastructure needs (e.g. for CW spaces), rebound effects, and systemic effects may compensate (if not overcompensate) for the commute-related energy savings.

In order to conduct comprehensive, and specifically quantitative, time-use and energy assessments of TC and other ICT use cases which impact time allocation, data on the marginal energy requirements of activities is required. This data depends specifically on the relationship between time spent on a given type of activity and the use and purchase of (energy-consuming) goods and services. These impacts have been out-of-scope in most assessments of energy impacts of activities and need further investigation.

This study is intended to encourage researchers to apply the time-use approach in combination with other production- and consumption-focused approaches in order to identify pathways for aligning digitalization with environmental protection. I hope this dissertation is an inspiration for future research in this field and for policy makers and ICT companies to actively develop and implement digital solutions which harness the potential of digitalization for improving quality of life and reducing environmental loads.

PART I:

DETERMINING THE STATUS QUO

9 Assessing indirect environmental effects of information and communication technology (ICT): A systematic literature review

Bieser, J., & Hilty, L. (2018b). Assessing indirect environmental effects of information and communication technology (ICT): A systematic literature review. *Sustainability*, *10*(8), 2662. https://doi.org/10.3390/su10082662

Abstract: Indirect environmental effects of ICT are those effects of ICT that change patterns of production or consumption in domains other than ICT, or more precisely, the environmental consequences of these changes. Digitalization as the societal process of ICT-driven change has created increasing interest in the indirect environmental effects of this technology. Assessments of indirect effects face various methodological challenges, such as the definition of the system boundary, the definition of a baseline as a reference or the occurrence of rebound effects. Existing studies use various approaches or methods to assess a spectrum of ICT use cases in several application domains. In view of the large number of assessments that have been conducted, the choices made when applying assessment methods, and the variety of ICT use cases in different application domains investigated, we present a systematic literature review of existing assessments of indirect environmental effects of ICT. The review provides a state-of-the-art overview of the methods used in the research field and is intended to support researchers in designing sound assessments which yield significant results. We identified 54 studies in seven main application domains using 15 different assessment approaches. The most common application domains are virtual mobility (e.g. TC), virtual goods (e.g. digital media), and smart transport (e.g. route optimization). LCA, partial footprint, and the "ICT enablement method" are the most common approaches. The major part of the assessments focuses on patterns of production (e.g. production of paper-based books vs. e-books), a smaller part on patterns of consumption (e.g. changes in media consumption). Based on these results, we identify as a research gap the investigation of ICT impacts on consumer behavior, which could, for example, focus on social practices, and account for the dynamic implications of change. Elaborating such an approach could provide valuable insights into ICT's impact on society and the resulting environmental consequences.

Keywords: Information and communication technology; digitalization; indirect environmental effects; environmental impact assessment; greening through ICT

9.1. Introduction

ICT has direct and indirect effects on the environment. Direct environmental effects of ICT include the resources used and emissions that are caused by the production, use, and disposal of ICT hardware. Indirect environmental effects of ICT are ICT-induced changes in patterns of consumption and production also in domains other than ICT and the environmental implications of these changes (Hilty & Aebischer, 2015; Pouri & Hilty, 2018). Both types of effects make ICT a relevant factor for the achievement of the UN SDG 12—Responsible consumption and production (United Nations, n.d.-c). Studies assessing indirect effects often conclude that they are desirable from an environmental perspective (e.g. reducing GHG emissions) and that they are in total clearly larger than the direct effects (e.g. leading to a net reduction of GHG emissions) (Bieser & Hilty, 2018c; GeSI & Accenture Strategy, 2015; Hilty & Bieser, 2017; Pamlin & Szomolányi, 2006).

To quantify these effects, researchers usually conduct some type of environmental impact assessment of indirect effects of ICT, which can be defined as "the process of identifying the environmental consequences of an ICT solution's capacity to change existing consumption and production patterns, taking into account the interrelated socio-economic, cultural, and human-health impacts, both beneficial and adverse, with the aim of informing decision-makers or the general public and mitigate unfavorable or promote favorable environmental consequences" (Bieser & Hilty, 2018a, p. 3).

Researchers from the ICT for Sustainability (ICT4S) community conducted environmental assessments of many ICT applications in various domains, while using different assessment methods. Due the large variety of ICT applications and assessment methods, it is difficult to compare these studies with each other. The methods face various challenges, such as the definition of the system boundary, the definition of the baseline used for comparison, the allocation of impacts to the ICT use case under study, or the estimation of rebound effects. These issues create degrees of freedom in the assessment methods, which lead to a high diversity of results, even for studies with similar research questions (Bieser & Hilty, 2018c).

For example, the SMARTer 2030 study by GeSI, the ICT industry's association for sustainability, suggests that ICT applications could avoid up to 20% of annual GHG emissions in 2030 (indirect effect) on a global scale, while the ICT sector causes only 2% of global GHG emissions (direct effect) (GeSI & Accenture Strategy, 2015). Similar results were reported before in GeSI's SMARTer 2020 and SMART 2020 study (GeSI et al., 2008; GeSI & BCG, 2012). In contrast, a System Dynamics model developed in a project commissioned by the Institute for Prospective Technological Studies (IPTS) of the European Commission on "The future impact of ICT on environmental sustainability" suggests that, by 2020, the positive and negative effects of ICT on GHG emissions tend to cancel each other out across application domains (Hilty, Arnfalk, et al., 2006). These diverging results can be explained by a difference in approaches: The IPTS study was based on a dynamic socio-economic model, whereas the newer studies used a static approach, which is based on a much simpler model (Bieser & Hilty, 2018c).

In view of the large number of assessments which have been conducted, the choices made when applying assessment methods, and the variety of ICT application domains investigated, we provide a review of existing studies on indirect environmental effects of ICT. The aim of this review is not to summarize and compare the actual results of the assessments, but rather to provide a state-of-the-art overview of the methods that are applied in the research field to support future researchers in designing sound assessments, which yield significant results.

In that sense, we will provide an overview of existing assessments answering the following three research questions:

RQ1: What assessments of indirect environmental effects of ICT have already been conducted?

RQ2: What ICT applications have been assessed?

RQ3: What assessment methods have been used for the assessment of indirect environmental effects of ICT?

Several researchers have already conducted literature reviews in the field of assessing environmental effects of ICT. Verdecchia et al. (2017) reviewed studies with regard to the types of environmental effects investigated (e.g. obsolescence effect, optimization effect). Yi and Thomas (2007) conducted a literature review about assessments of the environmental impact of e-business, Klimova (2018) on the use of knowledge management systems for "Green ICT" and "ICT for Greening", and Frehe and Teuteberg (2014) on the role of ICT in the field of "Green Logistics". Penzenstadler et al. (2012), Bozzelli et al. (2014), Calero et al. (2013), and Salam and Khan (2015) all provided literature reviews focusing on sustainability in the field of software systems. Although not being within the scope of this article, we want to mention that Krumay and Brandtweiner (2016), Grimm et al. (2014), and Arushanyan et al. (2014) reviewed the assessments of direct environmental effects of ICT.

For the purpose of this paper, the study by Horner et al. (2016) is especially relevant. They provide an overview of ICT4S taxonomies, application domains, and assessments of indirect environmental effects of ICT and find that the overall net effect of ICT is still unknown and that "increased data collection, enhancing traditional modeling studies with sensitivity analysis, greater care in scoping, less confidence in characterizing aggregate impacts, more effort on understanding user behavior, and more contextual integration across the different levels of the effect taxonomy" would increase the quality of research in this field (Horner et al., 2016, p. 1). They briefly mention the methods that are used in the assessments of indirect environmental effects of ICT, but without discussing their advantages and disadvantages in detail. This is the gap we intend to close with the present study.

9.2. Materials and methods

We conducted a systematic literature review to identify assessments of indirect environmental effects of ICT, according to the PRISMA framework and the guidelines for systematic literature reviews by Siddaway (Moher et al., 2009; Siddaway, no date).

We started by identifying the main search terms based on our research questions: ICT; environment; assessment; assessment method; indirect environmental effects of ICT.

For all of the main search terms, we derived alternative search terms by finding synonyms (e.g. "ICT" or "IT"), related terms, singular and plural forms (e.g. "assessment method" or "assessment methods"), and broader or narrower terms (e.g. "environment" or "GHG emissions"). An overview of the search terms used in the systematic literature search is provided in Table 8. We then determined final search terms by combining main search terms and their alternatives (e.g. ("ICT" OR "information and communication technology" OR "IT") AND ("environment" OR "sustainability" OR "sustainable") AND ("assessment" OR "evaluation" OR "case study")).

Main term	**Alternative terms**
Information and Communication Technology	ICT, information technology, IT, informatics
Environment	Sustainability, sustainable, environmental
Global warming potential*	Climate change, climate protection, global warming, GHG emissions, GHG, greenhouse gas emissions
Assessment	Evaluation, analysis, calculation, estimation, appraisal, case study
Assessment method	Method, approach, environmental assessment method, environmental impact analysis
Indirect environmental effects of ICT	Indirect effects, second order effects, greening through ICT, greening by ICT, green ICT, enabling effects
ICT for Sustainability***	ICT4S, Environmental Informatics, EnviroInfo

Table 8: Main and alternative search terms for the structured literature search. * We added "global warming potential" as one specific environmental impact category, because many assessments of indirect environmental effects of ICT focus on this impact category. ** We added the search term "ICT for Sustainability" and related terms because they refer to research communities focusing, among other topics, on environmental effects of ICT.

As suggested by Siddaway (no date), we selected the most common scientific literature databases and platforms Web of Science, Scopus, Google Scholar, and Google for the search. We also reviewed the conference proceedings of the two major conferences in the field of environmental effects of ICT: The international conferences ICT4S (ICT for Sustainability, http://ict4s.org/; proceedings 2013-2016) and the conference series EnviroInfo (Environmental Informatics, http://www.enviroinfo.eu/; proceedings 2011-2017).

We created a spreadsheet to record the search queries and the identified publications and used the reference management software Zotero to store the bibliographical information.

Finally, we executed the search queries on the mentioned databases. For all of the queries, we screened a maximum of the first 100 results. An exception was made for conference proceedings, where we screened all the papers in the respective volumes. The screening included the following steps: For all publications whose title indicated that they contain an assessment of an indirect environmental effect of ICT, we read the abstract and created a record if the abstract confirmed the assumption, or dropped the publication otherwise. In cases where we recognized that a specific query provided irrelevant results, we stopped screening the search results.

After the systematic search, we added publications already known to the authors as well as relevant publications that were referenced by publications that were identified in the systematic search. In particular, the review by Horner et al. (2016) references many studies which we included in our review. After reading all relevant publications, we dropped further 79 publications, because ICT, its environmental impact, or both were not treated as central aspects. Figure 11 provides the number of publications included and dropped in each step of the literature search.

Finally, we classified the identified studies according to four different criteria: (1) the ICT application domain covered; (2) the number of ICT use cases assessed; (3) whether the focus is on patterns of production (e.g. production of paper-based books vs. e-book readers) or consumption (e.g. changes in media consumption); and (4) the methodological approach applied. We describe these aspects in more detail in section 9.3.

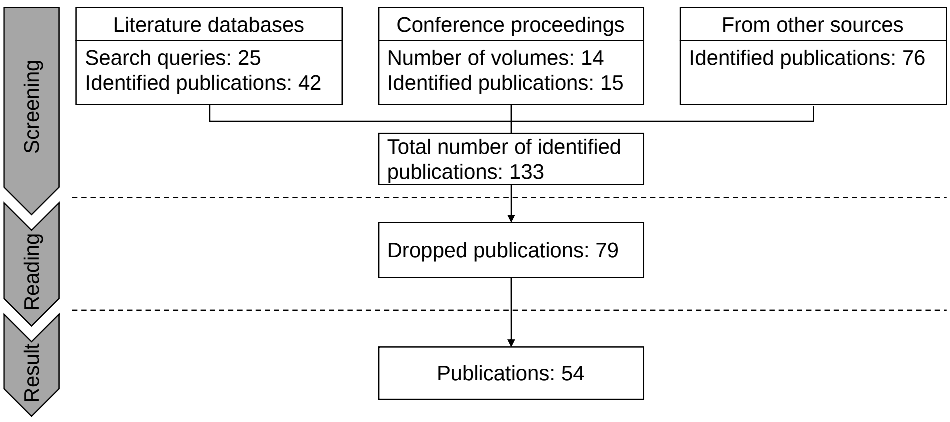

Figure 11: Number of search queries, volumes, identified and dropped publications in the screening phase (title and abstract), the reading phase (full text) and the final result.

9.3. Results

In the following, we present the results of our literature review, specifically (1) what application domains have been covered, (2) the number of use cases focused on, (3) whether the studies focused on ICT-induced patterns of production or consumption, and (4) the methodological approaches applied.

Where suitable, we mention example studies for our results. Table 9 provides an overview of all studies that were finally identified. Figure 12 and Figure 13 summarize the results of the literature review after applying the four criteria.

Study	Application domain(s)	Number of use cases	Production/ consumption	Modeling approach
Laitner et al., 2010	All (macroeconomic study)	Unspecified	Both	Regression analysis
GeSI & Accenture Strategy, 2015	Shared goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	12	Both	ICT enablement method
Bieser & Hilty, 2018c; Hilty & Bieser, 2017	Shared goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	10	Both	ICT enablement method
Malmodin & Coroamă, 2016	Smart energy	1	Both	Literature review/meta-analysis/scenarios
Davis et al., 2013	Smart energy, smart buildings	3	Unspecified	Literature review/meta-analysis
Masanet, 2010	Smart production, smart buildings	4	Production	Descriptive statistics
Ericsson et al., 2006	Smart transport	1	Both	Transport model/partial footprint
Huang et al., 2008	Smart transport	1	Production	Vehicle drivetrain model/partial footprint
Gonder, 2008	Smart transport	1	Production	Vehicle drivetrain model/partial footprint
AT&T, 2017	Smart transport, smart production, smart buildings, others	>2	Not disclosed	ICT enablement method
Mayers et al., 2014	Virtual goods	1	Production	LCA
Türk et al., 2003	Virtual goods	1	Both	Material input per service unit
Seetharam et al., 2010	Virtual goods	1	Both	LCA
Shehabi et al., 2014	Virtual goods	1	Both	LCA
Picha Edwardsson, 2014	Virtual goods	Unspecified	Both	Interviews/scenarios
Moberg et al., 2011	Virtual goods	1	Production	LCA
Kozak, 2003	Virtual goods	1	Production	LCA
Weber et al., 2010	Virtual goods	1	Production	LCA
Gard & Keoleian, 2008	Virtual goods	1	Production	LCA
Reichart & Hischier, 2001	Virtual goods	1	Production	LCA
Toffel & Horvath, 2004	Virtual goods, virtual mobility	2	Both	LCA
China Mobile, 2016; Tianjian et al., 2010	Virtual goods, virtual mobility, smart transport, smart production, smart energy	14	Both	ICT enablement method
Romm, 1999	Virtual goods, shared goods, virtual mobility, smart transport, smart production	>8	Both	Scenarios/literature review
Swisscom AG, 2017	Virtual goods, virtual mobility, smart transport, smart energy, smart buildings	7	Not disclosed	Not disclosed
WWF Canada, 2008	Virtual goods, shared goods, virtual mobility, smart transport, smart buildings	9	Both	ICT enablement method
Pamlin, 2008	Virtual goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	13	Both	ICT enablement method

GeSI et al., 2008	Virtual goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	39	Both	ICT enablement method
Verizon, 2018	Virtual goods, virtual mobility, smart transport, smart energy, smart buildings	6	Not disclosed	Not disclosed
British Telecom, 2016	Virtual goods, shared goods, virtual mobility, smart transport, smart production	19	Both	ICT enablement method
Hilty, Arnfalk, et al., 2006; Hilty et al., 2004	Virtual goods, shared goods, virtual mobility, smart transport, smart production, smart buildings	15	Both	System Dynamics
Deutsche Telekom, 2017	Virtual goods, shared goods, virtual mobility, smart transport, smart production, smart energy	9	Both	ICT enablement method
Malmodin & Bergmark, 2015	Virtual goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	17	Both	ICT enablement method
GeSI & BCG, 2012	Virtual goods, shared goods, virtual mobility, smart transport, smart production, smart energy, smart buildings	35	Both	ICT enablement method
Kitou & Horvath, 2003	Virtual mobility	1	Both	Partial footprint
Atkyns et al., 2002	Virtual mobility	1	Consumption	Survey/interviews/ partial footprint
Roth et al., 2008	Virtual mobility	1	Both	LCA
Xu et al., 2009	Virtual mobility	1	Both	Agent-based model/partial footprint
Coroamă et al., 2012	Virtual mobility	1	Both	Survey/partial footprint
Borggren et al., 2013	Virtual mobility	1	Both	LCA
Caird et al., 2015	Virtual mobility	1	Both	Survey/partial footprint
Hopkinson & James, 2003	Virtual mobility	1	Consumption	Survey/interviews
Weber et al., 2009	Virtual mobility	1	Production	Partial footprint
Sivaraman et al., 2008	Virtual mobility	1	Both	LCA
Takahashi et al., 2006	Virtual mobility	1	Both	LCA/survey
Kim et al., 2008	Virtual mobility, smart transport	1	Both	Transport model/partial footprint
Matthews et al., 2001	Virtual mobility, smart transport	1	Production	LCA
Matthews et al., 2002	Virtual mobility, smart transport	1	Production	LCA
Edwards et al., 2010	Virtual mobility, smart transport	1	Both	Transport model/partial footprint
Siikavirta et al., 2002	Virtual mobility, smart transport	1	Both	Transport model/partial footprint
Williams & Tagami, 2002	Virtual mobility, smart transport	1	Both	LCA
Pamlin & Szomolányi, 2006	Virtual mobility, virtual goods	6	Both	ICT enablement method
Telstra & Climate Risk, 2007	Virtual mobility, smart transport, smart energy, smart buildings	7	Both	ICT enablement method

Telstra, 2013	Virtual mobility, smart transport, smart energy, smart buildings	7	Both	ICT enablement method
Røpke & Christensen, 2012	Unspecified	Unspecified	Consumption	Interviews

Table 9: Studies by application domain, number of use cases, production/consumption focus, and modeling approach. "Unspecified" means that the criterion is not applicable for this study.

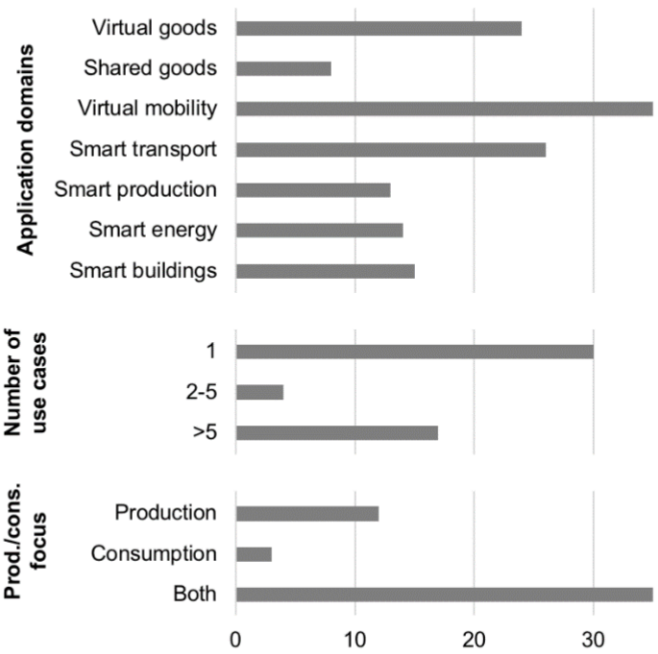

Figure 12: Number of studies by application domain, number of use cases, production vs. consumption focus. One study can cover more than one application domain.

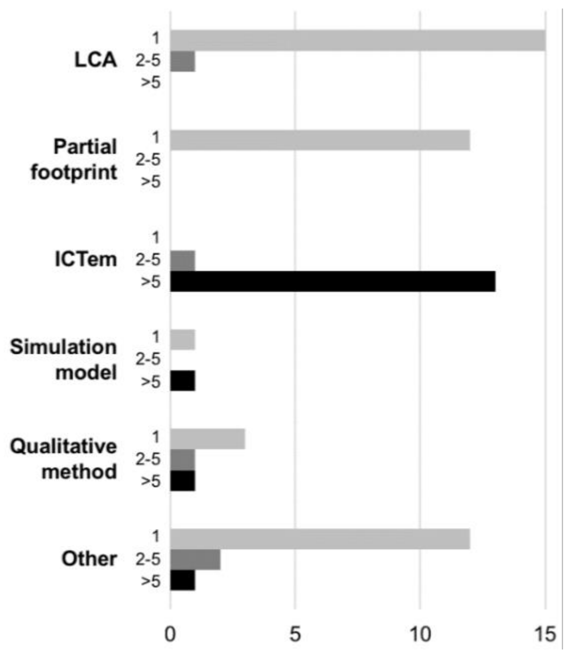

Figure 13: Number of studies by approach and number of use cases. Studies combining several methodological approaches were counted for each approach.

9.3.1 Application domains

Assessments of indirect environmental effects of ICT address how and to what extent ICT as an enabling technology changes patterns of production and consumption in domains other than ICT. We classified all of the assessments according to the application domains they covered and derived a set of common application domains. Finding a collection of application domains that are extensive and mutually exclusive is challenging. For example, the domain dematerialization, as used by British Telecom (BT), refers to how ICT "replaces the need to manufacture, publish, print and ship newspapers, documents, books, CDs and DVDs for residential customers" (British Telecom, 2016, p. 20), Hilty et al. use the term virtual goods to describe ICT's capacity to enable "a shift from material goods to services" (Hilty, Arnfalk, et al., 2006, p. 1262), whereas Coroama et al. (2015) use the term electronic media to cover the transition from paper-based books to e-book readers and from physical travel to video conferencing. Producing and delivering a newspaper online instead of paper-based could be classified under all three mentioned domains; however, video conferencing would be a part of electronic media, as defined by Coroama et al. (2015), but not part of dematerialization as defined by BT (2016) or virtual goods as defined by Hilty et al. (2006).

Despite these issues, we identified seven common application domains. These are mainly based on two well-cited studies of the overarching indirect environmental effects of ICT (GeSI & Accenture Strategy, 2015; Hilty, Arnfalk, et al., 2006) and allowed for us to classify almost all other studies identified in the literature review (Table 10). Most studies cover the application domains virtual mobility, smart transport and virtual goods (Figure 12), followed by smart buildings, smart energy, smart production, and shared goods. Other application domains mentioned are smart agriculture, smart water, or smart waste management; however, these are less frequently assessed.

Two studies could not be classified with respect to application domains. Laitner et al. (2010) conduct a regression analysis of historical macroeconomic time series data about the United Sates (U.S.) economy before and after the introduction of the semiconductor and thereby implicitly cover all potential application domains, without explicitly mentioning them. Røpke and Christensen (2012) assess how ICT—in general—changes everyday life, also without focusing on specific application domains.

Application domain	Description	Example use cases
Virtual goods	Replacing physical goods with ICT-based services	E-books, online newspapers, music and video streaming
Shared goods	Coordinating access to goods, increasing utilization	Sharing platforms
Virtual mobility	Replacing physical travel with ICT-based remote action	Video conferencing, e-commerce, e-health, distance learning, remote maintenance
Smart transport	ICT-enabled change of the process of transporting people or goods	Route optimization, traffic flow management
Smart production	ICT-enabled change of the processes and business models of production	Automation of production processes
Smart energy	ICT applications in the energy sector (mainly electricity supply)	Smart metering, demand side management, distributed power generation
Smart buildings	Change of building management enabled by ICT	Smart heating, smart lighting

Table 10: Main application domains, descriptions and example use cases in the domain.

9.3.2 Number of use cases

Most of the studies we identified assess specific ICT use cases (e.g. e-books, videoconferencing). Studies estimating the overall impact of ICT often select a number of the most common or prevalent use cases from various application domains and aggregate the environmental impacts across all use cases (e.g. GeSI & Accenture Strategy (2015), Malmodin & Bergmark (2015), Pamlin & Szomolányi (2006)). We have to consider that the studies use different abstraction levels and definitions for use cases, which is why it is difficult to match the use cases across studies. Therefore, the numbers provided in the third column of Table 9 and in Figure 12 and Figure 13 are to be interpreted with caution. From a methodological perspective, it is essential to distinguish between studies that are focusing on one use case only and studies investigating several use cases because in the latter case, interactions between use cases can (and should) be studied. Therefore, we distinguish between 'single-use-case studies' and 'multi-use-case studies' in the following.

In total, we found 30 'single-use-case studies' and 21 'multi-use-case studies'. The latter usually apply relatively simple estimation methods to determine a specific environmental impact for each use case (e.g. GeSI applies the 'ICT enablement method' in its SMARTer studies to estimate the ICT-induced GHG emission reduction potential for a collection of use cases (GeSI et al., 2008; GeSI & Accenture Strategy, 2015; GeSI & BCG, 2012; GeSI & The Boston Consulting Group, 2010)). There seems to be a trade-off between the depth of analyzing each use case vs. the scope of domains and use cases that are covered by the studies. Therefore, multi-use-case studies are often close to back-of-the-envelope calculations, also called "Fermi calculations", which try to derive a rough estimate from a few simple assumptions (Anderson & Sherman, 2010). In contrast, the single-use-case studies usually apply methods allowing for a deeper analysis, including LCA or partial footprint (e.g. Moberg et al. (2011), Kozak (2003)). Mostly, the aim of these assessments is not just to estimate the environmental impact of the use case under study, but also to unveil the hidden mechanisms and impact patterns behind the use case in order to derive recommendations for policies or ICT application design. In search for deeper analysis, some studies also use simulation models. Xu et al. (2009) create an agent-based model to investigate the impact of increasing Internet penetration on consumers' use of traditional and e-commerce book retailing schemes. Hilty et al. (2006) apply System Dynamics modeling to investigate the impact of ICT on the energy, transport, goods, services, and waste domains, and how these impacts affect total energy consumption and GHG emissions.

Three studies have no focus on specific use cases. Picha Edwardsson (2014) qualitatively explores the environmental impact of scenarios for future media use. As mentioned above, the studies by Laitner et al. (2010) and Røpke and Christensen (2012) could not be related to specific application domains.

9.3.3 Patterns of production and patterns of consumption

ICT changes both the patterns of production (e.g. by changing manufacturing processes) and patterns of consumption (e.g. by changing individual media use). As can be expected, changes in production and consumption patterns are closely interrelated. For example, optimization of logistics has decreased the cost of logistic services (the service can be produced at a lower price and faster), such that e-commerce retailers can afford to offer free delivery and return to consumers, which dramatically changed consumer online shopping behavior (e.g. the online retailer Zalando had an order return rate of roughly 50% in 2013 (Seidel, 2013)).

12 of the assessments identified in our literature review focused on ICT's impact on patterns of production. Moberg et al. (2011), for example, compares the environmental impact associated with

production, use, and disposal of paper-based books vs. e-books. Such studies commonly use product-oriented assessment methods, such as LCA or partial footprint.

35 assessments focusing on ICT's impact on patterns of production also consider changes in patterns of consumption. Many of these studies use the ICT enablement method. They first assess the impact of ICT on production processes and then the reaction of consumers to it. GeSI (2015), for example, calculate the GHG emissions that are associated with the provisioning of ICT-based learning, health, and transport services, and then estimate how many consumers will adopt these solutions in future.

Only three assessments focus on ICT's impact on patterns of consumption exclusively. For example, Atkyns et al. (2002) use survey results to assess employee TC behavior, as well as drivers and challenges of TC adoption, without assessing the actual environmental impact of TC compared to conventional commuting. These studies use consumer-centric assessment methods to identify changes in individual consumption, such as interviews or surveys.

9.3.4 Methodological approach

Researchers use a variety of approaches for the assessment of indirect environmental effects of ICT. The assessments identified in our literature review used 15 approaches, namely agent-based modeling, system dynamics, LCA, partial footprint, the 'ICT enablement method', regression analysis, descriptive statistics, material input per service unit, transport models, vehicle drivetrain models, scenario analysis, literature review, meta-analysis, interviews, and surveys. LCA, the ICT enablement method, and partial footprint are by far the most frequently used assessment approaches, whereas simulation methods and qualitative approaches are less often applied. In the following we describe the approaches and how they are applied in the field of indirect environmental effects of ICT. We exclude descriptive statistics, interviews, surveys, vehicle drivetrain models, literature review, and meta-analysis, as these are too generic. We further add the Software Sustainability Assessment method (SoSA), a recent approach proposed in the ICT4S community to assess the environmental impact of software systems (Lago, 2016, 2019). Figure 13 subsumes meta-analysis, scenarios, transport models, vehicle drivetrain models, regression analysis, descriptive statistics, surveys, and material input per service unit under 'others'. 'Qualitative methods' include interviews and literature reviews.

LCA is used to estimate the environmental impact of a product system, evaluated with environmental indicators, by modeling all exchange of energy and matter between the product system and its environment (ISO, 2006). There are different types of LCA, which we do not distinguish in this study. Finnveden et al. (2009) provide an overview about recent developments in LCA. For indirect environmental effects of ICT, LCA typically compares the environmental impact of two product systems that differ with regard to ICT application. For example, Moberg et al. (2011) compare the environmental impact of reading paper-based books and reading books using an e-book reader. By applying LCA, they find that the production of an e-book reader causes approximately the same amount of GHG emissions as the production of 30 to 40 average books.

Many authors in the field of indirect environmental effects of ICT focus their analysis on selected life cycle stages only. For example, in their analysis of TC, Kitou and Horvath (2003) evaluate the energy consumption of homes, offices, and ICT equipment, looking at their use phases only. A more comprehensive LCA would at least include the emissions that are caused by the production and disposal of the ICT equipment or other crucial assets. In line with ISO 14067, which specifies a "partial carbon footprint of a product" as the "sum of greenhouse gas emissions […] and removals […] of one or more selected process(es) […] of a product system […], expressed as CO_2 equivalents […] and based on the relevant stages or processes within the life cycle […]" (ISO, 2013, p. 2), we call such approaches partial footprints, even if the environmental indicator is not GHG emissions. Such studies calculate the emissions or energy consumption for selected processes only, without applying a full life cycle approach.

Material input per service unit is a product-oriented assessment approach developed by Schmidt-Bleek (1998) to measure the resource productivity of services. It calculates the natural resources required throughout the life cycle of a product per unit of service delivered.

System dynamics is "a method that permits researchers to decompose a complex social or behavioral system into its constituent components and then integrate them into a whole that can be easily visualized and simulated" (Tang & Vijay, 2001, p. 3). The interaction among system elements is modeled by connecting stocks with material flows, such as water running through pipes (flow) and increasing the water level in a bathtub (stock), and stocks and material flows with information flows (Tang & Vijay, 2001). The key strengths of System Dynamics are that it helps decomposing complex systems into causally connected variables and that it can be executed by computer simulation to observe the behavior of the system over time. It is for these strengths that System Dynamics is often used in policy analysis. In the literature review, we found only one application of System Dynamics. Hilty et al. (2006) used System Dynamics to simulate the impact of ICT on environmental sustainability in the year 2020 (starting in the year 2000) in order to evaluate policy scenarios.

In agent-based modeling, a system "is modeled as a collection of autonomous decision-making entities called agents. Each agent individually assesses its situation and makes decisions on the basis of a set of rules" (Bonabeau, 2002, p. 1). In a simulation experiment, agents repeatedly interact with each other and with their environment. Their collective action determines the behavior of the system as a whole (Bonabeau, 2002). Agent-based modeling is especially useful to study emergent phenomena, e.g. macroeconomic phenomena emerging out of behavior at the micro level (Railsback & Grimm, 2012). Xu et al. (2009) use agent-based modeling to test different e-commerce book retailing schemes, the reaction of consumers to it, and how these affect the CO_2 emissions that are associated with book retailing.

Scenarios "denote both descriptions of possible future states and descriptions of developments" (Börjeson et al., 2006, p. 723). Scenario analysis is a method in the area of future studies. Future studies are a collection of methods to "explore possible, probable and/or preferable futures" (Börjeson et al., 2006, p. 724). Comparing different scenarios that are based on different assumptions about future ICT development can provide insights on the environmental consequences of ICT application. Arushanyan et al. (2015) use scenario analysis in combination with LCA and develop a framework specifically for the environmental and social assessment of future ICT scenarios.

The ICT enablement method, as introduced by GeSI in 2010, can be used to quantify the carbon-reducing effect of ICT use cases. The ICT enablement method is useful to quickly provide a rough estimate of the environmental impact of an ICT solution (GeSI & The Boston Consulting Group, 2010). The approach is close to a Fermi problem or 'back-of-the-envelope calculation'. In the SMART 2020, SMARTer 2020 and SMARTer 2030 reports (GeSI et al., 2008; GeSI & Accenture Strategy, 2015; GeSI & BCG, 2012), GeSI uses the ICT enablement method by…

- identifying GHG abatement levers (e.g. reduction in transport demand),
- estimating baseline emissions,
- estimating the level of adoption of the use cases in the population,
- estimating the impact on GHG emissions per unit of adoption and
- estimating the rebound effect (for an example see Figure 14).

A feature that distinguishes the ICT enablement method from a partial footprint is that ICT enablement method focuses on the mechanisms that cause the changes of environmental impact. Such studies almost exclusively present favorable indirect environmental effects of ICT, even though the method would also allow for estimating the size of unfavorable effects (e.g. by including induction effects or obsolescence effects (Hilty & Aebischer, 2015)).

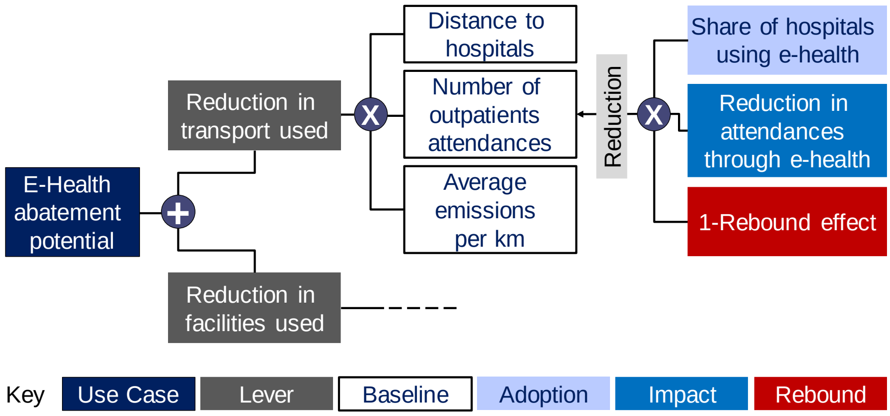

Figure 14: 'ICT enablement' method used in the SMARTer 2030 study (GeSI & Accenture Strategy, 2015) (cited from Bieser & Hilty (2018c)).

Studies that are focusing on the transport domain usually develop a transport model and assess how ICT changes transport. Transport models are usually combined with a partial footprint approach. Siikavirta et al. (2002), for example, model the impact of different e-commerce schemes on road truck delivery and estimate the avoided fuel consumption and resulting GHG emissions.

Using linear regression analysis (Rawlings et al., 2001), Laitner et al. (2010) estimate how the relationship between energy consumption (dependent variable) and economic growth and semiconductor investment (independent variables) in the U.S. changed after the introduction of semiconductor technologies. The application of regression analysis for indirect environmental effects of ICT can be manifold, for macroeconomic effects (see Laitner et al. (2010)) or for specific ICT applications (e.g. the effect of a traffic management system on the concentration of particulate matter in a city). However, it always treats the assumed causal mechanism as a black box and it does not reveal underlying system structures.

Even though we could not find application examples, we would like to mention the software sustainability assessment (SoSA) method, a recent approach to assess the environmental impact of software systems. SoSA analyzes the immediate, enabling, and systemic impacts of software systems on "economic, social, environmental and technical" sustainability (Lago, 2019, p. 1). The result is similar to a causal loop diagram and helps to understand the relevant impacts of a software system to improve software design (Lago, 2016, 2019).

9.4. Discussion

9.4.1 Applied methods and number of use cases

A comparison of methodological approaches is challenged by the variety of the purposes of the existing studies. For example, the ICT enablement method is useful for rough comparative assessments of ICT application domains and use cases. A study about the GHG abatement potential of ICT in Switzerland showed, for example, that the highest potentials to avoid GHG emissions through ICT can be found in the transportation, buildings, and energy domains (Accenture Strategy, 2016; Hilty & Bieser, 2017). However, such studies also face several methodological challenges, such as the definition of system boundaries, interaction among use cases, or rebound effects, which have to be carefully considered to judge the significance and comparability of results (Bieser & Hilty, 2018c). More detail-oriented methods, such as LCA or a partial footprint, are more useful to assess the inherent complexities of specific ICT use cases in order to improve the design of an ICT solution or derive policies to mitigate unfavorable environmental impacts or promote favorable environmental impacts at the product level. Dynamic simulation methods, such as agent-based modeling or System Dynamics, are also useful to develop such policies. While System Dynamics is most useful for describing causal mechanisms at the socio-economic macro-level, agent-based modeling is useful to explain macro-level phenomena with micro-level behavior.

9.4.2 Dynamic system modeling as an exceptional case

As Ahmadi Achachlouei (2015) points out, assessments of indirect environmental effects of ICT can either rely on dynamic or on static (steady-state) models. He performed different assessment studies using LCA, System Dynamics, and agent-based modeling, and recommends "employing an LCA method" (static) to assess "direct environmental effects of ICT production, use, and disposal" or indirect effects by comparing LCAs of "ICT applications with conventional alternatives" (p. 58). He also suggests using "system modeling methods" to "describe the drivers of change, as well as the dynamics of complex social, technical, and environmental systems that are associated with ICT applications" (p. 58).

In our study sample, most of the studies use LCA or similar static approaches to compare the environmental impact of a baseline product system or baseline scenario (representing a situation without the adoption of a given ICT use case) with a system or scenario with the adoption of an ICT use case (e.g. Moberg et al. (2011), Kozak (2003), Caird et al. (2015)). Only two studies use dynamic system modeling approaches—System Dynamics and agent-based modeling. By conducting simulation experiments with dynamic models, Hilty et al. (2006) and Xu et al. (2009) reveal causal mechanisms linking interventions (represented by changes in initial conditions and settings of model parameters) to environmental effects.

9.4.3 Consumption side is underexplored

Many assessments investigate how ICT changes patterns of production using a product-oriented modeling approach, such as LCA or partial footprint. Focusing on production is useful to understand the environmental consequences of (roughly) functionally equivalent product systems, with and without the application of ICT. A change in consumption behavior (e.g. people will read e-books instead of printed books), is treated as an exogenous variable. Focusing on consumption means to treat the demand levels for the several types of goods or services under study as endogenous variables. This is necessary if the study wants to show how ICT changes individual or collective consumption patterns.

Only three studies focus exclusively on consumption patterns in the above sense (Atkyns et al., 2002; Hopkinson & James, 2003; Røpke & Christensen, 2012). Such studies use consumer-centric assessment methods, such as interviews or surveys to interrogate consumers about their consumption behavior and potential changes. Environmental consequences are then estimated by comparing the environmental impact of the goods and services that are consumed by individuals before and after the ICT-induced change.

Practice theory can be used as a lens to investigate consumption. As opposed to other social science theories, which focus on individual attitudes, values, and beliefs, social practice theory focuses on "social practices ordered across space and time" (Birsl, 2016, p. 2; Katzeff & Wangel, 2015). For example, Røpke and Christensen (2012) assess how ICT changes the activities that are performed by individuals throughout one day and the energy consumption that is associated with these activities. They show that applying a social practice perspective can provide valuable insights into ICT's impact on society and the environmental consequences.

9.4.4 Limitations

A limitation of this systematic literature review is that we probably could not identify all relevant assessments of indirect environmental effects of ICT that exist in literature, or were biased by our personal background and opinions when manually including or excluding studies. These are limitations that systematic literature reviews face in general. We tried to minimize the risk of distorted results by deriving only robust results. As Mallet et al. (2012, p. 453) put it, systematic literature reviews, should be seen as "helping to get a robust and sensible answer to a focused research question".

9.5. Conclusions and outlook

We searched common scientific literature platforms and conference proceedings for studies assessing indirect environmental effects of ICT. We identified 54 studies assessing indirect environmental effects of ICT, in seven main application domains, using 15 different methodological approaches. The most common application domains are virtual mobility (e.g. TC), virtual goods (e.g. digital media), and smart transport (e.g. route optimization). LCA, partial footprint, and the ICT enablement method are the most common methodological approaches. LCA and partial footprint are commonly used in single-use-case studies to investigate the relative change that is induced by a specific way of applying ICT. The ICT enablement method is commonly used in multiple-use-case studies and it is sometimes used with the ambition to estimate and compare the environmental impact of digitalization in the large. Dynamic system models are less frequently used, but have shown to help explore the causal mechanisms behind ICT-induced change in socio-economic systems, including rebound effects.

More assessments focus on production rather than on consumption patterns. Both perspectives are required to fully understand how ICT changes economic processes and indirectly their environmental impact—what goods and services people consume, how they are produced, and how the product systems interact with the environment.

Some studies addressed the question how ICT changes social practices. Understanding how ICT changes consumer behavior, e.g. by analyzing activities of individuals, seems to be an underexplored, but essential aspect of the causal mechanisms that have to be understood for predicting the environmental impact of digitalization. Future research should close this gap by paying more attention to ICT-induced changes in social practices and related consumption patterns. In a digital society, this type of research could become instrumental for the achievement of the UN SDG 12—Responsible consumption and production.

10 Indirect effects of the digital transformation on environmental sustainability: Methodological challenges in assessing the greenhouse gas abatement potential of ICT

Bieser, J., & Hilty, L. (2018c). Indirect effects of the digital transformation on environmental sustainability: Methodological challenges in assessing the greenhouse gas abatement potential of ICT. In: Penzenstadler, B., Easterbrook, S., Venters, C. & Ahmed, S. I. (editors). ICT4S2018. 5th International Conference on Information and Communication Technology for Sustainability, vol 52, pages 68-81. https://doi.org/10.29007/lx7q

Abstract: The digital transformation has direct and indirect effects on GHG emissions. Direct effects are caused by the production, use and disposal of ICT hardware. Indirect effects include the changes to patterns of production and consumption in other domains. Studies quantifying both effects often conclude that net effects (indirect minus direct effects) can lead to a significant GHG emission reduction. We revisited a study by Accenture on ICT's GHG abatement potential in Switzerland by reassessing the main assumptions. Our results confirm that ICT has the potential to reduce GHG emissions in Switzerland, especially in the building, transport and energy domains. However, our results also suggest that the potential is smaller than anticipated and that exploiting this potential requires targeted action. Reasons for differences among these results (and the results of similar other studies) are: degrees of freedom in the assessment methodology, selection of ICT use cases, allocation of impacts to ICT, definition of the baseline, estimation of the environmental impact, prediction of the future adoption of use cases, estimation of rebound effects, interaction among use cases, and extrapolation from use case to society-wide impacts. We suggest addressing these methodological challenges to improve comparability of results.

Keywords: Information and communication technology, digitalization, climate change, greenhouse gas emissions, GHG abatement potential, environmental impact assessment.

10.1. Introduction

In September 2015, the UN adopted the SDGs, consisting of 17 goals to "end poverty, protect the planet, and ensure prosperity for all" (United Nations, n.d.-c, p. 1). As of October 2017, 195 member states have become party to the Paris Agreement, which "aims to strengthen the global response to the threat of climate change" and to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels" (Paris Agreement, 2015, p. 2). The current Swiss climate target aims at cutting domestic GHG emissions by 30% from 1990 to 2030.

The development of digital electronics has led to a convergence of technologies to store, transmit and process information, a process with far-reaching consequences (Hilty & Bieser, 2017). In recent years, "many and diverse domains of social life" increasingly structure "around digital communication and media infrastructures", a process called "digitalization" (Brennen & Kreiss, 2014, p. 1). Digitalization impacts GHG emissions in two ways: On the one side, an increasing amount of ICT hardware is produced, powered with electricity while being used, and finally disposed of—a system of processes which requires resources and causes emissions to the environment (direct effects). On the other side, ICT has influence on patterns of production and consumption, with manifold consequences (indirect effects). For example, ICT allows us to work from home and have virtual meetings, thus avoiding travel-related GHG emissions. In recent years, many studies have been conducted to quantify both direct and indirect effects. These studies usually conclude that indirect effects are positive (i.e., reducing GHG emissions) and clearly larger than direct effects. The conclusion is that net effects (indirect effects minus direct effects) can lead to a significant total reduction on GHG emissions (GeSI & Accenture Strategy, 2015; Pamlin & Szomolányi, 2006). For example, GeSI, the ICT industry's association for sustainability, claims that, on a global scale, ICT applications could avoid up to 20% of annual GHG emissions in 2030 (indirect effect), while the ICT sector causes roughly 2% of global GHG emissions (direct effect) (GeSI & Accenture Strategy, 2015).

Following such claims, the ICT4S community and the ICT sector increased their attention to the assessment of indirect effects of ICT on GHG emissions. Telecommunication network operators started estimating the indirect impact of their products and services on GHG emissions. For example, British Telecom (BT) estimated that, by 2020, their customers could avoid three times more GHG emissions by using BT products and services than BT causes itself. Emission avoidance would mainly occur through substitution effects, e.g. by reducing travel emissions through telepresence technologies (British Telecom, 2017). Swisscom (2017) estimated a factor of two by 2020 and AT&T (2017) a factor of ten by 2025.

A System Dynamics model developed in a project commissioned by the Institute for Prospective Technological Studies (IPTS) of the European Commission of the European Commission on "The future impact of ICT on environmental sustainability" in the EU yielded a different net effect of ICT on GHG emissions. The simulation results, recently validated with new data (Achachlouei & Hilty, 2015), suggest that by 2020, positive and negative effects of ICT on GHG emissions tend to cancel each other out across application domains. The authors conclude that a set of policies is necessary to specifically unfold the positive potential of ICT while inhibiting negative effects (Hilty, Arnfalk, et al., 2006). The diverging results can be explained by a difference in approaches: The IPTS study was based on a dynamic socio-economic model, whereas the newer studies tried to assess the potentials using a simple static approach. Such inconsistencies in methodological approaches make it difficult for decision makers to correctly interpret the results and take into account the climate change impact in ICT investment or policy decisions.

We will take a closer look at methodological challenges using the case of Switzerland as an example. We will first estimate the indirect impact of ICT on climate change in Switzerland, reconsidering ten ICT use cases previously treated in a study conducted by Accenture Strategy (2016) as a Switzerland-specific follow-up of the SMARTer 2030 study (GeSI & Accenture Strategy, 2015). In our context, the indirect effects are the changes to the GHG emissions (measured in CO_2-equivalents—CO_{2e}) caused in other sectors (such as the transport sector or the energy sector) by applying ICT in those sectors. Our study was conducted as a project commissioned by WWF Switzerland and Swisscom (Hilty & Bieser, 2017).

Based on the experiences gained in this study, we will then discuss the methodological challenges in the assessment of indirect effects of ICT on GHG emissions. Different ways of dealing with these challenges explain the variation in the results of studies using this type of impact assessment.

10.2. Related work

Existing studies assessing indirect environmental effects of ICT on GHG emissions either focus on individual ICT use cases or estimate the overarching indirect effect of ICT on GHG emissions. Assessments of individual ICT use cases include, e.g. the comparison of GHG emissions associated with printed books and e-books (Moberg et al., 2011), virtual mobility and physical mobility in a multisite conference setting (Coroamă et al., 2012), as well as traditional music delivery methods using physical CDs and digital music downloads (Weber et al., 2010).

For the purpose pursued in this paper, we reviewed existing studies assessing the overarching indirect environmental effect of ICT and provide an overview of the most relevant work. The system investigated in such studies is usually defined by geographic boundaries or by the products of an ICT company. These studies use various assessment methods to analyze a set of ICT application domains (such as transport) relevant in the system under study and a portfolio of use cases (such as 'car sharing') for each domain.

The project "The future impact of ICT on environmental sustainability" estimated the direct and indirect environmental effects of ICT in the European Union (Hilty, Arnfalk, et al., 2006). It was based on a System Dynamics model to analyze the impact of ICT production, use and disposal on the energy, transport, goods, services and waste domains and how these impacts affect total energy consumption and GHG emissions (among other environmental indicators). By simulating the development from 2000 to 2020, the authors found that the increasing and decreasing effects of ICT on total energy consumption and the resulting GHG emissions will roughly cancel each other out. Only by selectively promoting use cases with high abatement potential (such as intelligent heating) and inhibiting undesirable effects (such as rebound effects in transport), an overall reduction of GHG emissions would be possible. In 2014, the model was re-validated with updated empirical data, which qualitatively confirmed the results of the original study (Achachlouei & Hilty, 2015).

The World Wildlife Fund (WWF) conducted several studies to identify and measure the potential for ICT-enabled GHG emission reduction. The studies qualitatively and quantitatively explore the direct and indirect environmental impact of ICT in the EU and on a global scale (Pamlin, 2008; Pamlin & Szomolányi, 2006). For example, WWF estimated the GHG reduction potential in the EU through flexi-work, audio and video conferencing, online phone-bills, virtual answering machine and web-based tax return to be 48.37 Mt CO_2 compared to 4.73 Mt CO_2 caused by ICT directly.

Laitner et al. (2010) conducted a study based on historical macroeconomic time series data about the U.S. economy before and after the introduction of the semiconductor. They concluded that in 2006, semiconductor technologies avoided 20% of total electricity consumption in the U.S. economy through productivity gains, compared to a baseline scenario without new investments in semiconductor technology. By using aggregated data on the whole U.S. economy, they implicitly consider all application domains and use cases of ICT as well as the electricity consumption of ICT hardware (direct effect).

Malmodin and Bergmark (2015) assess the global GHG abatement potential of ICT in 2030 through making grids, buildings, transport, work, travel, services and agriculture smart. They find that ICT has the potential to avoid between 8% and 15% of global GHG emissions in 2030.

Assessments of indirect environmental effects of ICT also found their way into business practice. GeSI published a series of studies (SMART 2020, SMARTer 2020 and SMARTer 2030), in which they compared global direct and indirect impacts of ICT on GHG emissions (GeSI et al., 2008; GeSI & Accenture Strategy, 2015; GeSI & BCG, 2012). The latest report, SMARTer 2030, explicitly considers ICT's impact on mobility, manufacturing, agriculture, buildings and energy. It estimates the global GHG abatement potential through ICT application to be 9.7 times larger than the direct GHG footprint of ICT (9.7 is called the 'enablement factor'). Comparing the results of their studies shows that the GHG footprint (direct effect) of the ICT sector tends to decrease, while the GHG abatement potential through ICT seems to increase between 2020 and 2030.

In 2016, Accenture Strategy, who also supported GeSI in the SMARTer 2030 study, transferred the assessment of indirect effects of ICT of the SMARTer 2030 study to Switzerland. They concluded that, by 2030, ICT has the potential to avoid 18.4 Mt CO_{2e} in Switzerland, not considering rebound effects (for comparison: the total domestic GHG emissions in Switzerland amounted to 48.1 Mt CO_{2e} in 2015 (FOEN, 2017)).

Similar to GeSI and Accenture, many telecommunication network operators estimated GHG enablement factors of their products and services. To do so, they compare the GHG emissions of the activities performed by their customers before and after the application of each ICT product. They then put the aggregated difference into relation to the GHG footprint of their operations (GHG Protocol Scope 1-3[1]) and declare the result to be their GHG enablement factor. Table 11 provides an overview of the GHG enablement factors of different telecommunication network operators.

Telecommunication network operator	**Latest GHG enablement factor (year; unit)**	**Target GHG enablement factor (year; unit)**
AT&T (US)	no current factor	10:1 (2025; CO_2)
British Telecom (GB)	1.8:1 (2016/2017; CO_{2e})	3:1 (2017/2018; CO_{2e})
China Mobile (CN)	6.45:1 (2008; CO_2)	10:1 (2020; CO_2)
Deutsche Telekom (DE)	1.33:1 (2016; CO_2)	no target
NTT (JP)	12:1 (2016)	10:1 (2031; CO_2)
Swisscom (CH)	0.99 (2016; CO_{2e})	2:1 (2020; CO_{2e})
Verizon (US)	0.98-1.44:1 (2015; CO_{2e}; without Scope 3)	no target
Vodafone (GB)	1.9:1 (2016/2017; CO_{2e})	no target

Table 11: Overview of current and target GHG enablement factors of different telecommunication network operators according to their external reporting (AT&T, 2017; British Telecom, 2017; China Mobile, 2016; Deutsche Telekom AG, 2017; NTT Group, 2016; Swisscom AG, 2017; Tianjian et al., 2010; Verizon, 2017; Vodafone, 2016).

The outcomes of the overarching studies by Hilty et. al., Laitner, WWF, and GeSI, although not directly comparable due to different geographic and temporal scopes, yield varying net effects of ICT. Furthermore, if we compare the GHG enablement factors of different telecommunication network operators (Table 11), we can see—despite similarities in the underlying business models—that the enablement factors differ considerably. It is therefore important to identify the reasons behind this variety of results.

Without deeper analysis, we cannot claim that such studies provide a useful and reliable source of information for decision makers, enabling them to consider the (expected) environmental effect of an ICT application as a decision criterion. This is especially problematic as many businesses actively integrate this type of assessments into their marketing strategies, which in turn influences the decision-making of their customers.

To get some insight into the critical aspects of the methodology of such studies, we conducted a case study in which we reviewed the Accenture study for Switzerland and reconstructed it on the grounds of more precautionary assumptions. We dealt with the inherent uncertainty by not providing one

[1] The GHG Protocol Scope 1-3 standard provides reporting guidelines for GHG emissions caused by a company's own assets, their demand for energy e.g. electricity and activities outside in their upstream and downstream value chain e.g. procured goods (World Resources Institute & World Business Council for Sustainable Development, 2004).

forecast, but instead a set of three scenarios which differ in the assumptions taken about the development of the adoption and impact of the use cases analyzed.

10.3. Method

The goal of our case study was to estimate ICT's GHG abatement potential in Switzerland in 2030 by revisiting the study conducted by Accenture. The abatement potential quantifies the GHG emissions ICT can avoid in one year. We first analyzed the methodological approach taken by Accenture and then identified and re-evaluated—based on existing literature—the main assumptions. Finally, we defined three scenarios and recalculated the GHG abatement potential for each scenario.

In their study, Accenture transferred the results of the global GHG abatement potential of ICT in 2030, as identified in GeSI's SMARTer 2030 report, to the specific situation in Switzerland. SMARTer 2030 is based on twelve ICT use cases (such as 'e-health') and estimates the GHG abatement potential for each use case for ten focus countries (not including Switzerland), clusters the focus countries in four groups with macroeconomic similarities (GDP per capita, CO_{2e} emissions per capita, number of Internet users, and energy use) and extrapolates the focus country results to global figures using use-case-specific macroeconomic data (e.g. healthcare expenditure for the use case 'e-health'). The GHG abatement potential per use case (Figure 15) is estimated by…

- identifying GHG abatement levers (e.g. reduction in transport demand or reduction in facilities needed),
- estimating baseline emissions, i.e., the prospective emissions caused in 2030 with current patterns before the use case was realized (e.g. extent of travel to hospitals before significant 'e-health' adoption),
- estimating the level of adoption of the use case in 2030, i.e., the share of the population that will use this ICT solution (e.g. the number of patients or hospitals adopting "e-health'),
- estimating the impact on GHG emissions per unit of adoption of the ICT application (e.g. GHG emissions saved by the expected reduction in physical patient attendances in hospitals using 'e-health'),
- estimating the expected rebound effect (increase in demand due to higher efficiency (Gossart, 2015)).

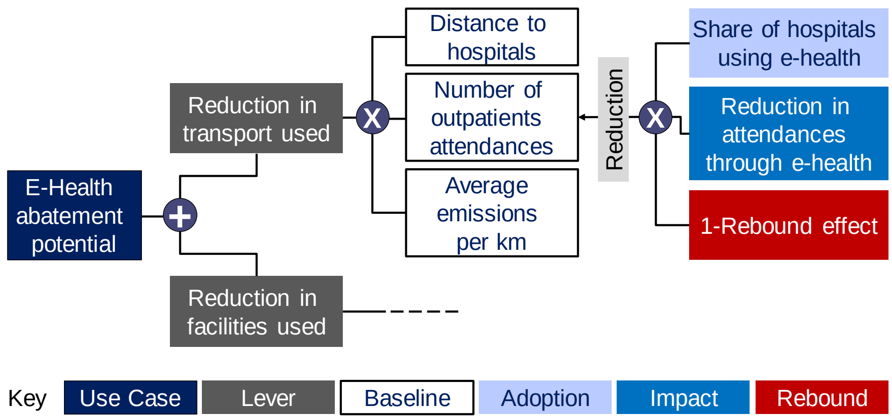

Figure 15: Calculation method based on SMARTer 2030 report at the example of 'e-health' (based on GeSI & Accenture Strategy (2015)). Rebound effects diminish the GHG reduction potential resulting from adoption and impact.

Out of the twelve ICT use cases in the SMARTer 2030 report, Accenture transferred ten to Switzerland ('smart agriculture' and 'smart manufacturing' were excluded). Accenture did not disclose how they transferred the results per use case to Switzerland. In our analysis, we revisited the assumptions taken at the global level and adapted them to the situation in Switzerland—specifically the values for adoption, impacts and expected rebound effects—to recalculate an adapted GHG abatement potential for each use case. Additionally, we excluded ICT use cases if ICT was only a minor contributor to their realization and it did not seem justified to allocate a major part of the GHG abatement potential to ICT.

Our case study is based on the idea of scenario modelling: Since we assume that the future can be influenced by the actions taken today, we refrain from making a forecast and provide a set of possible futures (scenarios) instead. The scenarios span the space in which the outcome can be influenced by directed actions, actions which increase either the adoption levels or the impacts (in terms of GHG reductions) of a use case. To summarize, we revised the existing Accenture study by reassessing underlying assumptions, excluding use cases with minor ICT contribution, introducing scenario modelling and by discussing the methodological challenges in this kind of studies.

A description of the scenarios is provided in Table 12. For detailed information on the assumptions, please refer to the technical report (Hilty & Bieser, 2017) and its supplementary information, which can be requested from the authors. Please note that the technical report, in contrast to this paper, uses a time horizon until 2025 for contractual reasons.

Scenario	**Description**
Pessimistic	The 'pessimistic' scenario combines (for each use case)… - an adoption level assuming that no directed actions to increase penetration of the use case are taken with - the lower boundary of the data points for the impact identified in latest research.
Expected	The 'expected' scenario combines (for each use case)… - an adoption level that can be expected according to measures currently implemented or planned (business as usual) with - the average of the data points for the impact identified in latest research.
Optimistic	The 'optimistic' scenario combines (for each use case)… - an adoption level assuming that actions accelerating penetration of the use case are taken with - the upper boundary of the data points for the impact identified in latest research.

Table 12: Scenarios used for the estimation of indirect effects.

10.4. Results

10.4.1 Total GHG abatement potential in Switzerland

Based on current expectations about the future development of the technology and its adoption, the potential for annual abatement will reach 3.98 Mt CO_{2e} in 2030. In the 'optimistic' scenario, the abatement potential can even increase to 11.32 Mt CO_{2e}. However, in the 'pessimistic' scenario (no directed actions supporting adoption, lowest plausible impact of technology on GHG reduction), the abatement potential will only reach 1.00 Mt CO_{2e}. Replacing the adoption levels in 2030 with the adoption levels of 2015 yields 1.11 Mt CO_{2e} abatement potential for the 'expected' scenario, showing that decision-makers can still influence the GHG abatement potential that will be reached in 2030 with targeted actions (Figure 16).

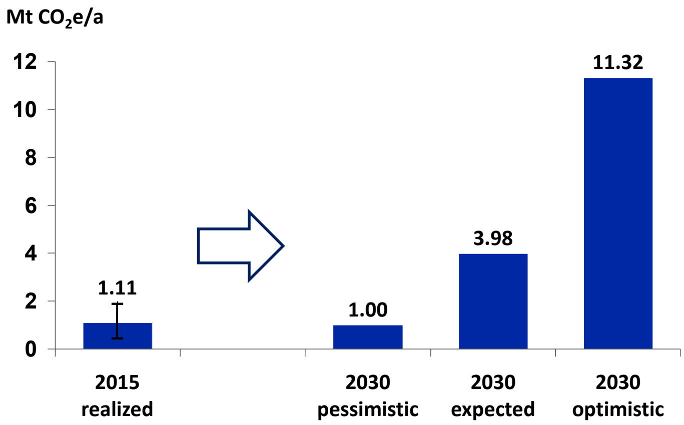

Figure 16: Realized GHG abatement in 2015 and GHG abatement potential in 2030 by scenario. The uncertainty in 2015 is due to uncertainty about the environmental impact of ICT in literature.

10.4.2 GHG abatement potential per use case

Abatement potential varies significantly across use cases. The largest potentials lie in application domains that are both energy-intensive and provide products or services continuously required by the whole society. This is true for the buildings, transportation and the energy sector which turned out to bear significant ICT-enabled GHG reduction potentials. Sectors, such as health or banking provide less GHG emission abatement potential in absolute terms (Figure 17) mainly because their share of GHG emissions is small.

The abatement potential of each use case is an aggregation of the reduction potentials of the levers identified in this use case. The GHG abatement potential usually varies across levers. For example, for the use case 'traffic control and optimization', the optimization of vehicle routes provides more GHG emission abatement potential than the contribution of ICT to a change of the modal split towards public transport. This may be specific for Switzerland and other countries where the share of public transport is already very high. Therefore, increasing the adoption of use cases is not always favorable, as their impact is context-dependent and must be evaluated in each individual scenario. Table 13 summarizes the most relevant levers per use case.

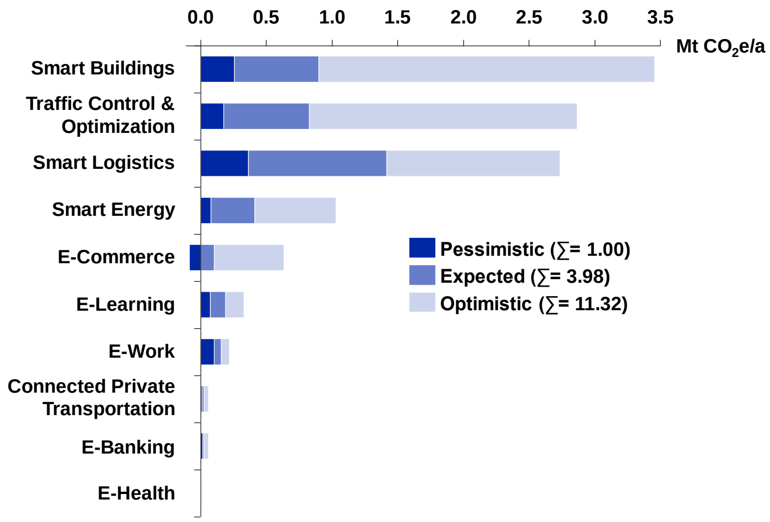

Figure 17: GHG abatement potential in 2030 in the 'pessimistic', 'expected' and 'optimistic' scenario by use case.

Use case	GHG abatement lever
Smart buildings	Building management systems reduce energy consumption of buildings
Traffic control & optimization	ICT enabled route optimization reduces transportation distances
Smart logistics	Sharing of logistic assets increases utilization of existing logistic assets and reduces transportation distances
Smart energy	Smart metering reduces energy consumption in households
E-commerce	E-commerce avoids shopping related transportation but increases transportation for distribution of goods
E-learning	E-learning avoids learning-related transportation
E-work	E-work avoids work-related transportation
Connected private transportation	Car and ride sharing reduces transportation with private vehicles
E-banking	E-banking avoids banking-related transportation
E-health	E-health avoids health-related patient transportation

Table 13: Description of main lever of GHG abatement potential in 2030 by use case.

10.4.3 Our results compared to Accenture results

Compared to the study of Accenture Strategy, the GHG abatement potential we estimated in the 'expected' scenario was lower for all use cases (Figure 18). Even in our 'optimistic' scenario, we estimated a lower GHG abatement potential for eight out of ten use cases. The results differ mainly because, on average, we estimated a significantly lower adoption in 2030 than Accenture Strategy and we were more conservative in allocating levers to ICT. In addition, we also estimated lower impacts and higher rebound effects on average than Accenture Strategy.

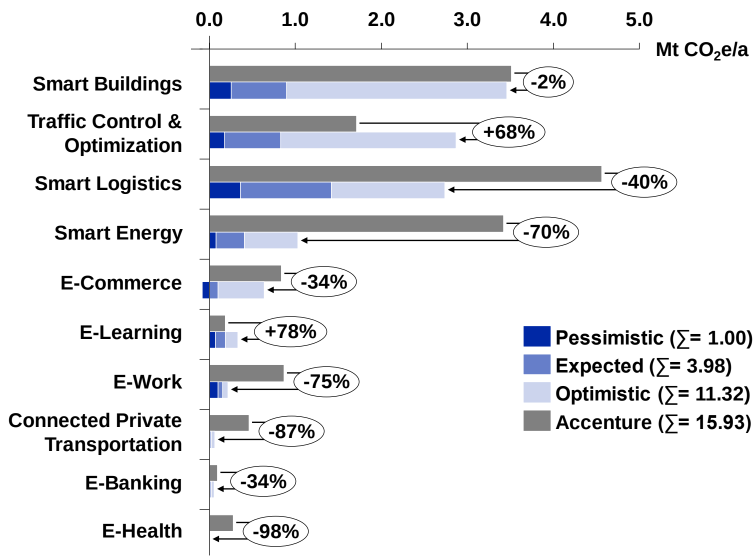

Figure 18: GHG abatement potentials in 2030 in the Accenture study and in our study by scenario. The percentages in brackets show the relative difference between Accenture results and our optimistic scenario.

10.4.4 Net effect of ICT on GHG emissions in Switzerland

If we assume that direct effects of the ICT sector in Switzerland will amount to roughly 2.50 Mt CO_{2e} in 2030 (extrapolated from Hilty & Bieser (2017)), this would equal 63% of the expected abatement potential in 2030 and correspond to an enablement factor of 1.59. If decision-makers manage to systematically explore ICT-related reduction potentials, we can expect an enablement factor of 4.53 ('optimistic' scenario). However, if actions to increase the GHG abatement potential until 2030 are omitted, the ICT use cases can only avoid 40% of the footprint of the ICT sector in 2030 ('pessimistic' scenario—enablement factor 0.40). The net effect of ICT on GHG emissions can be increased further if actions to minimize the footprint of the ICT sector are taken (Hilty & Bieser, 2017). More comprehensive LCA studies of ICT devices have shown that impact categories beyond global warming potential also matter (e.g. resource depletion, particulate matter, photo-oxidant creation potential, acidification potential and eutrophication of fresh water). However, the present study focuses on ICT's impact on GHG emissions.

10.5. Discussion

In the following discussion, we focus on the assumptions we reassessed in our case study as well as further methodological challenges which influenced the Accenture study results and thereby also our own results. The methodological challenges we identify seem to be of general importance for the assessment of indirect environmental effects of ICT (some are also described in Hilty et al. (2014) and Malmodin et al. (2014)).

10.5.1 Selection of use cases

GeSI (2015, p. 8) conducted the SMARTer 2030 report to research "the role Information and Communications Technology […] can play in cutting global CO_{2e} emissions". Accordingly, the study focused on ICT use cases with the potential for optimization or substitution effects (as described by Hilty and Aebischer (2015)) and thereby avoid GHG emissions. Use cases with induction effects (e.g. printers inducing the use of paper) or obsolescence effects (e.g. software updates make devices obsolete) were not in scope (except for 'e-commerce'). Systematically identifying such cases and including these in the study probably could have reduced the total GHG abatement potential. Defining the set of use cases is a general problem in the assessment of the overarching indirect effect of ICT on GHG emissions, since it is in principle impossible to analyze 'all' future ICT applications that are potentially relevant. This caveat also applies to our own study, as we cannot exclude the possibility that a disruptive application will change the situation more fundamentally than our projections can assume. This may include even better prospects for GHG abatement (some ideas are formulated in Hilty (2015)).

10.5.2 Allocation

GeSI and Accenture analyzed use cases which involve some sort of ICT application. However, the significance of the ICT application as an enabler of the use case varies a lot across use cases. For example, in the SMARTer 2030 report, GeSI identified 1.77 GT CO_{2e} global GHG abatement potential due to the increase in renewable energies. Although the substitution of renewable for fossil energy sources will probably not be possible without the help of ICT, many other technologies are required as well. It is therefore debatable whether the GHG reduction due to this substitution can be allocated fully to ICT applications. In contrast, for the realization of intelligent heating, ICT can be considered the main enabler. As the examples show, the assessment of ICT-induced GHG savings raises allocation issues as "ICT typically does not induce efficiency on its own, but only in a suitable technological, political or organizational context" (Coroamă, Schien, et al., 2015, p. 138). Especially for studies comparing the footprint of the ICT sector with its GHG abatement potential, there is no obvious way for allocating the abatement potential among ICT and other technologies required for its realization. Overestimating the net reducing effect of ICT on GHG emissions by applying a '100% for ICT' allocation rule (thus glorifying ICT's contribution to climate protection) can nourish the illusion that digitalization will save the climate without substantial action of stakeholders. However, there is no objective solution to this sort of allocation problem and this kind of discussion can be questioned as "important […] is certainly the carbon abatement, not whether it is ICT's exclusive merit" (Coroamă, 2017, p. 58).

10.5.3 Baseline

Assessments of indirect effects of ICT on GHG emissions need to identify baseline emissions, i.e., the emissions that would be expected if the ICT use case under study were not adopted (Hilty et al., 2014). Isolating the adoption of specific ICT use cases from a baseline scenario can be difficult since ICT has widely penetrated society. To estimate an indirect effect of ICT, would we seriously try to define the baseline as a scenario 'without' ICT? It is difficult to imagine how a world without ICT would look like. For example, if no Internet existed, our patterns of communication, our lifestyles and ways of making business most probably would have developed in a different way. This problem is even larger for prospective studies, since "the baseline scenario, […] as it expands into the future, is inherently speculative" (Coroamă, Schien, et al., 2015, p. 138).

Often, researchers choose a baseline provided by a recognized third party, such as the Intergovernmental Panel on Climate Change (IPCC). In such cases, to avoid double counting, one has to analyze the developments considered in the baseline scenario and ensure that they do not overlap with the use cases under study.

10.5.4 Impact

In our study, we estimated the actual impact of the use case levers on baseline GHG emissions (e.g. to what extent smart meters reduce household energy consumption). However, estimating the actual impact is tricky because ICT's "theoretical potentials materialize only under specific conditions" (Hilty et al., 2014, p. 1). For example, in a city with convenient public transportation, a car sharing system might replace public transport trips, whereas in rural areas, it might rather replace private car trips. The impact on GHG emissions will be very different depending on such contextual factors. Even explicit research on specific environmental impacts of ICT applications struggles to quantify the impact. Malmodin and Coroama (2016) find an invert correlation between the sample size and the energy reduction potential in studies about the energy consumption reduction impact of smart meters. Among the reasons for these difficulties are ICT's "exceptional dynamics of innovation and diffusion", its "social embedment and cross-sector application", its "diverse and complex impact patterns" (Erdmann & Hilty, 2010, p. 1) and the complexity of social and ecological systems, which makes it hard to isolate the impact of ICT and predict the outcome of an ICT application (Börjesson Rivera et al., 2014).

Due to these complex impact patterns, defining the system boundary is also challenging. An ICT application can have clearly recognizable consequences (e.g. reducing the fuel use of a combustion engine), but also hidden consequences, such as long-term rebound effects and other structural effects (e.g. how do social practices change in the long-run). In this study we tried to account for the uncertain impact by applying scenario technique, as suggested by Erdmann and Hilty (2010). In our expected scenario, we estimated on average a lower impact than Accenture, contributing to a lower GHG abatement potential.

10.5.5 Adoption

In our study, we had to estimate the future adoption of all ICT use cases in 2030. Future estimations always involve uncertainty, especially for ICT use cases due to ICT's "exceptional dynamics of innovation and diffusion" (Erdmann & Hilty, 2010, p. 1). In their studies, GeSI and Accenture often use the Gartner Hype Cycle (2017, p. 1), which provides "a graphic representation of the maturity and adoption of technologies and applications". Using the 'Hype Cycle' can be dangerous because, first, it classifies technologies and not use cases, and second, its classification dimensions (expectation of society and time on the market) do not necessarily reflect actual adoption.

The main issue we faced was a lack of forecast data (e.g. generated with technology diffusion models) for the adoption of the use cases. Where no forecasts were available, we had to rely on data from countries comparable to Switzerland or select proxy indicators. A strategy to deal with uncertainty is the collection of data from various relevant proxy indicators and, if available, also expert opinions to take an informed assumption. In case there are diverging opinions or forecasts, they can be assigned to different scenarios to make the uncertainty transparent. In our 'expected' scenario, we estimated on average a lower adoption than Accenture, contributing to a lower GHG abatement potential.

10.5.6 Rebound effect

Rebound effects are known to play an important role in ICT applications (Hilty, 2008). As stated by Gossart, "ICT are subject to important rebound effects of all kinds (energy, time, knowledge-related) […] because ICT are general purpose technologies that can generate high resource savings throughout the entire economy and society" (Gossart, 2015, p. 445). We included rebound effects in our calculations, however, we are aware of the high uncertainty in estimating rebound effects. From an economic point of view, rebound effects are based on demand elasticities, which are difficult to predict, especially in the long term. Observed elasticities are marginal values, therefore only valid for current absolute values. Additionally, ICT is a driver of GDP growth, which usually increases GHG emissions. However, the general discussion about growth and decoupling of GDP from resource flow—although a crucial issue—cannot be covered by this paper, since it is not specific for ICT.

In our study and in the Accenture study, rebound effects are represented as one relative reduction of the GHG abatement potential. Thereby, it is unclear how direct and indirect rebound effects shall be combined, as the method does not provide any guidance how to do so. For example, for 'e-health', consuming health services becomes more convenient and patients save time and money. A direct rebound effect would lead to increased use of healthcare services, whereas an indirect rebound effect would lead to increased consumption of other products and services with the time and money saved on health services.

In our study, we conducted a literature review to identify the most relevant rebound effects for the specific use cases, however, also struggled with lack of relevant data for all use cases. On average, we estimated higher rebound effects than Accenture, leading to a lower GHG abatement potential

10.5.7 Interaction

In studies analyzing several use cases individually to sum up their GHG abatement potentials, interaction between use cases may be an issue. Our study, as the Accenture study, analyzes ten use cases individually and mostly treats them as separate systems. However, interaction between use cases is plausible. First, abatement potentials of one use case (e.g. avoided travel due to 'e-health') may affect abatement potentials of other use cases (e.g. fuel saved through route optimization by 'traffic control and optimization'). GeSI and Accenture state that they account for such interactions. Second, there may be more complex systemic effects of use cases. Selected use cases may fundamentally change our patterns of production and consumption, leading to immediate or remote impacts on other use cases. For example, 'e-work' may fundamentally change commuting habits, which not only has influence on mobility patterns, but also our shopping behavior in the long run. For analyzing such effects, dynamic modelling and simulation techniques are required.

10.5.8 Extrapolation

GeSI and Accenture provide the macroeconomic indicators used for extrapolating the use case results to the global scale. However, the detailed calculation is not transparent. Malmodin and Coroama (2016) warn against extrapolating results from case studies that may not be representative.

10.6. Conclusion

ICT is an important enabler for a low-carbon economy in Switzerland. Regarding GHG abatement, there is an unprecedented opportunity and a resulting social responsibility for the ICT sector to take ambitious and targeted actions to enable other sectors to implement ICT-based ('smart') low-carbon solutions, both in terms of technologies and business models. This can mainly be done by further developing smart solutions in buildings, traffic control and optimization, logistics, and energy.

However, ICT-based solutions can only unleash its GHG reduction potential if targeted actions are taken. If no actions are taken and expected impacts cannot be realized, ICT will not contribute to climate protection in Switzerland. Rebound effects (increasing demands due to lower cost), compensating for the abatement, pose an additional risk.

Our study showed that, in absolute terms, ICT could enable the Swiss economy to save up to 11.32 Mt CO_{2e} per year (optimistic scenario). However, this figure has to be interpreted with care as assessments of indirect environmental effects of ICT face several methodological challenges, mainly implied by the complex, cross-sector impact patterns of ICT. How a study deals with these challenges has a crucial influence on the result. In our study, we reassessed the adoption levels, the impact, allocation and rebound effects of an existing study by Accenture and thereby reduced the identified GHG abatement potential already by roughly 29% ('optimistic'scenario).

By analyzing related studies and reflecting on our own study, we identified the following methodological challenges for studies assessing indirect ICT impacts: the selection of the use cases, allocation problems regarding the contribution of ICT among several involved technologies, the definition of the baseline to measure relative impacts, contextual factors influencing the impact of a given use case, the inherent uncertainty in predicting adoption, estimating rebound effects of different types, potential interaction among use cases, and the necessity to extrapolate from case studies that may not be sufficiently representative.

We suggest the development of recommendations addressing these methodological challenges to improve the comparability and significance of the results and provide decision makers with more reliable information on the GHG abatement potential of ICT. Studies assessing the indirect effect of ICT on GHG emissions should explicitly consider the methodological challenges described in paragraph 10.5 and transparently discuss their approach to addressing these challenges. Also, uncertainty should be explicitly addressed, especially with regard to rebound effects.

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PART II:

DEVELOPING A NEW ASSESSMENT APPROACH

11 An approach to assess indirect environmental effects of digitalization based on a time-use perspective

Bieser, J., & Hilty, L. (2018a). An approach to assess indirect environmental effects of digitalization based on a time-use perspective. In: Bungartz, H.-J., Kranzlmüller, D., Weinberg, V., Weismüller, J. & Wohlgemuth, V. (editors). Advances and New Trends in Environmental Informatics. Progress in IS. Springer, Cham, pages 67-78. https://doi.org/10.1007/978-3-319-99654-7_5

Abstract: The digital transformation has direct and indirect effects on the environment. Direct effects are caused by the production, use and disposal of ICT hardware. Indirect effects include the changes to patterns of production and consumption enabled by ICT in other domains. Studies of indirect environmental effects of ICT often focus on individual applications domains and their use cases, which implies that these studies cannot capture systemic effects of ICT adoption. We argue that interaction among ICT use cases is crucial to explain systemic environmental effects of ICT. In order to capture these interactions, we suggest focusing on ICT impacts on individual lifestyles, in particular time use, because (1) time is a limited resource for everyone, a fact which makes time budget constraints a central link among different activities and (2) many ICT use cases relax time and space constraints of individuals, thus changing time allocation. With this approach, we take into account that individual lifestyles are a major determinant of the overall environmental impact and that ICT diffusion changes individual time-use patterns and therefore lifestyles. Based on these considerations, we propose a conceptual framework that describes the relationship between ICT use, time-use patterns and environmental impacts.

Keywords: Information and communication technology, ICT, digitalization, indirect environmental impacts, environmental impact assessment, time-use approach, lifestyles.

11.1. Introduction

In September 2015, the UN adopted the SDGs, consisting of 17 goals to "end poverty, protect the planet, and ensure prosperity for all" (United Nations, n.d.-c, p. 1). As of October 2017, 195 member states have become party to the Paris Agreement, which "aims to strengthen the global response to the threat of climate change" and to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels" (Paris Agreement, 2015, p. 2). A recent report about the status of the 2 °C target shows that the "gap between the reductions needed and the national pledges made in Paris is alarmingly high" (UNEP, 2017, p. xiv), showing the need for further action.

The development of digital electronics has led to a convergence among technologies to store, transmit and process information. This process has far-reaching consequences for our patterns of production and consumption (Hilty & Bieser, 2017). In recent years, "many and diverse domains of social life" increasingly structure "around digital communication and media infrastructures"—a process called "digitalization" (Brennen & Kreiss, 2014, p. 1).

Digitalization impacts GHG emissions in two ways:

— On the one side, an increasing amount of ICT hardware is produced, powered with electricity while being used, and finally disposed of—a system of processes which requires resources and causes emissions to the environment (direct effects).

— On the other side, ICT has influence on patterns of production and consumption, with manifold consequences (indirect effects). For example, ICT allows us to work from home and have virtual meetings; thus, avoiding travel-related GHG emissions.

Many studies have been conducted to quantify both direct and indirect effects. Most of these studies conclude that indirect effects are desirable for environmental protection (e.g. reducing GHG emissions) and clearly larger than direct effects (e.g. leading to a significant total reduction of GHG emissions) (GeSI & Accenture Strategy, 2015; Pamlin & Szomolányi, 2006). For example, GeSI, the ICT industry's association for sustainability, claims that, on a global scale, ICT applications could avoid up to 20% of annual GHG emissions in 2030 (indirect effect), while the ICT sector will cause roughly 2% of global GHG emissions (direct effect) (GeSI & Accenture Strategy, 2015).

To assess the indirect environmental impact of ICT, most studies estimate the environmental consequences of individual ICT use cases (e.g. 'e-health' or 'e-learning') or the overarching effect of ICT. However, for the latter, the overarching effect of ICT is often assessed by estimating the aggregated impact of several individual use cases. Such assessments face several methodological challenges, such as defining the baseline, estimating the environmental impact, predicting the future adoption of use cases, estimating rebound effects, or extrapolating from the single use case to society-wide impacts (Bieser & Hilty, 2018c). Beyond, the assessment of one or more individual use cases often neglects one crucial phenomenon: interaction among use cases. For example, while a study on TC may show that working from home can avoid work-related trips (and thereby save travel-related GHG emissions), it does not capture how TC in combination with other use cases such as e-commerce, e-health or e-learning might more fundamentally change individual lifestyles. Such changes may only be seen from a more systemic perspective.

Analyzing lifestyles from a time-use perspective can provide a more comprehensive understanding about the indirect environmental impact of ICT including the interaction among use cases because (1) individual lifestyles (how do people spend their time) are a major determinant of environmental impacts, (2) time is naturally limited and thereby provides a natural constraint to behavior and (3) most ICT use cases impact individual time use (e.g. 'e-work', 'e-health', 'e-learning', 'traffic control and optimization' reduce travel time). Only few time-use studies in the field of indirect environmental effects of ICT exist. Hence, there is significant potential to improve the understanding of indirect environmental effects of ICT by taking a time-use perspective.

In this paper, we first introduce approaches to assess indirect environmental effects of ICT, discuss the challenge to capture interaction in such assessments, and propose the time-use approach as a promising approach to overcome this challenge. As a first step towards an assessment methodology based on this approach, we introduce a conceptual framework for the interconnection between ICT use, time-use patterns and environmental impact.

11.2. Assessment of indirect environmental effects of ICT

To assess the environmental impacts of ICT, researchers conduct environmental impact assessments. The International Association for Impact Assessment (2018, p. 1) states that "Impact assessment, simply defined, is the process of identifying the […] consequences of a current or proposed action". The Convention on Biological Diversity (2018, p. 1) states that an "Environmental Impact Assessment […] is a process of evaluating the likely environmental impacts of a proposed project or development, taking into account interrelated socio-economic, cultural and human-health impacts, both beneficial and adverse". According to the European Commission (2018, p. 1), "Environmental assessment can be undertaken for individual projects, such as a dam, motorway, airport or factory […] or for public plans or programmes […]". The target of environmental impact assessments is to inform decision makers or the general public about the environmental consequences of certain actions (European Commission, 2018). Beyond, environmental impact assessments aim at proposing measures to decision-makers to mitigate unfavorable and promote favorable environmental consequences.

Based on these definitions, we can define the 'assessment of indirect environmental effects of ICT' as the process of identifying the future environmental consequences of an ICT solution's capacity to change existing production and consumption patterns, taking into account interrelated socio-economic, cultural and human-health impacts, both beneficial and adverse, with the aim of informing decision-makers or the general public and mitigate unfavorable or promote favorable environmental consequences. Example applications are the change of the design of an ICT solution (e.g. a real-time public transport information system) or the development of a policy for ICT solutions (e.g. about the use of public parking space by car sharing system providers). Such assessments often focus on the promotion of favorable environmental consequences, for example focusing on GHG abatement potential (the potential to reduce GHG emissions, e.g. by replacing physical travel with video conferencing). Most assessments estimate the environmental consequences of ICT use cases in specific domains (e.g. the health or transport sector). Estimations of the overarching effect of ICT often just aggregate the impact of individual use cases. In its SMARTer 2030 study, GeSI, for example, estimates the global GHG abatement potential of ICT by estimating the GHG abatement potential for 12 individual use cases (GeSI & Accenture Strategy, 2015). In their assessments, researchers apply a variety of assessment methods such as System Dynamics (Hilty et al., 2004), agent-based modeling (Xu et al., 2009), the ICT enablement method (Bieser & Hilty, 2018c; GeSI & Accenture Strategy, 2015; GeSI & The Boston Consulting Group, 2010; Hilty & Bieser, 2017) or LCA (Moberg et al., 2011).

11.3. Interaction among ICT use cases

Environmental impact assessments involve many methodological challenges such as selection of ICT use cases, allocation of impacts to ICT, definition of the baseline, prediction of the future adoption of use cases, estimating rebound effects, and extrapolating from use cases to society-wide impacts (Bieser & Hilty, 2018c). In this study, we focus specifically on one challenge, which is the interaction among use cases.

The SMARTer studies by GeSI have been very influential in the area of GHG abatement potentials of ICT (GeSI et al., 2008; GeSI & Accenture Strategy, 2015; GeSI & BCG, 2012). The most recent study, SMARTer 2030, finds that by 2030 ICT will have the potential to avoid 20% of global GHG emissions, compared to a baseline scenario assuming no further adoption of ICT solutions (GeSI & Accenture Strategy, 2015). To attain this result, GeSI selected twelve ICT use cases and assessed the GHG abatement potential for each use cases individually (see Figure 19).

GeSI avoided double counting of GHG abatement potentials between the baseline and use cases and among use cases by deducting GHG abatement potentials which have been considered twice (e.g. the use case 'e-work' avoids travel-related transport, which is part of the total passenger transport volume assumed as a baseline for the use case 'traffic control and optimization').

However, another form of interaction among use cases has not been considered: If we assume that adoption of all use cases in the 'SMARTer 2030' study would achieve 100%, this would imply that by 2030 we would work from home ('e-work'), shop from home ('e-commerce'), learn from home ('e-learning'), bank from home ('e-banking') and see the doctor from home ('e-health'). Not only would such a development result in relatively reclusive lifestyles, which does not seem very plausible, it also contradicts recent observations on the development of passenger transport demand, which, even in Europe, is still increasing (European Environment Agency, 2017).

By aggregating the GHG abatement potential of individual use cases, GeSI makes the implicit assumption that each use case affects a closed system which does not interact with other 'use case systems'. However, use cases do interact, as the following example will illustrate.

A single man works at a company which just introduced TC and decides to work from home on Friday. As dinnertime is approaching, he drives with his car to the next supermarket to buy groceries. Before the introduction of TC, he usually bought the groceries on his way home from work. Hence, TC avoided a work-related trip but induced a shopping-related trip. However, assuming that grocery-home-delivery is offered in his area, he could also have avoided the shopping-related-trip. This is, however, not granted because he may still prefer to go out. This example shows how 'e-work' without and with 'e-commerce' can lead to different outcomes in terms of passenger transport. In general, this means that use cases are not independent systems but interact with each other because ICTs have "diverse and complex impact patterns", "exceptional dynamics of innovation and diffusion" and "cross-sector application" (Erdmann & Hilty, 2010, p. 1), or in other words: systemic effects. Increasing diffusion of ICT leads to more complex systemic effects, a trend which implies that there will be a growing error if one tries to predict the overall effect by simply aggregating individual ICT use cases. Selected use cases may fundamentally change our patterns of production and consumption, leading to collateral impacts on other use cases. Therefore, in order to estimate the overall, systemic indirect environmental effect of a given set of ICT solutions, one should take a whole-system approach considering the interaction between use cases.

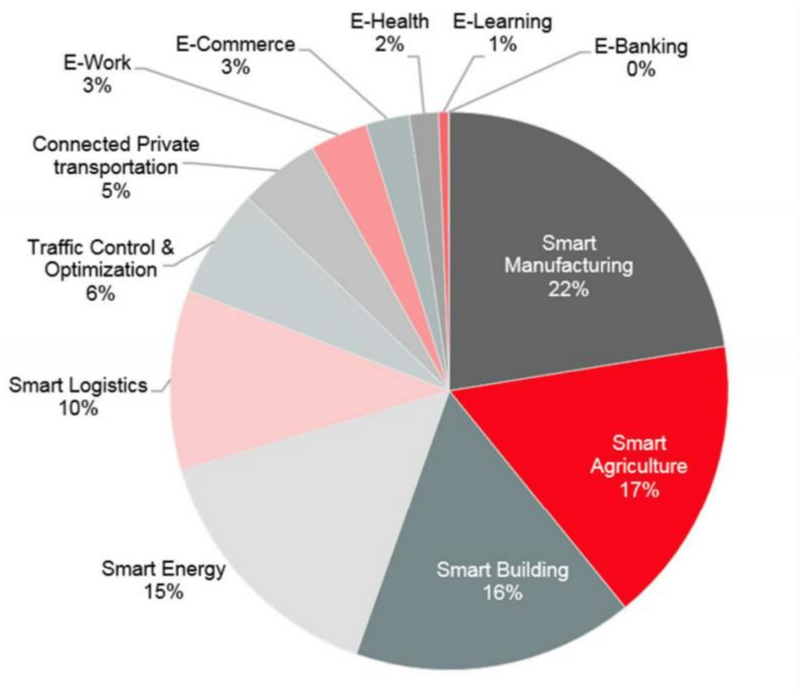


Figure 19: Share of total GHG abatement potential in 2030 by use case (GeSI & Accenture Strategy, 2015).

11.4. The time-use approach for the assessment of indirect environmental effects of ICT

Applying a whole-system approach can be challenging as ICT solutions have various immediate and remote effects on different sectors and aspects of life. Trying to include several use cases along with their interdependencies in one assessment increases the number of entities and relationships to be considered extensively. Such a complex system will have too many unknown parameters and therefore too many degrees of freedom. In order to reduce the complexity, we propose a change of perspective by focusing on time use.

11.4.1 The time-use approach

A promising approach to consider the interactions among use cases and keeping complexity at a reasonable level is the time-use approach. Instead of analyzing energy or material flows, the time-use approach primarily focusses on individual lifestyles, i.e. the allocation of time of individuals—as members of private households—to everyday activities (Jalas, 2002). Used as a perspective to understand indirect environmental effects of ICT, the time-use approach emphasizes the impacts of ICT on patterns of consumption (How do individuals spend their time?) and the environmental consequences.

In field studies collecting time-use data, individuals usually keep diaries about their daily activities. A large collection of multinational time-use data for various timeframes has been collected and standardized by the Centre for Time Use Research at the University of Oxford since the mid 1980s (Gershuny & Fisher, 2013). To assess the environmental impact of lifestyles, time-use data is commonly linked with data on household expenditure, energy consumption of households, life cycle inventory (LCI) data[2] and environmentally extended economic input-output tables[3] (Aall et al., 2011; Jalas, 2005; Minx & Baiocchi, 2009; Røpke & Godskesen, 2007).

11.4.2 Assessments of indirect environmental effects of ICT with a time-use approach

The assessment of indirect environmental effects of ICT can benefit from the time-use approach for two reasons: (1) individual lifestyles are the place where the decisions are made that—via a shorter or longer causal chains—lead to major environmental impacts, and (2) ICT influences lifestyles by ‘softening’ time and space constraints on activities, thus allowing for changes in individual time allocation (Jalas, 2002; Røpke & Christensen, 2012).

What makes the time use an attractive perspective for systems modelling is that time is naturally limited, as every individual, rich and poor, has the same amount of time available (24 hours on any given day), in contrast to financial budget, which is unevenly distributed across individuals (Druckman et al., 2012). First, this makes it easier to compare different lifestyles, and second, it forces the researcher to analyze how changes in time allocation to one activity are compensated with changes in time allocation to other activities. For example, if the researcher finds that TC saves 20 minutes of commute time per day on average, he or she must also answer the question how the saved time is spent. If we add further ICT use cases to the assessment, they again change the rules of the game in which all activities compete for the same, naturally limited resource—time—with each other. ICT use cases may also add to the list of potential activities themselves: think of computer gaming.

[2] Life cycle inventory data is data describing all exchanges (e.g. energy) from and to a technosphere of a product throughout the whole product life cycle. LCI data is used for LCAs and provided by LCI databases, such as ecoinvent (ecoinvent, n.d.).

[3] An environmentally extended input-output table “depicts the economic transactions between the different sectors and the final demand of a country [...] extended with data on the pollutant emissions and resource uses of the individual economic sectors and the final demand” (Frischknecht et al., 2015, p. 1).

To resume our example from above: When including TC and ‘e-commerce’ in one assessment, we have to explain how much time individuals save through TC, how much time they save through ‘e-commerce’, and how they spend the time saved. The time-use perspective forces us to consider interdependencies between use cases because of the hard 24-hour time budget constraint.

Many ICT use cases discussed in literature have an impact on individual time use. Table 14 provides an overview of the use cases discussed in the SMARTer 2030 report and their impact on individual time use (detailed information on the “mechanics” of the use cases can be found in the appendix of the report (GeSI & Accenture Strategy, 2015)). 7 out of 12 ICT use cases have an immediate impact on time use and the activities performed by individuals, emphasizing that time is a relevant phenomenon to understand ICT impacts. While 5 out of 12 ICT use cases do not immediately impact individual time use, they change the environmental impact of activities performed by individuals. Smart agriculture, for example, changes the production of agricultural goods, thereby changing the environmental burden associated with the activity eating; smart energy changes the integration of renewable energies into the electricity grid and thereby the environmental burden associated with all electricity consuming activities.

Use case	**Impact on time use of individuals**
Connected private transportation	Reduces travel time through additional transport services (e.g. car or ride sharing)
E-banking	Reduces travel time for banking
E-commerce	Reduces travel time for shopping
E-health	Reduces travel time for health services
E-learning	Reduces travel time for learning
E-work	Reduces travel time for commuting or business trips
Smart agriculture	No impact on individual time use
Smart building	No impact on individual time use
Smart energy	No impact on individual time use
Smart logistics	No impact on individual time use
Smart manufacturing	No impact on individual time use
Traffic control and optimization	Reduces travel time through more efficient routes

Table 14: ICT use cases (based on the SMARTer 2030 report (GeSI & Accenture Strategy, 2015)) and their impact on individual time use.

Also, time-use data “is a very good anchor for linking other models or information from other data sources” such as location, interaction, expenditure or environmental data (Minx & Baiocchi, 2009, p. 823). By analyzing individual time allocation, we can understand human behavior and decision making in a social context as well as its environmental implications (Minx & Baiocchi, 2009). Finally, time use does not change as fast as other elements of society and provides a solid fundament for analysis and action (Jalas, 2002).

To date, only few researchers have been applying a time-use approach to assess in-direct environmental effects of ICT.

Lenz and Nobis (2007) conduct an empirical study about the impact of ICT on fragmentation of activities and travel time using cluster analysis. Fragmentation, as introduced by Couclelis, means the interruption of one activity by another and the sub-sequent continuation of the former. ICT specifically enables spatial fragmentation (activities can be carried out at different locations), temporal fragmentation (formerly uninterrupted activities are now broken up into pieces which are performed at different times) and fragmentation of the manner of activities (linkage of activities is broken up, e.g. shopping does not require physical trips anymore) (Couclelis, 2000; Lenz & Nobis, 2007).

Wang and Law (2007) conduct an empirical study using a structural equation model to analyze the impact of ICT use on travel behavior in Hong Kong. They find that the use of ICT leads to more trips and increases the time spent for travel.

Røpke and Christensen (2012) use qualitative interviews to show that ICT use leads to a 'softening' of time and space constraints of activities and increases the complexity of activities (e.g. simultaneous activities). In that sense, ICT can make activities more energy intensive as it diversifies practices, in particular through multitasking and activation of 'dead time'.

Hilty et. al. (2004) apply System Dynamics to simulate scenarios of the impact of ICT on environmental sustainability within the time horizon 2000-2020. The sub-model for passenger transport applies a time-use approach to model the individual choice of different transportation means. In principle, individuals consider the time efficiency[4] and the prices of different transport modes (whereby virtual mobility was added as an additional mode to the conventional, physical transport modes) to choose the optimum mode. If the time efficiency of a mode changes, e.g. congestion slows down individual car traffic or the option to do some work while traveling in public transport saves travel time, the optimum can change, and the modal split will adapt with some inertia in a way that respects the given time budget constraint (Hilty et al., 2004). The study finds that ICT has an increasing effect on total passenger transport (in passenger-kilometers, all physical modes added up) due to two main effects: intelligent transport systems making several physical modes more efficient and "the time utilization effect of mobile ICT applications". Both effects "contribute significantly to passenger transport growth by creating a time rebound effect" (Hilty, Arnfalk, et al., 2006, p. 1626).

The results of these studies support the notion that a time-use approach is useful for a holistic assessment of indirect environmental effects of ICT.

11.4.3 Towards a framework of indirect environmental effects of ICT and individual time use

Building on evidence that ICT impacts time use and that a time-use approach is a promising perspective to assess indirect environmental effects of ICT, we will develop a first conceptual framework.

One of the largest shares of environmental impacts is caused by construction, use and maintenance of infrastructures (e.g. buildings, streets; other major sectors with environmental impacts include agriculture and manufacturing (European Environment Agency, 2016)). Therefore, a strong link between individual lifestyles and environmental impacts is the use of infrastructures. At the same time, many existing and upcoming ICT use cases change individual time-use patterns and thereby also the utilization of existing infrastructures. For example, TC avoids physical commuting trips, directly lowering utilization of transport infrastructure and office buildings. Vice versa, as individuals share infrastructures with other individuals, utilization of infrastructures also affects individual time-use patterns. For example, individuals rather prefer a public transport mode if there are "not many people on the vehicle" (Beirão & Sarsfield Cabral, 2007, p. 483). In that case, a low utilization of transport

[4] Time efficiency in the model by Hilty et al. (2004) refers to the amount of people a transport mode can transport over a specific distance in a specific period of time (person-kilometers/hour). In case passengers can use travel time for other purposes (e.g. working on a laptop in a train) this utilized time is deducted from the travel time. In many cases the time utilization potential of transport modes increases through ICT (e.g. in self-driving cars).

infrastructure increases the probability of individuals choosing the respective transport mode; that is, the utilization impacts the time-use patterns. But if utilization drops too low, the frequency of supply may be reduced and demand will further sink due to lower time efficiency. In addition, there are direct links between ICT use and infrastructure utilization, such as intelligent transport systems that directly increase the time efficiency of the transport process. In Figure 20, we provide an overview of the relationships between ICT use, time-use patterns, infrastructure utilization and environmental impacts.

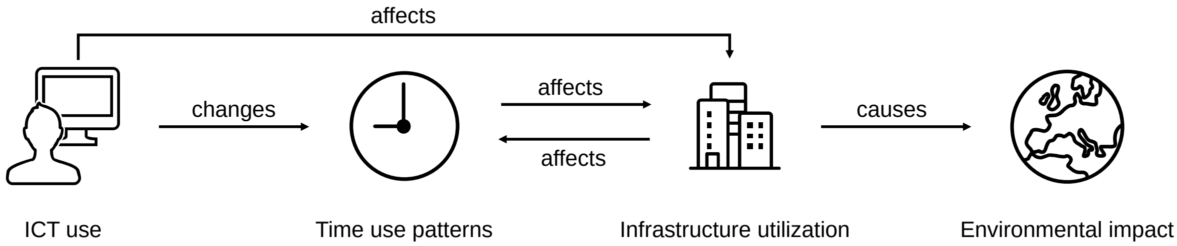


Figure 20: Relationships between ICT use, time-use patterns, infrastructure utilization and environmental impact.

We will illustrate the framework with one concrete example. Bill, an office worker who usually works from the employer's office five days per weeks uses transport infrastructure for his commute, office infrastructure during work and his residential infrastructure during leisure time. Once his employer introduced TC, Bill decides to work from home two days per week, which substantially changes his time allocation, his use of transport, office and residential infrastructure and the associated environmental impact caused by electricity and fuel consumption. On days when he expects the office to be too crowded for focused work, or when he expects significant delays in public transport because of an international event in the city he also decides to work from home—so the infrastructure utilization influences his time use. In the long-run, the office worker might even consider moving from the city to a suburb because TC eliminated the need to live close to the employer's office. At the same time, his employer decides to reduce his office space, which is now available for other businesses and might prevent the construction of additional office buildings and the associated environmental impacts. Taking a time-use perspective, we can explain impacts of ICT use on time use as well as on changes in infrastructure utilization and environmental impact.

11.5. Conclusion

The ongoing digitalization of our daily lives has significant indirect environmental consequences. It mainly depends on these indirect effects whether digitalization will foster or hinder the achievement of global environmental targets. Assessments of indirect environmental effects try to capture these phenomena in order to understand the causal mechanisms behind and develop measures to mitigate unfavorable or promote favorable environmental consequences of digitalization. Most of these assessments highlight the environmental impact of specific ICT use cases. In order to understand broader and long-term indirect effects of ICT adoption (such as rebound effects or lifestyle changes), one also has to consider how use cases interact and cause more fundamental, systemic changes to the existing patterns of production and consumption. By focusing on individual use cases, the prevailing assessment methods cannot assess systemic effects and therefore do not provide a reliable basis for the development of environmental policies with regard to digitalization. To capture systemic effects, we propose applying a time-use approach. Instead of analyzing energy or material flows, the time-use approach focusses on how individuals allocate their time to everyday activities (social practices), assuming that time allocation is the key element of individual lifestyle. The time-use approach is suitable for assessing indirect environmental effects of ICT because (1) individual lifestyles are a major determinant of environmental impacts, (2) time is naturally limited and thereby provides a natural constraint to behavior and (3) most ICT use cases impact individual time use. Also, the time-use perspective allows to assess interaction among ICT use cases in a natural way, as ICT changes fundamental constraints of activities (e.g. ‘e-work’ allows working from home instead of the employer’s office), while all activities compete with each other for the same limited resource—time. Studies assessing indirect environmental effects of ICT with a time-use approach are still scarce. Paying more attention to lifestyles, in particular time use, may add a valuable source of insight to impact assessment methodology and thus may help to develop technologies and policies to reach global environmental targets.

12 Conceptualizing the impact of information and communication technology on individual time and energy use

Bieser, J., & Hilty, L. (2020). Conceptualizing the impact of information and communication technology on individual time and energy use. Telematics and Informatics, 101375. https://doi.org/10.1016/j.tele.2020.101375

Abstract: The energy requirements of everyday activities such as housework, travel or sleep differ considerably; hence, individual time use—the pattern of activities individuals perform during a day—is crucial for the energy consumption associated with lifestyles. Increasing use of ICT in everyday life changes individual time use and thus affects the associated energy requirements. ICT can have increasing or decreasing effects on energy use (e.g. it can reduce transport through virtual mobility or increase transport by creating the desire to travel to places seen on the Internet). Understanding the relationships between ICT, time, and energy use is essential to promote its desired impacts and prevent socially and environmentally unfavorable (unsustainable) ones. Despite various approaches to time use across disciplines, no consistent conceptual framework of the impact of ICT on time use and environmental impact exists so far. In this paper, we review existing literature on (1) ICT impacts on time use, and (2) environmental impacts of time use. Aiming to bridge differences across disciplines and methodological approaches, we develop a conceptual framework for systematically assessing the impact of ICT on time and energy use. The core of this framework is the categorization of ICT impacts on the relaxation of time and space constraints to activities, parallelization, fragmentation, substitution, avoidance, and delegation of activities, changes to the duration and manner of activities, changes to the process of activity planning, and generation of new ICT-based activities. In a broader systems perspective, these effects also trigger causal chains which can form feedback loops and thus change time-use patterns with some delay (systemic effects). Changes in time use affect direct energy requirements through the energy used to perform activities (e.g. in the form of electricity or fuels). Indirect energy requirements, the energy embedded in goods, only change if production of goods can be avoided (e.g. if TC leads to fewer cars being purchased). The net energy impact of a given ICT use case depends on direct and indirect energy requirements of the activities performed before and after adoption of the use case. We demonstrate the application of the framework by qualitatively assessing time and energy use impacts of a frequently discussed ICT use case: TC.

***Keywords*:** Information and communication technology, time use, time allocation, activities, energy use, rebound effect.

Highlights

- Conceptual framework of ICT impacts on time and energy use
- Specification of ICT impacts on activity planning and execution
- Discussion of direct and indirect energy impacts of ICT-induced changes of time use
- Qualitative assessment of time and energy impacts of TC

12.1. Introduction

The amount of time available to everyone, rich or poor, on any given day is equal and limited. How people use their time allows conclusions about their lifestyles and the state of society. Individual time use—the activities individuals perform on any given day—is not only a core aspect of lifestyle, it also has environmental consequences. For example, the GHG emissions associated with a trip from Zurich to a meeting in Paris and back by plane are 10 times larger than accessing the same meeting by train and more than 300 times larger than having a virtual meeting using videoconferencing technology (Warland & Hilty, 2016).

Time use has been addressed in several academic disciplines. Specialized approaches have evolved, such as ‘time allocation theory’ (economics), the ‘time-use approach’ (economics), ‘time geography’ (human geography), ‘time prosperity’ (economics), ‘activity-based modeling’ (engineering and technology), and ‘practice theory’ (sociology) (Becker, 1965; Cascetta, 2009; Giddens, 1984; Hägerstrand, 1985; Heitkötter & Schneider, 2004; Jalas, 2002). Jalas’ (2002) time-use approach is one of the few approaches which systematically address environmental impacts of time use. He defines a lifestyle as a “dynamic pattern of consumption activities” (p. 111) and estimates energy requirements of goods and services used to perform activities (e.g. commuting by car or even sleeping while heating the house are activities which require energy). Palm, Ellegård and Hellgren have developed an approach to estimate and visualize energy consumption of activity sequences performed by household members (Ellegård & Palm, 2011; Hellgren, 2015; Palm et al., 2018). Many subsequent studies have investigated the environmental impact of everyday activities and found that environmental impacts caused by activities such as sleep, travel, housework, or shopping differ considerably and that the individual patterns of allocating time to activities (time-use patterns) are crucial for the sustainability of lifestyles (Druckman et al., 2012; Jalas, 2002; Sekar et al., 2018). Figure 21 provides an illustrative example of the energy use of activities during one day.

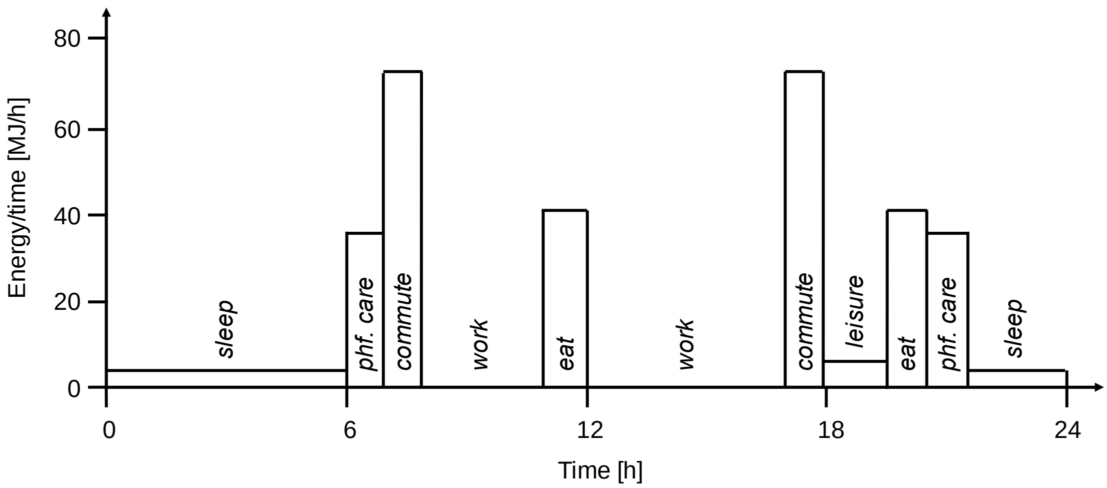


Figure 21: Illustrative example of time allocation and energy implications during one day, based on Jalas’ study on energy requirements of activities of Finnish households 1998-2000 (Jalas, 2005). ‘Phf care’ means personal, household, and family care (e.g. washing laundry). Energy requirements for sleep (e.g. due to heating) are estimated by the authors since the original study does not include them. The energy requirements of work are zero because in a consumption-oriented perspective, all energy requirements of producing goods and services are allocated to their final consumption.

ICT has penetrated society to an extent that lets people structure their lives around the possibilities it provides—a process called digitalization (Brennen & Kreiss, 2014). ICT’s impact on the environment has been addressed in the literature (Añón Higón et al., 2017; Asadi et al., 2017; Bieser & Hilty, 2018b, 2018c) as well as ICT’s impact on time use (and thus on the environment), for example:

- ICT can help us save time and reduce environmental impacts, e.g. by replacing physical travel with virtual mobility (Bieser & Hilty, 2018a; Coroamă et al., 2012; Hilty & Bieser, 2017).
- ICT can "make information about people and activities much more accessible" and therefore create the "desire to travel to participate in those activities and interact with those people" (Mokhtarian, 1990, p. 235).
- Certain amounts of energy, time, and information are needed to produce any good or service (Spreng's Triangle) and ICT increases the use of information, which can reduce energy and/or time needs (Spreng, 2015, 2001).
- ICT impacts the time efficiency of activities and can increase the pace of life, i.e. "the speed and compression of actions and experiences" (Rosa, 2003, pp. 8-9; Wajcman, 2008), which can have positive or negative environmental consequences. This depends on how the time saved on one activity is used for others, a crucial idea of our approach.

These examples show that ICT can have diverse impacts on individual time use and thereby reduce and/or increase environmental loads. Understanding the relationships between ICT, time-use, and environmental impact is essential to promote its desired impacts and prevent socially and environmentally unfavorable (unsustainable) ones. Existing approaches to time use and the associated environmental impacts represent a variety of perspectives and focus on different aspects; however, no consistent conceptual framework of the impact of ICT on time use and environmental impact exists so far. In this paper, we develop a framework of ICT impacts on time and energy use. The framework provides harmonized terminology across disciplines and allows researchers to identify, structure, and analyze potential ICT impacts systematically. It thereby supports the assessment and discussion of ICT applications, especially from the perspective of environmental impacts.

12.2. Approach

In this paper, we...

(1) review existing literature on the impact of ICT on individual time use and structure it according to different areas of life (leisure, work, maintenance, and transport),
(2) discuss the relationships between lifestyles, activities, and energy requirements from a time-use perspective,
(3) develop a conceptual framework for ICT impacts on individual time use (specifically on activity planning and execution) and discuss the implications for energy use and
(4) demonstrate the application of the framework with an example use case: TC.

We build the framework based on existing literature on ICT and time use as well as Jalas' time-use approach because it explicitly quantifies direct and indirect ICT energy impacts from a time-use perspective. To do so, we identify basic mechanisms of ICT impacts on time and energy use which apply to all areas of life and harmonize terminology across approaches in different disciplines.

12.3. ICT impacts on time use

Various hierarchies of abstraction for describing everyday activities exist, ranging from a low abstraction level (activities, e.g. 'playing football') to a medium level (activity categories, e.g. 'doing sports') to a top abstraction level with only a few broad categories (areas of life, e.g. 'leisure').

In the following, we provide an overview of studies describing ICT impacts on time use, structured according to a high abstraction level: leisure, work and maintenance activities. We add a section on transport, as it is a widely discussed application domain of ICT which interacts with time use in all areas of life.

12.3.1 Leisure

Various definitions for leisure activities exist, centering around three aspects: (1) leisure activity needs to be pleasant and freely chosen; (2) the output of leisure activity is not marketable; and (3) leisure activity "is consumed simultaneously and therefore cannot be delegated to anybody else" (third person criterion) (Beblo, 2001, p. 2; Mokhtarian et al., 2006; Tinsley et al., 1993).

Mokhtarian et al. (2006) investigate the impact of ICT on leisure and related travel and identify four types of ICT impacts on leisure activities:

— replacement of traditional leisure activities with ICT-based counterparts (e.g. substituting cinema with DVDs),
— generation of new ICT activities (e.g. surfing the Internet),
— ICT-enabled reallocation of time to other activities (e.g. commute time saved through TC may be allocated to leisure activities) and
— ICT as enabler/facilitator/modifier of leisure activities (e.g. ICT provides access to large amounts of information about possible leisure activities and facilitates communication).

Regardless of the type of impact, the motivation for performing a leisure activity determines "which kinds of leisure activities are more likely to be impacted by ICT" (Mokhtarian et al., 2006, p. 267). For example, activities aiming at physical exertion (e.g. swimming) or sensual enjoyment are potentially not substituted through ICT-based counterparts. For activities of cognitive stimulation (e.g. art galleries) or creative activities (e.g. painting) "ICT may provide a new dimension to the participation in these activities", e.g. through virtual mobility (Mokhtarian et al., 2006, p. 267).

12.3.2 Work

Work, or labor, is one of the inputs needed to produce useful output and usually "includes all activities that do not have to be performed by a particular individual" (Beblo, 2001, p. 2). Lee (2016, p. 1) summarizes various impacts of ICT on work, e.g. ICT can disrupt or change business models, loosen up traditional boundaries between companies, and change "place and time [...], as well as content, structure and the process of work". Routine jobs are replaced by machines and work "is now more cognitively complex, more team based, more dependent on social skills [...] and technological competence, more time pressured, and more mobile" (p. 2).

With respect to time use, ICT fragments the activity work—it allows us to perform activities at different places and times (Couclelis, 2000). Virtual mobility solutions can eradicate the need for work-related travel (e.g. through teleconferencing, remote maintenance). ICT can allow workers to fit working hours to personal preferences, e.g. by increasing flexibility in time and place of work (Leung & Zhang, 2017). However, there are arguments that digital technologies can increase workload, pressure people to multitask, harm work-life balance, raise stress levels and affect human health (Barnett et al., 2011; Leung & Lee, 2005).

12.3.3 Maintenance

Maintenance activities such as chores or personal care are often not performed voluntarily (in contrast to leisure) and do not involve the exchange of time for money (in contrast to work) (Beblo, 2001; Mokhtarian et al., 2006).

ICT impacts on maintenance activities are less researched than on leisure or work activities. Røpke et al. (2008) discuss the impact of ICT on household energy use and state that ICT creates additional maintenance activities, namely ICT maintenance. Lenz and Nobis (2007) find that many people who use ICT also fragment private activities, in particular shopping. Choudrie and Dwivedi (2007) investigate the impact of broadband Internet on 20 everyday activities in UK in 2004/2005, four of which can be considered maintenance activities (shopping in stores, housework, time with family, receiving/making phone calls). They find that broadband users spend less time on in-store shopping than narrowband users, but time spent on housework did not differ significantly.

The increasing diffusion of smart home solutions creates additional types of impacts on maintenance activities, e.g. through automation of household tasks (e.g. robotic vacuum cleaners) or remote control (e.g. controlling room temperature from outside the home). Energy efficiency improvements of household appliances (which today are often enabled by making the appliances 'smart') can also lead to increased use of such appliances (Woersdorfer, 2010).

12.3.4 Transport

Researchers from several disciplines have addressed the question how ICT changes transport demand, modal split, the efficiency of transport, transport infrastructures, and vehicles; these issues, explicitly or implicitly, are also connected to individuals' time use. In a review of research on the relationship between telecommunications and travel, Salomon (1986) discusses two conceptual relationships,…

- telecommunications substituting transport and
- telecommunications enhancing transport,…

concluding that the relationship between telecommunications and transportation is not unidirectional. Similarly, Mokhtarian et al. (2006) investigate the impact of ICT on leisure activities and related travel and find that "[f]or some types of effects [...] the adoption of ICT is likely to reduce travel; for others [...] the primary effect is likely to be generation of new travel" (p. 282).

In her seminal work, Mokhtarian (1990) discusses the supply-demand relationship between transport and telecommunication. According to her, telecommunications can...

- increase efficiency of transport supply (e.g. through traffic routing systems),
- reduce transport demand (e.g. through substituting physical commuting with TC) or
- increase transport demand (e.g. through making "information about people and activities much more accessible" and creating "the desire to travel to participate in [...] activities and interact with [...] people" (p. 235). This phenomenon is also discussed by Fortunati and Taipale (2017).

Couclelis (2000) discusses the impact of ICT on fragmentation of activities and implications for travel. Here 'fragmentation' means the interruption of one activity by another activity and the subsequent continuation of the former. Through ICT, more and more activities are no longer bound to particular times of day and/or places. As a consequence, the individual's flexibility in building chains of activities increases, which may lead to greater transport demand. Lenz and Nobis (2007) find that in 2003 in Germany specific lifestyles (e.g. those of people who rely on mobile phones or computers for work, because they travel for work or work from home) are more prone to fragmentation than others (e.g. those of conventional full-time workers). However, they hypothesize that it might not be that "ICT use [...] has an impact on travel behavior, but high travel frequency induces demand for ICT" (pp. 202f.).

Wang and Law (2007) conducted an empirical study on the impact of ICT use on travel time and behavior in Hong Kong. They found that the use of ICT leads to more trips and increases the time spent for travel. Hilty et al. (2006; 2004) conducted a simulation study on impacts of ICT on the environment which indicates that ICT makes transport more efficient and that virtual mobility such as TC or virtual meetings "serves as a loophole when the time used for travel tends to exceed an acceptable limit"

(p. 1626). The model also took into account that ICT enables "better possibilities for time utilization during transport" (p. 1626).

Several inconsistencies can be found among the results of studies investigating ICT impact on transport. For example, assessments of TC, videoconferencing, e-health, or e-commerce usually conclude that ICT use decreases the need for travel (GeSI & Accenture Strategy, 2015). In contrast, studies investigating the systemic relationship between ICT and travel find that ICT might also increase travel demand (Mokhtarian, 1990; Mokhtarian et al., 2006; Salomon, 1986). Differences in results can be explained by different system boundaries: studies of specific ICT use cases (e.g. substitution of physical commuting with TC) often assume a relatively narrow system boundary, e.g. they investigate immediate impacts associated with the use case while neglecting feedback loops that become apparent in a broader systems perspective and can create rebound effects (e.g. time saved on commuting will be spent on other activities, or transport demand is not constant) (Ahmadi Achachlouei & Hilty, 2014; Bieser et al., 2019; Bieser & Hilty, 2018a).

12.4. ICT energy and climate impacts from a time-use perspective

In the following we discuss the environmental impacts of time use and specifically ICT impacts on time and energy use based on Jalas' time-use approach. Jalas' approach was chosen because it systematically addresses environmental impacts of time use.

12.4.1 Environmental impacts of time use

In his seminal article on the time-use approach, Jalas (2002, p. 111) defines lifestyles as a "dynamic pattern of consumption activities". He allocates household expenditure, energy consumption, and input-output data to temporal activities and estimates the direct and indirect energy requirements of activities per hour (e.g. 83 MJ/h for leisure-time travel, 16 MJ/h for housework, 3 MJ/h for reading). Direct energy requirements represent the direct consumption of energy carriers during the performance of an activity. These include fuel consumption of transport vehicles, fuel or electricity consumption for heating and cooling buildings (e.g. oil, gas, electricity), and electricity consumption of electrical and electronic appliances (e.g. stoves, lights, TV sets). Indirect energy requirements are embedded energy, i.e. the "energy use of producing the goods and services that are needed in the activity" (e.g. production of a car) (Jalas, 2002, p. 114). The time geography approach by Palm, Ellegård and Hellgreen also connects energy requirements with activities. In contrast to Jalas' time-use approach, it focuses on the analysis of activity sequences and their direct energy requirements (Ellegård & Palm, 2011; Hellgren, 2015; Palm et al., 2018).

Many researchers have followed this approach. For example, Aal (2011) estimated the energy requirements of leisure activities in Norway in 2001, Minx and Baiocchi (2009) estimated activity material requirements in West Germany in 1990, Yu et al. (2019) estimated activity CO_2 emissions in China in 2008, Druckman et al. (2012) estimated activity GHG emissions in Great Britain in 2005 and Smetschka et al. (2019) estimated activity GHG emissions in Austria in 2010. In recent years, the energy requirements of new ICT-based, especially online, activities (e.g. video streaming) have gained attention (Coroamă, Schien, et al., 2015; Hilty & Aebischer, 2015; Kern et al., 2018).

12.4.2 ICT energy impacts from a time-use perspective

From a time-use perspective, net energy impacts of ICT depend on the energy requirements of the activities performed before and after adoption of an ICT use case (e.g. TC, e-commerce). Changes in time allocation have an immediate impact on direct energy requirements. For example, driving an average car for 30 additional minutes directly increases energy consumption. However, driving for 30 additional minutes has no immediate effect on indirect energy requirements, in this case the energy required to produce the car. Only if the utilization of a durable good—the share of time the good is in productive use—increases does the indirect energy requirement per time unit decrease; yet total indirect energy requirements remain constant. However, if utilization of a good drops so low that a person decides to stop owning such a good, indirect energy requirements are avoided. For example, if someone bought a car mainly for commuting to work, TC might reduce his or her use of the car to such an extent that he or she might sell the car or not buy a new one after it reaches the end of its service life.

ICT time rebound effects occur when ICT-enabled increases in time efficiency lead to an increase in energy use. Sorrel and Dimitropoulos (2008, p. 644) argue that consumers can choose "between energy services with different levels of time and energy efficiency" (e.g. walking vs. driving a car) and that due to "time costs forming a significant proportion of the total cost of many energy services, consumers and producers have sought ways to improve the time efficiency, rather than the energy efficiency".

12.5. A conceptual framework for assessing ICT impacts on time and energy use

In the following, we develop a conceptual framework of ICT impact patterns on time and energy use. Based on the literature summarized in section 12.3, we distinguish between immediate impacts of ICT on planning and execution of activities (see 12.5.1) and systemic effects with consequences for time use (see 12.5.2). We discuss the implications of these impact patterns for direct and indirect energy use in section 12.5.3.

12.5.1 Impacts of ICT on activity planning and execution

We distinguish two phases in an observed timeframe, namely activity planning and activity execution:

- Activity planning: the process of selecting and scheduling the activities to be performed for a specific time horizon (Cascetta, 2009). Activity planning can be performed implicitly or explicitly and take from almost none up to a significant amount of time.
- Activity execution: the performance of the planned activities

Each time an individual plans, he or she selects and schedules one or more activities within a certain time horizon of planning (planning horizon). Each activity has a unique starting point, duration, and location (Figure 22).

ICT impacts both activity planning (selection, scheduling, planning horizon/duration/frequency) and activity execution (manner, duration, fragmentation). Table 15 summarizes the impacts we describe in the following. Figure 23 provides a graphical representation of six patterns of ICT impact on activity planning and execution.

Activity selection

ICT can change the activities people perform by substituting, avoiding, or delegating activities, as well as by creating additional (ICT-based) activities. For example, ICT can replace a physical visit to the local bank branch with an e-banking session (substitution) and eradicate the need to travel to the bank branch (avoiding). Another example is e-commerce, which allows individuals to avoid trips to physical stores; the goods are transported to the home by a logistics service provider (delegation).

ICT use cases may also add to the list of potential activities themselves (e.g. surfing the Internet, video streaming, browsing social media).

Activity scheduling

ICT use leads to a relaxation of both time and space constraints to be considered in activity scheduling:

- Relaxing time constraints: Many activities which originally had to take place during specific time periods can be performed flexibly at any time (e.g. opening hours of banks vs. e-banking).
- Relaxing space constraints: Activities that used to be tied to one or a few locations can be carried out at additional locations (e.g. working from home).

A consequence of relaxed time and space constraints is that there are more options to perform activities simultaneously. If someone writes an article on the train, working and traveling activities are parallelized. Røpke and Christensen (2012, p. 355) state that ICT can also lead to "activation of 'dead time'" (e.g. surfing the Internet while waiting for the bus).

Planning horizon, duration, and frequency

The time spent on planning can potentially be shortened or prolonged through ICT. On one hand, ICT can save time spent on planning by enabling the user to gather information required for planning faster (e.g. with a calendar app) or by automating parts of the planning process. On the other hand, ICT can increase the time spent on planning. For example, online travel guides (e.g. TripAdvisor or Foursquare) provide an overwhelming number of options for sightseeing activities, hotels, and restaurants. Instead of choosing one out of a few options listed in a conventional, paper-based travel guide, individuals might compare a large number of alternatives and maybe even suggestions from various online travel guides. Also, ICT increases individuals' flexibility in building chains of activities: the more options there are, the harder it is to choose and the more time is needed to make an optimal or at least a 'good enough' decision. Furthermore, the relaxation of time and space constraints mentioned above can reduce the need for planning or the complexity of the planning process.

ICT can also change the planning horizon. Again, this can go in both directions. If ICT-based solutions provide the user with better forecasts (e.g. traffic or weather forecasts), this reduces uncertainty about the future and could enable users to extend their planning horizon. However, mobile connectivity also weakens the requirement to commit to a plan in advance because coordination with others is possible at short notice. People can therefore plan activities more spontaneously, after waiting for the best available information before choosing the preferred alternative. The possibility to communicate with anyone at any place at any time can thus trigger frequent replanning of activities as people can more flexibly change or cancel commitments already made. Even before the classical mobile phones were replaced by smartphones, Mokhtarian et al. (2006, p. 279) stated that "mobile phones permit an impulsivity of activity engagement (spontaneous arrangement of meetings; last-minute reservations) that was not previously possible (or at least not easy)".

That ICT would reduce the frequency of replanning is less plausible, and we could not find any evidence in the literature for this effect.

Activity manner

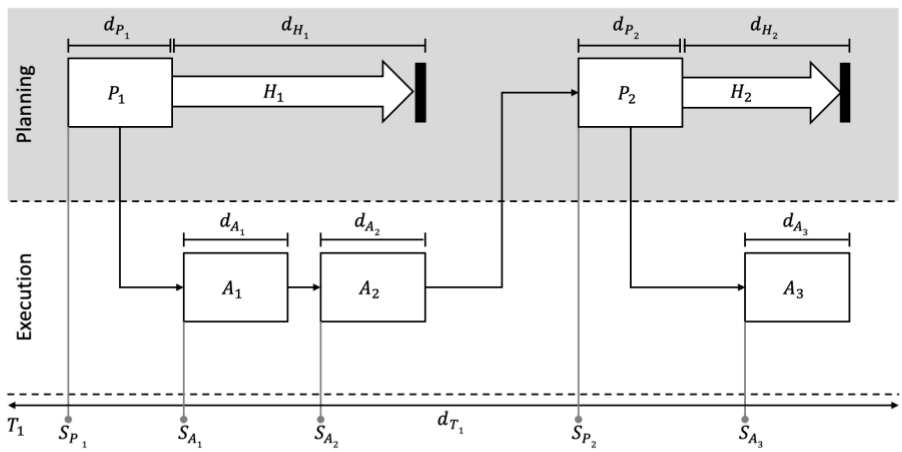
ICT also changes the manner of performing activities, i.e. the activities themselves. For example, film cutting used to be done with scissors and the processing possibilities were limited, while digital video processing provides numerous processing possibilities, such as filters or even 3D-effects. The actual impact of ICT on the way of doing things is highly activity-specific.

Activity duration

ICT also changes the time needed to perform activities. In many cases, the duration decreases due to ICT-enabled efficiency gains. For example, due to navigation systems, car drivers can find the fastest travel route and use live traffic information to avoid traffic jams. In other cases, the extra time needed to set up and maintain ICT solutions supporting the activity, deal with security issues and the consequences of software errors can compensate or even overcompensate for the efficiency gain expected from using the solution.

Activity fragmentation

The relaxation of time and space constraints through ICT has the side effect of creating options to fragment activities. Formerly uninterrupted activities are now broken up into pieces which are performed at different times and places (temporal and spatial fragmentation). For example, conventional office workers commonly went to work in the morning and home in the evening; their work activity was interrupted only by their lunch break. Today, someone's work day might be fragmented into time spent working at home in the morning (writing a report), at the office in the afternoon (meetings), and at a friend's house in the evening (e-mail), with non-work activities in between. Activity fragmentation can also occur when ICT distracts our attention from activities, thereby interrupting them, especially if people continuously receive incoming communications and information updates on various digital channels (e.g. e-mail, SMS, WhatsApp, LinkedIN, Facebook, Instagram, Tinder). In contrast, mobile work enables people to choose their working locations freely and intentionally select locations in which interruptions are improbable.



T_n Observed timeframe n
d_{T_n} Duration of timeframe n
A_n Activity n
d_{A_n} Duration of activity n
S_{A_n} Starting point in time of activity n
P_n Planning activity n
d_{P_n} Duration of planning activity n
S_{P_n} Starting point in time of planning activity n
H_n Planning horizon of planning activity n
d_{H_n} Length of planning horizon of planning activity n
L_{A_n} Location of activity n
$N_{T_n}^{A}$ Number of activities in timeframe n (without planning activities)
$N_{T_n}^{P}$ Number of planning activitieis in timeframe n
$N_{H_n}^{A}$ Number of activities in planning horizon of activity n

Figure 22: Conceptual framework of activity planning and execution over time.

Phase	Aspect	Guiding question(s)	ICT impact pattern
Activity planning	Activity selection	Which activities will I perform?	- Substituting activities - Avoiding activities - Delegating activities - Creating additional activities
	Activity scheduling	When will I perform activities? Where will I perform activities?	- Relaxation of time constraints - Relaxation of space constraints - Parallelization
	Planning horizon, duration and frequency	How long do I plan in advance? How much time do I spend on planning? How often do I plan activities?	- Shorter/longer planning horizon - Less/more time spent on planning - More frequent replanning
Activity execution	Activity manner	How do I perform an activity?	- Impact highly activity-specific - E.g. decreasing/increasing complexity of the activity
	Activity duration	How long does an activity take?	- Shorter/longer activity duration
	Activity fragmentation	Do I complete an activity once I started it?	- Interrupting activities - Increasing focus on activities

Table 15: ICT impact patterns on activity planning and execution.

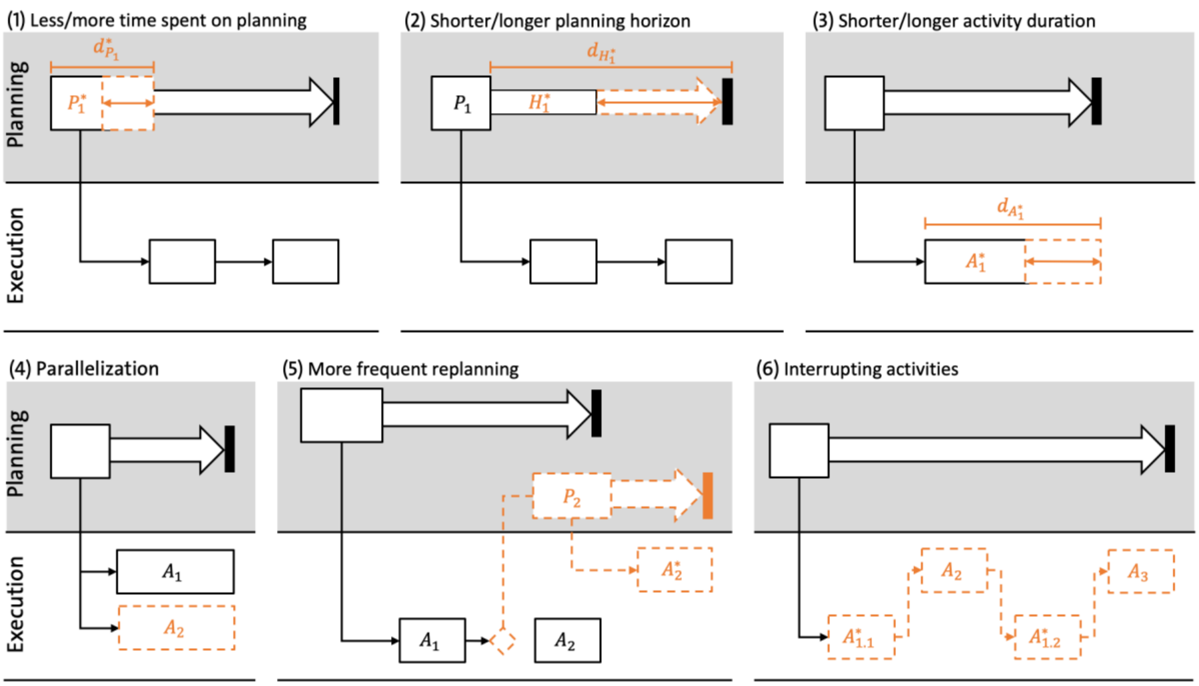


Figure 23: Selected ICT impact patterns on activity planning and execution.

12.5.2 Systemic ICT effects on time use

Systemic effects of ICT on time use are effects which only occur through the relationships between variables in the broader system in which the ICT use case takes place. Specifically, ICT impacts on time use can trigger causal chains which form feedback loops. Thus, changes in time use can trigger other changes in time use with some delay. For example, given that TC reduces time spent on commuting and adds flexibility to time and place of work ("flexiplace" and "flexitime"), it may influence families' decisions regarding where to live, jobs, investments in their dwellings and vehicles, simply because longer commuting distances become more acceptable (Salomon, 1986; Schiff, 1983). If this results in, for example, living in a rural instead of an urban area, this feeds back on individual time use, e.g. time spent on traveling for groceries, the mode of travel, or the type of leisure activities. In the long term, such developments can even lead to changes in land use patterns, such as "more decentralized and lower-density land use patterns" (Mokhtarian, 2009, p. 12).

Due to such systemic effects, the long-term consequences of ICT impacts on time use are difficult to predict. In an assessment of such effects, additional variables and their interactions need to be considered. This significantly increases the complexity of the problem and requires systems thinking and complex systems modeling.

12.5.3 Implications for energy requirements

The direct energy impact of ICT-induced changes in time allocation is the difference between the sum of energy requirements of the activities performed before and after the adoption of the ICT use case under study. If activities with high direct energy requirements are replaced with activities with low direct energy requirements (e.g. physical travel with virtual mobility), net energy requirements decrease—and vice versa. Most motorized transport activities (e.g. car, public transport) have relatively high direct energy requirements, whereas nonmotorized transport (e.g. bicycle, walking), common leisure (e.g. reading, watching TV) or maintenance activities (e.g. cleaning) have relatively low direct energy requirements (Druckman et al., 2012; Jalas, 2002). In Table 16, we describe the direct energy impacts of ICT impact patterns on activity planning and execution.

Indirect energy requirements depend mainly on purchase of goods and services used to perform an activity, including the use of infrastructures which need to be built and maintained. Changes in time allocation only impact indirect energy requirements if they trigger additional production (e.g. buying an additional desktop computer to work from home) or avoids production (e.g. not purchasing a car because of TC). With respect to infrastructure use, if ICT based solutions lead to a long-term change in demand for infrastructures, changes in building and operation of infrastructures can be expected.

The energy implications of systemic ICT impacts on time use depend on the nature of the change.

Phase	Aspect	ICT impact pattern	Direct energy impacts
Activity planning	Activity selection	Substituting activities	If high-energy activities are replaced with low-energy activities, net energy requirements decrease—and vice versa.
		Avoiding activities	Energy requirements associated with avoided activity are avoided.
		Delegating activities	Only leads to changes in direct energy requirements if activity manner and/or duration change as well.
		Creating additional activities	Additional energy requirements associated with new activity. Reduction of energy requirements if new activity substitutes other activity.
	Activity scheduling	Relaxation of time constraints	No impacts if activity duration and manner do not change. However, relaxed constraints increase individuals' flexibility in building chains of activities with potential impacts on activity selection, duration, and energy use (e.g. working from home can induce additional shopping trips which otherwise could have been combined with commuting).
		Relaxation of space constraints	
		Parallelization	More activities can be performed in the same time frame. Additional energy requirements associated with additional activity.
	Planning horizon, duration and frequency	Shorter/longer planning horizon	Change in planning horizon, duration, and frequency only impacts direct and indirect energy requirements if activity selection, duration, or manner changes.
		Less/more time spent on planning	
		More frequent replanning	
Activity execution	Activity manner	Impact highly activity-specific	Depend on goods and services used before and after the change of activity manner (e.g. in contrast to traditional film cutting, digital video processing requires computers which consume electricity).
	Activity duration	Shorter/longer activity duration	Direct energy requirements decrease/increase with time spent on activity (e.g. driving a car longer increases total fuel consumption).
	Activity fragmentation	Interrupting activities	Activity fragmentation only impacts direct and indirect energy requirements if activity selection, duration, or manner changes.
		Increasing focus on activities	

Table 16: Direct energy impacts of ICT impact patterns on activity planning and execution.

12.6. Example application of the framework

ICT provides the potential to reduce travel demand by replacing physical presence by virtual presence and by providing remote access to data. One important use case of this substitution is to replace physical commuting by TC (in particular by working from home). In the following, we demonstrate the approach by qualitatively applying the framework to TC. We focus mainly on impacts on activity planning and execution and associated energy requirements; and only sparsely on systemic impacts because they are more difficult to predict and less research has been conducted in this field.

12.6.1 Activity selection

By working from home, telecommuters can avoid the trip to work and associated direct energy requirements (Mokhtarian et al., 1995). Indirect energy requirements of commuting decrease if telecommuters decide to give up or not purchase a vehicle (e.g. car, motorcycle) or if demand for transport infrastructure decreases. The energy reductions due to avoided transport depend mainly on the choice of transport mode, commuting distance, traffic congestion, and TC frequency (Kitou & Horvath, 2003; Mokhtarian et al., 1995). In the long run, changes in transport demand due to TC can impact the supply of transport infrastructure and services and thereby also influence modal split and finally, in a feedback loop, individuals' time use (systemic effects) (Mokhtarian et al., 1995).

Time saved on commuting will be spent on other substitute activities. If commuting is substituted with travel for other purposes, no larger changes of energy requirements can be expected (assuming the same transport modes are used). If commuting is substituted with non-transport activities, a decrease in energy requirements can be expected because transport has higher direct and indirect energy requirements than most other common activities (e.g. for 'leisure' or 'phf care') (Jalas, 2002).

12.6.2 Activity scheduling

TC relaxes time constraints of work. For example, some telecommuters can work early in the morning or at night when the employer's office might be closed. However, if the time spent on work remains constant, no larger changes in energy requirements due to relaxed time constraints can be expected.

TC also relaxes space constraints of work; in particular, people can work from home instead of the employer's office. This can increase residential energy consumption (e.g. due to additional heating and lighting at home). Mokhtarian et al. (1995) summarize early studies which consider household energy impacts of TC and conclude that increases in residential energy consumption account for 11-25% of travel energy savings. Plus, TC can also reduce energy consumption at the employer's office (e.g. less lighting and heating required, reduction in office space) (Robèrt & Börjesson, 2006).

If a larger share of workers telecommutes and telecommuters and employers reconsider their place of residence or business due to changes in commuting frequency, then living and office space requirements as well as changes in land use patterns can occur (systemic effects) with consequences for time and energy use (e.g. due to changes in travel distances) (Mokhtarian et al., 1995). However, de Abreu e Silva and Melo (2018) conclude that workers' residential location decisions (and the associated commuting distance) influences the choice whether to telecommute or not—and not vice versa.

12.6.3 Planning horizon, duration, and frequency

We could not find studies on impacts of TC on planning horizon, duration, and frequency.

12.6.4 Activity manner

TC changes the way of working, e.g. because telecommuters conduct virtual instead of physical meetings to collaborate with colleagues. This increases use of ICT infrastructures with consequences for energy requirements. Kitou and Horvath (2003) estimated that changes in use of computers, copiers, printers, and fax machines at home and at the workplaces due to TC have a small impact on energy requirements compared to energy impacts of avoided commuting; however, they did not consider additional ICT collaboration platforms and tools which might be required due to TC.

Telecommuters might also perform other work activities when they work from home (e.g. more individual work at home, more collaborative work in the office). The energy impacts of this change are difficult to estimate.

12.6.5 Activity duration

People might spend more or less time on working when telecommuting (e.g. less time because they are less interrupted by colleagues and can focus on their work; more time because of the possibility to also work at times when the employer's office is closed). Energy impacts depend on the (substitute) activities more/less time is allocated to (see activity selection).

12.6.6 Activity fragmentation

Telecommuters can experience fewer interruptions when working from home because of the physical distance to colleagues. However, ICT collaboration tools (e.g. e-mail, messaging services) can also interrupt telecommuters if colleagues often send messages or call. The energy impacts of these changes depend on changes in the activity duration of work and consequences for other activities.

12.6.7 Overall assessment

To summarize, most changes in energy requirements of TC depend on changes in activity selection, scheduling, and duration. As transport is an activity with higher direct and indirect energy requirements than most other activities, a net decrease in energy requirements through TC can be expected from a time use perspective. However, systemic effects of TC (e.g. due to changing land use patterns) are difficult to predict, and more research in this field is required for a final conclusion.

12.7. Conclusion

In this paper, we presented a framework of the impacts of ICT on time and energy use based on existing literature on the impact of ICT on time use and on Jalas' time-use approach. The framework provides an interdisciplinary terminology to identify and describe ICT impacts on time use and systematically assess its consequential effects on energy use (or other environmental impact categories).

The framework describes ICT impacts on activity execution and planning in some detail. Systemic ICT impacts on time use, however, are described on a more abstract level because they depend on the interaction between variables in the broader use case system and are more difficult to predict. In order to include such effects into the assessment, long-term empirical studies and complex system models would be required. Most existing approaches for assessing the environmental impacts of time use allocate environmental impacts to the person who performs the activity, whereas many activities serve further people (e.g. cleaning benefits all household members).

Our qualitative demonstration of the approach for the use case TC indicates that TC has the potential to reduce net energy use because transport has higher direct and indirect energy requirements than most common activities. A comprehensive environmental assessment of the most important ICT use cases from a time-use perspective requires detailed data on ICT-induced changes in time allocation to activities and associated impacts on energy use. We would therefore recommend this for future research.

We encourage researchers to apply our framework to investigate environmental effects of ICT from a time-use perspective and to provide more empirical evidence on this matter. Only if such effects are included in the environmental and social assessment of increasing ICT use can we develop measures to harness the potential of ICT to increase quality of life and protect the environment.

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PART III:

DEMONSTRATING THE APPROACH

13 Toward a method for assessing the energy impacts of telecommuting based on time-use data

Bieser, J., Höjer, M., Kramers, A., & Hilty, L. (2020). Toward a method for assessing the energy impacts of telecommuting based on time-use data. Submitted for publication.

Abstract: Most TC studies focus on travel impacts and do not consider changes in time spent on non-travel activities (e.g. leisure) and the energy impacts of these changes. We demonstrate a time-use approach to assess interrelations between changes in commuting time and time spent on travel and non-travel activities. We show that time-use data can help to address TC research gaps such as the assessment of changes in time spent on non-travel activities and to consider interactions between time use on workdays and on weekends. A qualitative energy assessment shows that non-travel energy impacts matter because several non-travel activities have high energy requirements. However, little is known about the relationship between changes in time spent on a given activity and the impact of such changes on the activity's energy use—which would require modeling of the marginal energy requirements of activities. These depend on the use of energy-consuming equipment while performing the activity and the frequency of the purchase of goods and services to be able to perform the activity. If future research explores these relationships, the time-use approach can become key for assessing energy impacts of TC and of other digital technology applications which impact individuals' time allocation.

Keywords: Time use, telecommuting, home office, energy consumption, information and communication technology, ICT, indirect environmental effects.

Highlights

- Demonstration of time-use approach to assess indirect environmental effects of ICT
- Using time-use data to assess interrelations between commute time and time spent on travel and non-travel activities
- Energy impacts of TC on non-travel activities matter
- Further research on marginal energy requirements of activities required

13.1. Introduction

ICT has direct and indirect effects on the environment. Direct environmental effects of ICT include the impacts caused by the production, use, and disposal of ICT hardware. Indirect environmental effects of ICT are ICT-induced changes in patterns of consumption and production, including those in domains other than ICT (e.g. e-commerce, car sharing, smart homes) and the environmental implications of these changes (Bieser & Hilty, 2018c; Faucheux & Nicolaï, 2011). Studies have shown that assessments of indirect environmental effects of ICT face various methodological challenges (e.g. the definition of system boundaries, estimation of rebound effects), and mostly focus on changes in patterns of production and do not consider the impacts on consumption such as changes in time use (Bieser & Hilty, 2018a, 2018b).

Time rebound effects occur when increases in time efficiency of producing a service do not yield the expected energy savings due to intensification of the same activity or other energy-consuming activities (Brenčič & Young, 2009; Sorrell & Dimitropoulos, 2008). Various researchers have investigated time rebound effects (Binswanger, 2003; Brenčič & Young, 2009; Jalas, 2002; Sorrell & Dimitropoulos, 2008) and various ICT applications are subject to time-rebound effects (Börjesson Rivera et al., 2014; Gossart, 2015). A widely discussed ICT application which is subject to time rebound effects is the replacement of physical presence at a workplace with virtual presence and the resulting reduction of travel-related environmental impacts (TC). This may have the form of home-office work, as it became common during the COVID-19 lockdown, or can also be practiced in a CW space close to the home.

Studies investigating TC commonly estimate how much commuting can be avoided, whether TC induces additional travel for other purposes, and assess the associated environmental impacts (e.g. Mokhtarian et al. 1995, Glogger et al. 2008, Lachapelle et al. 2018). Still, most assessments of environmental impacts of TC focus on changes in travel. However, reducing commuting allows telecommuters to spend the time saved on commuting on non-travel activities such as 'leisure', which are associated with their own environmental impacts. In order to include non-travel activities into the assessment, time-use data of travel and non-travel activities is required. Besides time rebound effects, TC can also lead to income rebound effects, which occur, when telecommuters spend money saved on commuting on other energy-intensive goods or services. These are out of scope in this study.

A promising approach to investigate indirect environmental effects of ICT (such as time rebound effects) is the time-use approach introduced by Jalas in 2002 (Jalas, 2002; Bieser & Hilty, 2018b). The time-use approach focuses on temporal constraints of consumption by investigating individuals' time allocation to everyday activities and the associated environmental impacts. Various researchers have used time use diaries, expenditure records and environmental data to estimate environmental impacts of individual time use (Aall, 2011; Jalas & Juntunen, 2015; Smetschka et al., 2019). However, the approach has seldom been used to investigate indirect environmental effects of ICT—neither in general nor for the case of TC.

The aim of this article is to demonstrate the time-use approach for investigating energy impacts of TC and to identify further steps to improve the assessment. By exploring this field, we want to inspire and trigger further applications of the time-use approach to investigate indirect environmental effects of ICT from a time-use perspective. Improving the understanding of environmental impacts of ICT use is essential to align ICT applications with environmental protection.

In section 13.2, we summarize existing work on TC impacts on travel and non-travel activities and the environmental impacts of these activities and point out important research gaps. In section 13.3 and 13.4, we provide a first demonstration of the time-use approach for assessing energy impacts of TC which can help closing the identified research gaps. Section 13.5 discusses advantages as well as limitations of the approach. Section 13.6 briefly summarizes the main conclusions and points at important fields for further research.

13.2. Related work

In the following we summarize results of studies of impacts of TC on travel and non-travel activities (13.2.1) and the environmental impacts of travel and non-travel activities (13.2.2).

13.2.1 Impacts of telecommuting on travel and non-travel activities

TC has been studied since the late 1980s, up until today focusing mainly on North America, Europe and Asia (Hamer et al., 1991; Kim, 2017; Ma et al., 2019; Mokhtarian et al., 1995; Tanguay & Lachapelle, 2019). Thus, when interpreting the results of TC studies, we have to consider that differences in behavioral patterns, work and travel habits as well as socio-economic conditions between regions and time periods exist.

Most TC studies focus on its impacts on daily travel (e.g. Glogger et al. 2008, Lachapelle et al. 2018, Tanguay & Lachapelle 2019), many of which find that TC reduces daily commute (e.g. Glogger et al. 2008, Jaff & Hamsa 2018, Shabanpour et al. 2018), some of which find that reducing commuting leads to a small increase in travel for other purposes (e.g. Henderson et al. 1996, Lachapelle et al. 2018).

Few studies also investigate TC impacts on total travel per week and thereby can also consider changes in trip allocation between workdays and weekends. For example, Hamer et al. (1991) find that the number of trips on workdays and on weekends decreases. De Abreu e Silva & Melo (2018, p. 433) also consider full-week travel and find that "teleworkers travel more than non-teleworkers with similar location and motorization patterns", because they have longer commute distances and engage in more non-commute travel. In fact, in recent years, many studies argue that TC can lead to an increase in work and non-work travel, because telecommuters live further away from their work place (Zhu 2012, Hu & He 2016, Chakrabarti 2018). However, some of these studies argue that residential relocation decisions are mainly driven by other factors and not by the possibility for TC (de Abreu e Silva & Melo, 2018; Kim et al., 2012).

Some studies consider impacts of TC on household members (Hamer et al., 1991; Kim et al., 2015). For example, Hamer et al. (1991) find a reduction in travel of household members of telecommuters and argue that a plausible explanation is an increased "hominess" feeling, which occurs because household members are not alone at home during TC days.

While most TC studies focus on TC impacts on travel, less literature on research on non-travel activities (e.g. leisure, personal care) exist; even though, these activities are also associated with environmental impacts (see 13.2.2). Most of these studies find that reduced commuting time is associated with more time spent on non-travel activities (Fujii & Kitamura, 2000; Gould & Golob, 1997; He & Hu, 2015; Kuppam & Pendyala, 2001; Paleti & Vukovic, 2017). Some studies find that saved commute time is mainly put into non-mandatory activities (e.g. leisure, going shopping) (Asgari et al., 2016; Asgari & Jin, 2017). One study finds that saved commute is mainly spent on additional work and not leisure (Rhee, 2008). However, these studies do not assess the environmental impacts associated with non-travel activities such as leisure.

13.2.2 Environmental impacts of travel and non-travel activities

Various studies of environmental impacts of time use have been conducted since the late 1980s until today (Jalas, 2005; Schipper et al., 1989; Yu et al., 2019), focusing mainly on energy requirements (e.g. Aall 2011, Jalas & Juntunen 2015, De Lauretis et al. 2017) or GHG emissions (e.g. Druckman et al. 2012, Smetschka et al. 2019) associated with activities. Some studies estimate direct and some also indirect energy requirements and GHG emissions per time unit spent on the activity (e.g. in kWh/h or kg CO_2e/h). Direct energy requirements and GHG emissions are caused by the direct consumption of electricity or fuels during an activity (e.g. the electricity consumption of a TV set or the fuel consumption of a car). Indirect energy requirements and GHG emissions are 'embedded' in the goods and services used to perform an activity, such as the energy required to produce an electronic device or a car (Bieser & Hilty, 2020; Jalas, 2002).

Comparability of results across such studies is limited by the differences across time periods and regions under study, the set of activities analyzed, the aggregation of activities to activity categories, the types of environmental impacts considered (e.g. direct vs. indirect environmental impacts) and the environmental impact indicator. Still, some similarities between results of such studies exist. In the following, we focus on energy impacts of activities for simplicity. Most arguments also apply to GHG emissions.

Most studies find that travel activities are associated with very high direct and indirect energy requirements (Druckman et al., 2012; Jalas & Juntunen, 2015; Schipper et al., 1989; Smetschka et al., 2019). As early as 1989, Schipper et al. (1989, p. 297) compared time use and direct energy use in U.S. households in 1985-86 and found that "a minute spent traveling uses 8 and 12 times as much energy, respectively, as a minute spent in service buildings or at home". Energy impacts of time spent on 'travel' are high due to direct fuel consumption of vehicles, but also due to embedded emissions in transport infrastructure and vehicles (De Lauretis et al., 2017; Druckman et al., 2012). Some studies allocate energy impacts of travel to out-of-home activities (e.g. 'entertainment and culture' or 'sports') and find that travel depicts a major share in their environmental impacts (De Lauretis et al., 2017; Druckman et al., 2012). However, energy requirements differ across transport modes. For example, car travel is associated with high direct energy requirements, whereas walking or biking cause no direct energy requirements (mobitool, 2016).

Most studies which assess energy impacts of 'eating and drinking' (not considering 'food preparation') find that it is associated with high energy requirements (Druckman et al., 2012; Jalas & Juntunen, 2015; Yu et al., 2019), mainly because of indirect energy consumption and emissions "that arise along the food supply chain, including, for example, emissions due to fertilisers, pesticides and transportation" (Druckman et al., 2012, p. 155). Also 'repairs and gardening' have very high energy requirements due to energy embedded in equipment used (Druckman et al., 2012; Jalas & Juntunen, 2015; Yu et al., 2019).

Some 'phf care' activities have high energy requirements. For example, 'personal care' and 'food preparation' have very high energy requirements per time unit due to energy-consumption for cooking appliances and heating water for personal hygiene (De Lauretis et al., 2017; Druckman et al., 2012; Yu et al., 2019). Other common 'phf care' activities such as 'cleaning and tidying the house', 'washing clothes' and caring for others have lower energy requirements per time unit (De Lauretis et al., 2017; Jalas, 2002).

Common leisure activities (e.g. 'reading', 'watching TV', 'sports', 'spending time with family and friends') have relative low energy requirements per time unit which are caused by energy-consuming leisure equipment or the production of the equipment used (De Lauretis et al., 2017; Druckman et al., 2012; Jalas & Juntunen, 2015; Yu et al., 2019). However, leisure activities with high energy requirements exist such as motorized outdoor recreation (Aall, 2011). Also, leisure activities can have high energy requirements due to energy embedded in leisure services provided (e.g. running a theater) (Druckman et al., 2012). The increased materialization of leisure activities (e.g. through specialized equipment used for 'sport' activities) poses a risk for both, direct and indirect energy requirements of leisure activities Røpke and Godskesen 2007.

'Sleep and rest' has very low energy requirements because almost no energy-consuming equipment is used for it (De Lauretis et al., 2017; Druckman et al., 2012; Smetschka et al., 2019; Yu et al., 2019).

All home activities are associated with some energy requirements for heating, cooling and lighting the building. Smetschka et al. (2019, p. 7) allocate carbon emissions caused by housing to 'personal time' and find that "the carbon footprint [of personal time] per hour is still relatively low, simply because this is also the most time-consuming category, where 79% of it amounts to sleeping time".

The described studies allocate expenditures and associated energy impacts to an average time allocation pattern at a specific time period. However, there is a lack of data on marginal energy impacts of activities—energy impacts of a change in time use (e.g. due to TC). While the relation between time use and direct energy inputs is linear for some activities (e.g. driving a car), for other activities there is no direct correlation between energy inputs and time spent on an activity (e.g. playing a music instrument) (Jalas & Juntunen, 2015).

13.2.3 Research gaps

Based on the literature review, we can identify the following three research gaps:

(1) Most TC studies focus on travel impacts and only few studies on TC impacts non-travel activities and associated environmental impacts exist.
(2) Most TC studies focus on TC impacts on daily travel and only few studies on TC impacts on weekly travel exist. However, interactions between time use on workdays and weekends exist.
(3) Existing studies of environmental impacts of time use thoroughly assess the direct and indirect energy impacts and GHG emissions of activities at a specific point in time. Yet, little is known about the environmental impacts of a change in time spent on activities.

In this article, we demonstrate an approach to address the first two research gap by means of time-use data and discuss how it can be combined with environmental data to address the third research gap.

13.3. Approach

Conducting TC experiments to collect primary data of TC impacts on time use requires larger experimental set-ups. Another approach is to use secondary data from time-use studies which have already been conducted. We demonstrate a methodological approach to investigate interrelations between time spent on commuting and on other activities based on secondary time-use data. Thereby, we include travel and non-travel activities as well as daily and weekly activity times in the assessment.

13.3.1 Analysis of time-use data

Data selection and preparation

To demonstrate the approach, we use time use data from the Multinational Time Use Study (MTUS) by the Centre for Time Use Research at the University of Oxford (Gershuny & Fisher 2013). The MTUS aggregates data from various field studies which collected time-use data by asking individuals to keep diaries about the activities they performed on any given day. We use the harmonized aggregate file, in which each observation describes the number of minutes spent on 69 distinct activities on a diary day (the sum of time spent on all activities is 24 h or 1440 min). From this file, we selected the most recent time-use study which contained 7-day (full week) diaries, which is the time-use study from the Netherlands in 2005. Since the dataset does not contain information on TC adoption of diarists, we compare time allocation on workdays with different amounts of time spent on commuting. Thus, results do not provide information on effects of TC adoption but on interrelations between 'commute' time and time spent on other activities.

To compare full weeks with different 'commute' times, we created a second data set which sums up all daily observations of one weekly travel diary in one line (weekly dataset; the sum of time spent on all activities is 7 days or 10'080 min). Thus, each observation in the weekly dataset reflects time use of one diarist during one week.

We clustered all activities into nine main activity categories: commute, private travel, business travel, eating and drinking, work, leisure, phf care, sleep and rest, other (education, undefined use of time). For simplification, we use the term *activity* to refer to these *activity categories* in the following.

Time spent on commuting and on other activities depends on the employment status of individuals and can also differ on unusual workdays or during unusual workweeks. In order to focus the analysis on typical workers on typical workdays and in typical workweeks, we remove the following observations:

— days with 'business travel' in the daily dataset and weeks with more than 4 h 'business travel' in the weekly dataset,
— days/weeks for which 'commute' is larger than 4 h per workday or 20 h per week,
— days/weeks for which 'work' is smaller than 4 h per workday or 20 h per week, and
— observations of unemployed or retired people and students.

For the comparison of workdays with different 'commute' times we also removed weekends from the daily dataset.

Still, there might be various other factors which affected the time use of the diarists during the diary day and week, which are not captured in the time-use data (e.g. doctor appointments, picking up children from school). Plus, the choice of transport modes impacts time spent in transport; however, the data does not contain information on transport modes uses.

Also, other demographic and socio-economic factors influence time use of individuals (e.g. having a partner, household size, having children). As this analysis is done for demonstrative purposes, we do not control for other economic and socio-demographic variables. Thus, the results of this analysis should not be understood as an actual assessment of TC impacts on time use but a demonstration of the methodological approach we are proposing.

As the Dutch time-use survey recorded time use in 15-minute intervals, the variable 'commute' is discrete. To further reduce complexity and increase comprehensibility of results, we clustered 'commute' into seven daily and seven weekly 'commute' classes:

— daily 'commute' classes: 0; (0, 30]; (30, 60]; (60, 90]; (90, 120]; (120, 150]; (150, +∞)
— weekly 'commute' classes: 0; (0, 150]; (150, 300]; (300, 450]; (450, 600]; (600, 750]; (750, +∞)

As the 'no commute' classes shall contain observations of days and weeks, when people mainly worked from home, we also removed workdays on which diarist worked from locations different from home (or more than 4 h per week in the weekly dataset) and less than 4 h per workday from home (or 20 h per week in the weekly dataset)[5]. This step is required because the datasets do not capture information on TC adoption. Note that for the daily data set observations from one diarist can be part of different daily 'commute' class, whereas for the weekly data set, observations from one diarist can only be in one weekly 'commute' class.

The final daily dataset contains 2,695 workdays from 810 diarists and the weekly dataset 691 weeks from 691 diarists. Table 17 shows the number of observations by 'commute' class for both data sets.

Daily 'commute' class	0	(0, 30]	(30, 60]	(60, 90]	(90, 120]	(120, 150]	(150, +∞)
Number of observations	149	831	821	380	262	129	123
Weekly 'commute' class	0	(0, 150]	(150, 300]	(300, 450]	(450, 600]	(600, 750]	(750, +∞)
Number of observations	18	208	225	124	67	27	22

Table 17: Number of observations by 'commute' class in the daily and weekly dataset.

[5] 'Work´ time at home and other locations is captured separately in the MTUS dataset.

Data analysis

To demonstrate the approach, we conduct a graphical data analysis by plotting the average time spent on activities by time spent on commuting (clustered in 'commute' classes) and on other activities on a line chart (Figure 24, Figure 25).

Given the fact that most TC studies focus on daily travel and do not capture differences in time use between different days of the week (see 13.2.3), we also investigate differences in time use across 'commute' classes by day of the week (e.g. it is possible that people who commute less spend more time traveling on weekends). Therefore, we cluster all observations in the daily dataset according to the weekly 'commute' classes and plot for each 'commute' class the average time spent on activities by day of the week (Figure 26).

13.3.2 Energy impacts

Finally, we discuss the direct energy impacts of substituting commuting with other activities based on the literature summarized in 13.2.2. We do not quantify the impacts due to a lack of data on marginal energy impacts of activities.

13.4. Results

13.4.1 Time-use analysis

Time spent on travel and non-travel activities on a workday by 'commute' class

Figure 24 shows the average time spent on an activity on a workday clustered into 'commute' classes.

Less time spent on commuting on a workday seems to be associated with more time spent on 'sleep and rest', 'leisure', 'phf care', 'private travel' and 'eating and drinking'. Differences in time spent on 'leisure' and 'phf care' on a workday across 'commute' classes are on average higher than for other activities. 'Work' shows a different pattern: higher daily commute time is by tendency associated with higher 'work' time. However, on days when people commute very long, they work less.

Weekly time spent on travel and non-travel activities by 'commute' class

Figure 25 shows the average time spent on an activity during one week clustered into 'commute' classes.

For 'sleep and rest', 'leisure', 'phf care', 'eating and drinking' and 'private travel' we can observe similar patterns as in the comparison of workday activity times.

Two major differences between daily and weekly data can be observed: (1) The magnitude of the lines is different, because on weekends people usually don't work and have more 'leisure' and 'phf care' time. (2) For weekly data, the 'no commute' class differs from all other observations. Working from home all week is associated with spending more time on 'work' and 'eating and drinking' and less time spent on 'leisure' and 'phf care'.

Note that, in the analysis of workday activity times (Figure 24) observations from one diarists can be clustered to different 'commute' classes. Thus, differences between 'commute' classes reflect also within-person differences and can only be used to compare differences in time allocation between days with different commute times. In the analysis of weekly activity times (Figure 25), observations from one diarist are only assigned to one weekly 'commute' class. Thus, differences between 'commute' classes reflect between-person differences. As such, the weekly 'no commute' class might represent a very specific group of people, for example self-employed people, which can be an explanation for observed differences.

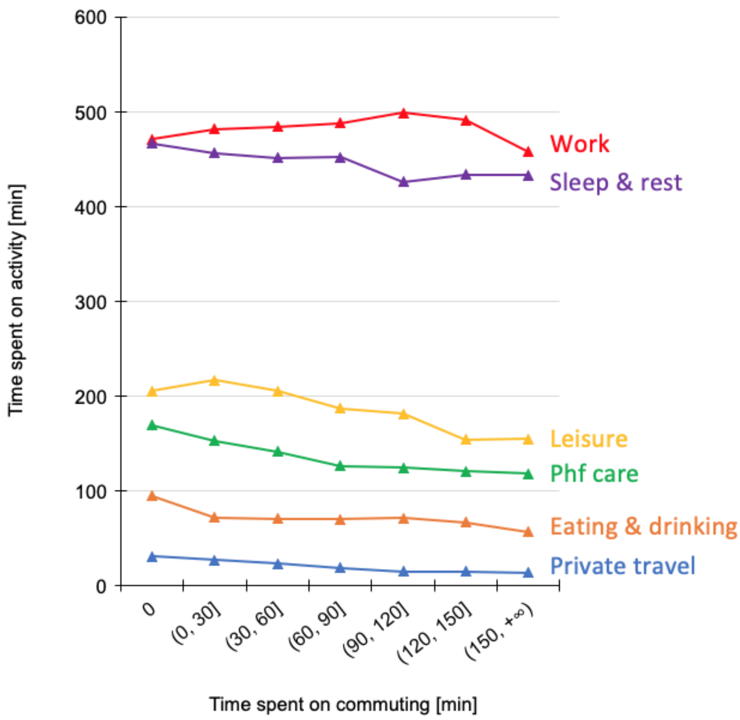

Figure 24: Average time spent on an activity on a workday by ‘commute’ class.

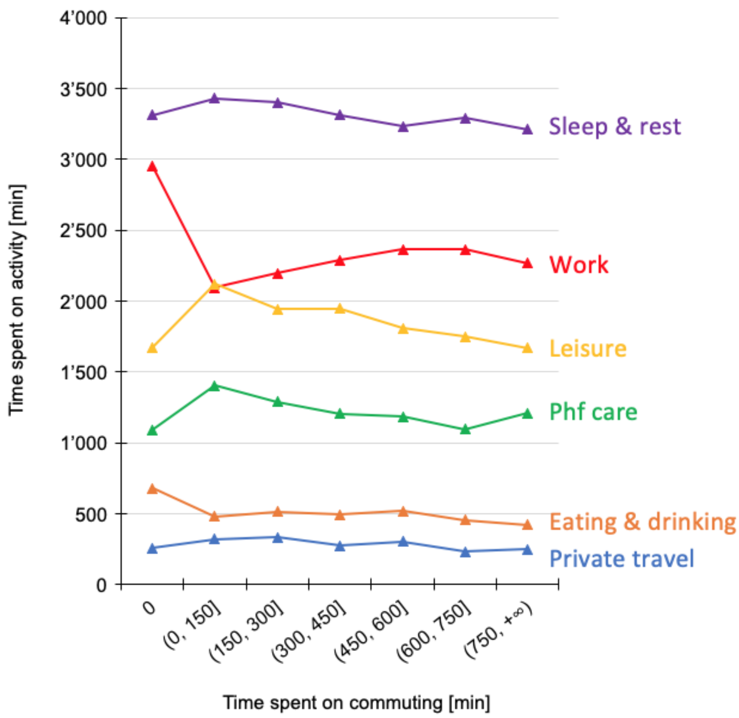

Figure 25: Average time spent on activity during one week by ‘commute’ class.

Time spent on travel and non-travel activities by day of the week and 'commute' class

Figure 26 shows the average time spent on an activity by weekly 'commute' class and day of the week. 'Commute' classes are coded with a color gradient from little (bright yellow) to a lot of time spent on commuting (dark red). Note that each activity chart has a different value range. As in Figure 25 differences between 'commute' classes reflect between-person differences.

Again, we can observe an interrelation between time spent on commuting and time spent on other activities by day of the week. People who spend less time on commuting during a week spend more time on 'private travel' on workdays. In all 'commute' classes time spent on 'private travel' is higher on weekends than on workdays. Interestingly, people who spend a lot of time on commuting—(750, +∞) 'commute' class—spend much more time on 'private travel' on Saturdays than people who commute less; whereas, people who do not commute ('no commute' class) spend the lowest amount of time on 'private travel' on Saturdays.

Unsurprisingly, 'work' time is much lower on weekends than on workdays for all 'commute' classes. The 'no commute' class differs from all other classes; that is, people who do not commute at all spend more time on 'work' on weekends than people who do commute.

People who do not commute at all during the week spend on average more time on 'eating and drinking' than people who do commute. For all 'commute' classes, no large differences in time spent on 'eating and drinking' between weekends and workdays exist.

The patterns of 'leisure' and 'phf care' are similar. Spending less time on commuting during a week is associated with spending more time on 'leisure' and 'phf care' on workdays. For all 'commute' classes, time spent on these activities is higher on weekends than on workdays. Again, the 'no commute' class differs: people who do no commute at all, spend less time on 'leisure' and 'phf care' on weekends than people who do commute.

No clear differences in time spent on 'sleep and rest' across 'commute' classes can be observed; For all 'commute' classes, time spent on 'sleep and rest' is slightly higher on weekends than on workdays.

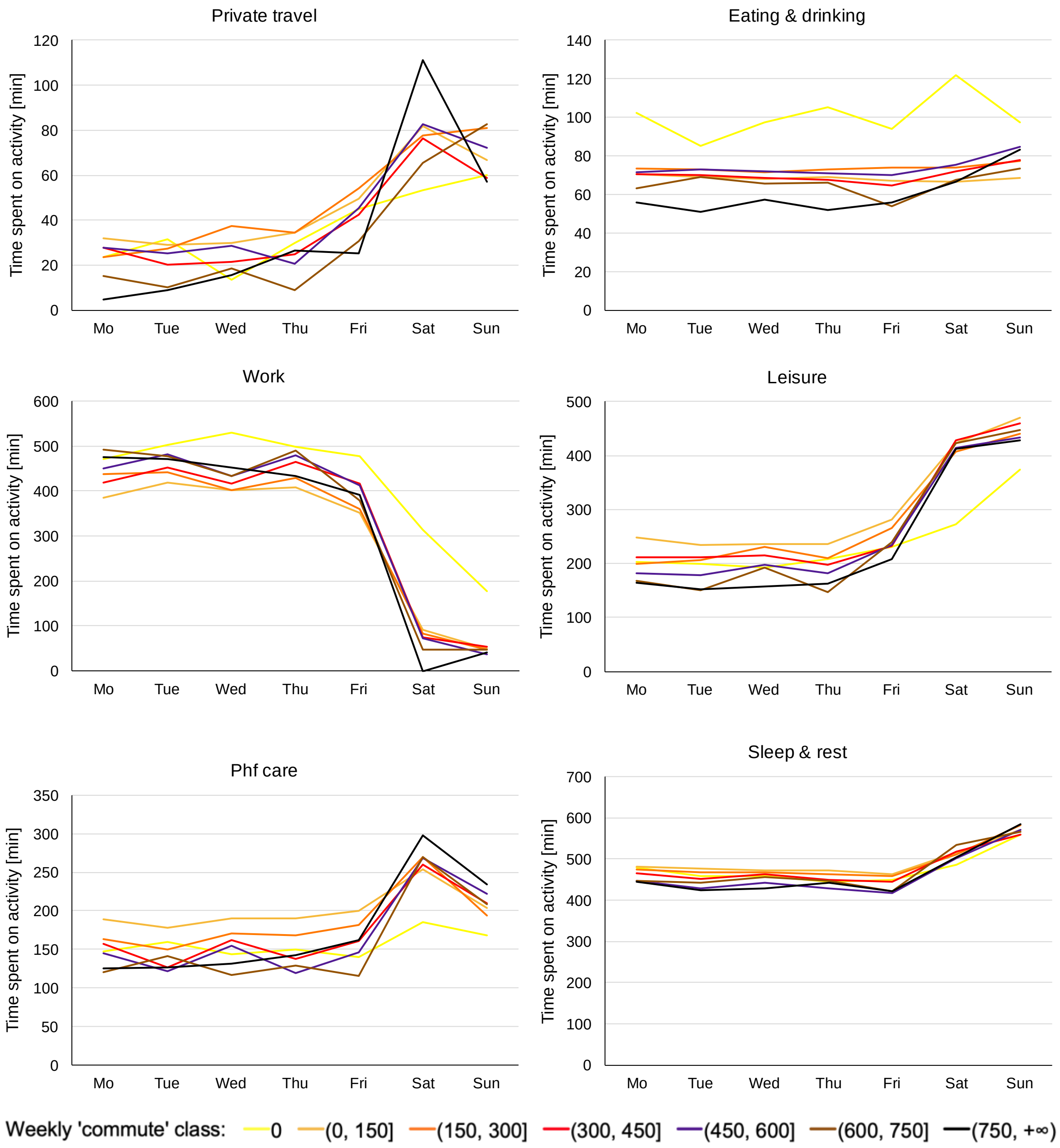

Figure 26: Average daily time spent on activity by day of the week and weekly 'commute' class (time spent on 'commute' during the whole week).

13.4.2 Impacts of changes in time use on energy requirements

Impacts of changes in 'commute' time on energy requirements of travel and non-travel activities depend on marginal direct and indirect energy requirements of activities. In the following, we discuss marginal direct and indirect energy impacts of substituting commuting with other travel and non-travel activities based on literature on environmental impacts of time use summarized in 13.2.2.

Travel-related direct energy impacts

Direct energy requirements of travel activities are proportional to the time spent on travel (e.g. driving a car longer increases fuel consumption) (Jalas & Juntunen, 2015). However, transport modes differ in their direct energy requirements. Direct energy requirements of car commuters are significantly higher than those of pedestrians, cyclists or users of public transport (mobitool, 2016). As such, energy savings through commute reductions are highest for users of individual motorized transport (e.g. cars), lower for users of public transport and zero for pedestrians and cyclists (assuming no e-bikes are used).

When estimating travel-related energy savings through changes in 'commute' time, possible changes in transport mode choice also have to be taken into account. For example, a commuter who usually buys groceries at a train station when changing commuter trains might drive to a grocery store by car when he or she works from home.

Direct energy impacts on non-travel activities

Marginal energy impacts of non-travel activities depend on:

(1) Changes to the use of energy-consuming 'household appliances and leisure equipment'
(2) The power consumption of the appliances and the equipment

While there is a lack of data on impacts of changes in time use on use of energy-consuming goods and services, we can discuss direct energy requirements of non-travel activities based on the literature summarized in 13.2.2, data on common activities in the Netherlands and energy requirements of appliances and equipment.

Phf care: In the Netherlands, common 'phf care' activities are 'cooking', 'tidying up and cleaning', 'doing the laundry' and 'looking after children' (Roeters, 2018a).

While 'tidying up and cleaning', 'doing the laundry' and 'looking after children' have relative low direct energy requirements compared to (motorized) travel, energy requirements of cooking are high (De Lauretis et al., 2017; Druckman et al., 2012; Yu et al., 2019). This poses a risk for reducing energy requirements through TC as working from home can increase meal preparation at home. Albeit, this switch can also have a decreasing effect on energy requirements of cooking at places where telecommuters eat when they do not work from home (e.g. the employer's cafeteria).

Leisure: Most common leisure activities in the Netherlands and other European countries are 'watching TV', 'reading', 'meeting friends' and 'doing sports' (Aall, 2011; Jalas, 2002; Roeters, 2018b; Wennekers et al., 2016), which all are estimated to have lower direct energy requirements than (motorized) transport (De Lauretis et al., 2017; Druckman et al., 2012; Jalas & Juntunen, 2015; Yu et al., 2019), because these require none or only low-energy equipment. Still, leisure activities which require energy-intensive equipment or services exist (e.g. motorized outdoor recreation) (Aall, 2011; Druckman et al., 2012). Thus, substituting commuting with common leisure activities only poses a risk for increasing energy requirements if people use highly energy-intensive equipment or services or start operating many energy-consuming leisure devices in parallel.

Eating and drinking: Direct energy requirements of 'eating and drinking' are low, because it does not require use of energy-consuming appliances (Druckman et al., 2012; Jalas & Juntunen, 2015; Yu et al., 2019). Spending more time eating only increases total energy requirements if more food is then consumed or people increase their use of 'eating and drinking' services (e.g. food delivery, going to restaurants); however, these are both indirect energy requirements. Thus, spending more time on 'eating and drinking' due to saved commuting can be expected to reduce direct energy requirements. Still, there seems to be a risk for increasing indirect energy requirements.

Sleep and rest: 'Sleep and rest' has very low direct energy requirements, because almost no energy-consuming equipment is used for it (De Lauretis et al., 2017; Druckman et al., 2012; Smetschka et al., 2019; Yu et al., 2019).

Work: In principle, TC can impact energy consumption in the employer's office (e.g. due to electricity required to power ICT equipment) and at home. In a consumption-oriented perspective, all energy consumption for 'work', no matter if at the employer's office or at home, needs to be allocated to the final consumption of the goods or services produced. Thus, changes in the energy requirements of 'work' would change the energy embedded in goods and services consumed to perform other activities. This impact depends on complex supply-demand relationships and has not been addressed in any of the studies of environmental impacts of time use.

Heating, cooling and lighting of buildings: Residential energy consumption in EU households is mainly caused by space and water heating, lighting and appliances, cooking, space cooling and other energy consumption (eurostat, 2019). Working from home increases time spent at home and, thus, can affect residential energy consumption. However, heating impacts depend on the presence of other people at home (e.g. spouse, children) during the day and on common heating patterns in the region in question. Only if people actually reduce heating energy consumption when they are not at home (e.g. by manually turning off heaters before leaving the dwelling) does increased occupancy increase heating energy consumption. In some cases, increased occupancy can even reduce heating energy consumption due to body heat of occupants (Hinchey, 2019).

According to a study in the Netherlands in 2000, the presence of residents during weekdays increases the energy consumption for space and water heating by 2,722 kWh/year (= 7.5 kWh/day) (Guerra Santin et al., 2009). In contrast, driving alone in a gasoline car requires roughly 1.5 kWh per person-kilometer (mobitool, 2016). Thus, changes in residential energy consumption due to increased occupancy can be relevant.

Overall assessment: Based on existing literature on direct energy requirements of activities, we find that substituting motorized commuting with many common 'leisure' and 'phf care' activities, 'sleep and rest' or 'eating and drinking' can be expected to reduce direct energy requirements. Highest risks for increasing direct energy requirements through this substitution are due to increased 'travel for other purposes', 'cooking at home', 'energy-intensive leisure activities' and an increase in energy required for heating, cooling and lighting buildings. An early study of the impact of time-saving household appliances on residential energy consumption in Canada in 2003 found that "households with time-saving appliances adjust the amount of time they allocate to using some leisure appliances in the home"; however, the study does "not find evidence that would suggest that ownership of a time-saving appliance results in an increase in residential energy use" (Brenčič & Young, 2009, p. 2866).

However, for people who usually bike or walk to work, direct energy savings through reduced commuting are zero. Thus, any additional energy impact due to substitute activities, increases net direct energy requirements. As such, direct energy savings due to a reduction in commute time depend on the commuting mode choice of individuals, which can be very different across regions. In the Netherlands in 2015 75% of commute kilometers were travelled by car, 12% by train and 6% by bicycle (Statistics Netherlands, 2015). Therefore, for the average Dutch commuter, reducing commute time yields a reduction in fuel consumption.

Still, actual direct energy impacts of substituting other activities for commuting depend on marginal direct energy requirements of activities which in turn depend on the actual impact of changes in time use on use of energy-consuming appliances. This relationship needs to be researched further.

Indirect energy requirements

Changes in time use only impact total indirect energy requirements if the production of goods and services used for activities changes. If the utilization of a durable good—the share of time the good is in productive use—increases, the indirect energy requirement per time unit decreases; yet total indirect energy requirements remain constant (Bieser & Hilty, 2020, p. 5). For example, car sharing can increase the time a car is in productive use. Thus, indirect energy requirements (the energy required to produce the car) per time unit decrease. If the total number of produced cars (and vehicle-miles traveled) does not change, no change in total indirect energy requirements can be expected. However, little is known about the impact of reducing commute time on purchase of goods and services. This relationship also needs further investigation.

13.5. Discussion

In the following, we discuss advantages and limitations of using time-use data for assessing energy impacts of TC.

13.5.1 Using time-use data for analyzing travel and non-travel impacts of telecommuting

Using time-use data, we were able to assess associations between time spent on commuting and other activities and thereby address some of the main research gaps in existing TC literature.

First, we could include non-travel activities in the assessment. This is important because not only travel activities, but also non-travel activities cause environmental impacts.

Also, we could assess weekly travel and non-travel time use and thereby implicitly capture interaction between weekdays and weekends. This was possible, because the Dutch time-use data captured full-week time-use diaries. Most existing TC assessment focus on daily activity times.

Some time-use studies collect data from more than one household member. In principle, such data can be used to investigate time use of household members of telecommuters, which is debated in TC literature (Hamer et al., 1991; Kim et al., 2015). Some time-use studies also capture activity sequences, which could be used to investigate temporal, spatial and sequential changes in travel (e.g. telecommuters might postpone commutes to a later time of day to avoid rush hours).

A drawback of using time-use data to assess time-use impacts of TC is that most time-use studies collect cross-sectional data and do not capture information on TC behavior explicitly. Such data does not allow to make causal inference about impacts of time spent on commuting (or even TC) on time use for other activities. This is also the case in our example demonstration: We use Dutch time-use data to compare time allocation on days with different 'commute' times and between people with different 'commute' times; however, whether individuals actually change their behavior due to changes in 'commute' time (or even TC adoption) cannot be assessed. Still, the data provides indications for possible interrelations between commute times and time spent on other activities.

Also, only little time-use data from recent years is available. We used Dutch time-use data from 2005, which was the most recent data set in the MTUS, one of the biggest collections of time-use data, which captured full-week diaries.

For demonstrating the approach, we focused on typical workers and excluded, for example, unemployed people or students. Comprehensive TC assessments using time-use data should control for further demographic and socio-economic characteristics, which can have an effect on individual time use (e.g. 'having a child' or 'cohabiting' can impact time spent on 'phf care'). Most time-use studies collect data on economic and socio-demographic characteristics (e.g. vehicle ownership, number of children in household, job type) of individuals, which can be used in such assessments. Special care should be granted to the transport modes used, which impact time spent in transport and energy requirements of commuting. The data used in this study, did not capture the transport modes.

Still, the graphical time-use analysis demonstrates that time-use data can be used to observe interrelations between commute time and time spent on other activities. It shows that there is an unexploited potential to use time-use data for assessing travel and environmental impacts of TC and other ICT use cases that affect time allocation, which is the purposes of this study.

13.5.2 Assessing direct and indirect energy impacts of changes in time spent on commuting and on other activities

A large amount of literature on environmental impacts of time use, focusing on travel and non-travel activities, exists. As Minx and Baicocchi (2009, p. 823) put it, time-use data "is a very good anchor for linking other models or information from other data sources" such as environmental data.

In most TC literature, impacts of changes in 'commute' time on non-travel activities, and their environmental impacts are out of scope. Thus, there is potential to close this research gap by linking time-use and environmental data. We demonstrate this possibility by qualitatively assessing direct energy impacts of substituting other activities for commuting. Based on existing literature on energy impacts of activities we could identify some main risks for increasing direct energy requirements through TC. These risks are that saved commute time is spent on 'travel for other purposes', 'cooking at home' and 'energy-intensive leisure activities'. Also, a possible increase in 'residential energy consumption' should be included in energy assessments of TC. If commuting is replaced with common 'leisure' activities in the Netherlands, 'caring for others', 'sleep and rest' or 'eating and drinking', there is a high potential for a reduction in direct energy requirements.

These results are based on commonalities of results of studies of direct energy impacts of time use from various time periods and regions; still, differences between regions and time periods are possible. In order to conduct comprehensive, and specifically quantitative energy assessments of TC from a time-use perspective data on marginal energy requirements of activities is required, which has not been in scope of most studies of environmental impacts of time use. Estimating marginal direct energy requirements requires data on impacts of changes in time use on use of energy-consuming appliances, while estimating marginal indirect energy requirements requires data on impacts of changes in time use on purchase of goods and services. Gathering this data and drawing robust conclusions is challenging as the behavioral response due to changes in time use can be very different for different time-use categories (e.g. a change in 'commute time' can have other consequences than a change in 'housework time'), for individuals with different demographic and socio-economic characteristics (e.g. individuals with and without children) and also depends on individual preferences and needs.

13.6. Conclusion

The assessment of indirect environmental effects of ICT faces various methodological challenges such as the consideration of rebound effects. In this paper, we demonstrate the time-use approach to assess energy impacts of TC by assessing interrelations between time spent on commuting and on other activities. We show that time-use data can help to assess indirect environmental effects of ICT from a time-use perspective. For the special case of TC, time-use data can help to address some existing research gaps in TC literature such as the assessment of changes in time spent on non-travel activities and the consideration of interactions between time use on workdays and on weekends. In fact, a qualitative energy assessment of substituting other activities for commuting shows that energy impacts of non-travel activities matter, because several non-travel activities (e.g. 'cooking', 'energy-intensive leisure') are associated with high direct and indirect energy requirements. Thus, quantitative energy assessments of TC have to include both, energy impacts of travel and non-travel activities, that can change due to the reallocation of saved commute time.

In order to conduct comprehensive, quantitative assessments of indirect environmental effects of ICT, further research on marginal energy requirements, specifically on the relationship between time spent on a given type of activity and the use and purchase of goods and services is required. If future research explores these relationships further, the time-use approach can not only be a key element in assessing energy impacts of TC considering travel and non-travel impacts, but also be used for environmental assessments of various other ICT applications which impact individual time allocation.

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14 Impacts of telecommuting on time use, travel and energy: A case study of co-working in Stockholm

Bieser, J., Vaddadi, B., Kramers, A., Höjer, M., & Hilty, L. (2020). Impacts of telecommuting on time use, travel and energy: A case study of co-working in Stockholm. Submitted for publication.

Abstract: While existing TC research heavily discusses travel impacts of home-based TC, little is known about the impacts of working from a local CW sace on travel and non-travel activities and their energy impacts.

We conduct a case study of time-use and travel impacts of a CW living lab in a suburb of Stockholm. Based on time-use data collected from 20 telecommuters, we identify differences in time-use and travel patterns depending on the work location (employer's office, CW space, home office). We discuss the impacts of these differences on the direct energy requirements associated with various activities performed.

The results indicate that, on average, the telecommuters reduce travel-related direct energy consumption on days when working from the CW space or from home, compared to days when working from the employer's office. This is because the CW telecommuters spend less time in transport and normally use the same commute transport mode on TC days or even a less energy-intensive one. For example, some telecommuters switch to biking or walking on CW days, which is feasible because the CW space is in the local neighborhood.

Based on these results, we conclude that working from a local CW space and from home have the potential to reduce energy consumption, provided that telecommuters reduce travel time, use low-energy transport modes on TC days, that the total (heated, cooled) office space needed across all work locations does not increase, and telecommuters do not spend the money and time saved on other highly energy-intensive activities.

Keywords: Telecommuting, co-working, time use, living lab, energy consumption, information and communication technology.

Highlights:

- Impacts of working from home or a local co-working space on time use and travel
- Travel time on TC days is shorter than on employer office days
- Many telecommuters use commute transport modes that are equally or less energy-intensive on TC days
- Discussion of energy impacts of TC from a time-use perspective

14.1. Introduction

Digital ICT enables new forms of producing and consuming goods and services, which can have both positive and negative impacts on the environment (Bieser & Hilty, 2018c). A promising ICT application to reduce environmental impacts is TC by remote access to data, which enables workers' virtual presence to replace their physical presence at the employer's office and thus avoids physical commuting. In line with the South Coast Air Quality Management District (California), Mokhtarian (1991, p. 11) defines TC as "working at home or at an alternate location and communicating with the usual place of work using electronic or other means, instead of physically traveling to a more distant work site".

Home-based TC (or home office) has been adopted by many companies worldwide and discussed in research for decades. Working from a CW space, another special case of TC, is an increasingly viable solution for companies as the number of CW spaces worldwide increases (deskmag, 2019). CW "describes any situation where two or more people are working in the same place together, but not for the same company" (DTZ, 2014, p. 3). CW spaces are "shared workplaces utilised by different sorts of knowledge professionals […] working in various degrees of specialisation in the vast domain of the knowledge industry" (Gandini, 2015, p. 194).

The idea of CW spaces evolved in the 1980s. Since then, there has been a growing demand for CW which has been met by an increasing number of CW space providers ranging from smaller companies operating only one CW space up to multinational CW space providers such as WeWork (Haucke & Östmarck, 2017). The 2019 Global Co-working Survey estimated that by the end of 2019, 2.2 million people worked in 22,000 CW spaces worldwide, hosting 90 members on average (deskmag, 2019). In Sweden, the website coworker.com (2020) currently lists 93 CW spaces.

The idea that TC can reduce environmental loads by reducing physical commuting and the related energy consumption and emissions has been discussed for a long time (Höjer, 2002; Lachapelle et al., 2018; Mokhtarian et al., 1995; O'Keefe et al., 2016). However, TC can also increase energy consumption, which can diminish the environmental gains associated with the reduction in physical commuting. In fact, telecommuters will spend time not spent on commuting on other activities such as 'private travel' or 'leisure', which are associated with their own environmental impacts (a pattern known as the time rebound effect) (Binswanger, 2003; Brenčič & Young, 2009; Jalas, 2002; Sorrell & Dimitropoulos, 2008). Special attention has to be given to transport modes, since their energy impacts differ strongly. TC can even be viewed as an additional transport mode that competes in a dynamic system with the physical ones, which include both individual and public transport (Hilty et al., 2004).

While several studies have investigated TC impacts on travel (Glogger et al., 2008; Lachapelle et al., 2018; Roth et al., 2008; Tanguay & Lachapelle, 2019), there are fewer studies on TC impacts on time spent on other activities such as 'leisure' or 'everyday chores'. Also, most research has focused on the travel impacts of home-based TC, whereas there are only a few studies on the environmental travel impacts of working from CW spaces in residential neighborhoods. Considering that many CW spaces are located in city centers, people living in suburbs would still face a significant commute when working from there.

The aim of this article is to explore the potential and actual time-use, travel, and energy impacts of working from home or a CW space in a residential neighborhood. The results will help to identify conditions under which TC at a larger scale can be a viable approach to reduce environmental impacts.

We first summarize related work in the field and derive research questions based on the research gaps identified (section 14.2). We then answer the research questions using data from a living lab CW space in a residential neighborhood in the south of Stockholm. For comparison, we use time-use data from a larger Swedish population sample (sections 14.3 and 14.4). We discuss the travel, non-travel, and energy impacts of TC in light of the results of this analysis (section 14.5) and provide a conclusion (section 14.6).

14.2. Related work

In the following, we summarize related work on TC impacts on travel (14.2.1) and non-travel activities (14.2.2), both for TC in general and for the specific case of CW (14.2.3). In addition, we summarize work on energy impacts of travel and non-travel activities (14.2.4).

14.2.1 Telecommuting impacts on travel

The impact of TC on travel has been studied for decades. Most studies conducted before 2000 focus on North America and Europe (Hamer et al., 1991; Koenig et al., 1996; Roth et al., 2008). TC has gained more attention in Asia in the last two decades (Jaff & Hamsa, 2018; Kim, 2017; Kim et al., 2012; Ma et al., 2019), but research activity in North America also remained high (Chakrabarti, 2018; Hu & He, 2016; Shabanpour et al., 2018; Tanguay & Lachapelle, 2019; Zhu et al., 2018).

Several early studies find that TC reduces travel (e.g. Hamer et al. (1991), Glogger et al. (2008), O'Keefe et al. (2016), Jaff and Hamsa (2018), Shabanpour et al. (2018)); however, in recent years, various analyses indicate that TC leads to an increase in work and non-work trips (e.g. Chakrabarti (2018), He & Hu (2015), Hu & He (2016), Zhu (2012)). A frequently discussed question in such studies is whether telecommuters live further away from their work location and thus cover a greater commuting distance. For example, a study by Zhu (2012) based on U.S. household travel data from 2001 and 2009 indicates that TC increases daily work and non-work trip duration, frequency, and distance. The study suggests that telecommuters live further away from work than non-telecommuters and have higher travel budgets which are reallocated to travel for other purposes when they telecommute (Zhu, 2012). Also, Chakrabarti (2018, p. 19) argues that "telecommuting can increase non-motorized travel and physical activity" and that "[i]ncrease in transit ridership and reduction in VMT [vehicle-miles traveled] are not automatic".

Moreover, the causal relationship between TC adoption, residential relocation, and travel is not unidirectional. For example, a study using 2006 household travel data from Seoul analyzes the relationship between TC and residential location and finds that telecommuters tend to live in more outlying areas than non-telecommuters (Kim et al., 2012). The authors argue that the offices of companies allowing TC tend to be located in more outlying areas and that telecommuters, being in later stages of their lives, live closer to their work location. This is supported by evidence of telecommuters' commuting distances being shorter than those of non-telecommuters. Also, De Abreu e Silva and Melo (2018) argue that relocation decisions are mostly driven by factors other than TC. In an early study, Höjer (2000) argues that if people become better 'telecommunicators' over time (i.e. they improve their skills in communicating at a distance) in combination with a shift toward network organizations, then this changes the preconditions for TC, and its impact on travel behavior can change as well. The current COVID-19 pandemic shows that many people are already skilled 'telecommunicators'—these skills are now being put into practice at a new level.

When assessing travel impacts of TC on a household level, various factors, such as car availability or impacts on household members, should be taken into account. In a review of early TC studies, Mokhtarian et al. (1995, p. 293) state that "[t]here is no evidence that household travel increases. In view of the fact that at least in the U.S. studies, TC households tend to have nearly one vehicle per licensed driver, the availability of the telecommuter's auto may be expected to have a negligible impact on household tripmaking". This relationship was investigated further in a later study in the Seoul Metropolitan area: Kim et al. (2015, p. 197) find that increased car availability due to TC is relevant in households with less than one vehicle per household member because "in such households (with insufficient vehicles available), the vehicle otherwise used for mandatory travel, such as for the household head's commute, can be used for non-commute purposes or by other household members if the household head does not use it for commuting". In an early TC study in the Netherlands, Hamer et al. (1991) find that household members' travel does not increase. This is explained by the observation that household members perceive an increased "hominess" feeling and travel less when the telecommuter is at home. These results emphasize that the validity of the arguments presented in the studies depends on differences between time periods as well as on geographical and cultural differences between the regions under study.

14.2.2 Telecommuting impacts on non-travel activities

TC impacts on non-travel activities have been less researched than impacts on travel activities. Both early and recent studies show that shorter commute time (including TC) is associated with more time spent on non-travel activities such as shopping or leisure (Fujii & Kitamura, 2000; Gould & Golob, 1997; He & Hu, 2015; Kuppam & Pendyala, 2001; Paleti & Vukovic, 2017), which is not surprising in view of the 24-hour time budget constraint. One study examines the direction of the causal relationship using 2010/11 household travel data from the New York metropolitan region and argues that people who decide to participate in non-mandatory activities (e.g. leisure and maintenance activities) on a given day are more likely to decide to telecommute on that day (Asgari & Jin, 2017). A study using the same data shows that telecommuters spend more time on non-mandatory activities, that full-day telecommuters spend more time on discretionary ones, and part-day telecommuters more time on maintenance and shopping activities (Asgari et al., 2016). In contrast to this, a study using spatial equilibrium model finds that the commute time saved is mainly used for additional work and not for leisure (Rhee, 2008). Other studies investigate the impact of TC on the temporal and spatial distribution of activities and find that TC does not have a large effect on the timing and location of non-mandatory activities (Asgari et al., 2019) and that part-day telecommuters tend to shift their commute from the morning to midday (Asgari & Jin, 2018).

14.2.3 Working from co-working spaces

Most TC studies focus on home-based TC. There are only a few studies on travel and non-travel impacts of CW. Existing studies on CW often focus on other aspects, such as different types and locations of CW spaces (e.g. Kojo & Nenonen 2016, Mariotti et al. 2017), motivations and preferences of co-workers (e.g. Stam and Vrande 2017, Weijs-Perrée et al. 2019), and the impacts of CW on productivity and well-being (e.g. Houghton et al. 2018). Yu et al. (2019) provide a systematic literature review of future flexible working models (with the use of CW spaces as a special case) and their impact on the urban environment, the economy and urban planning.

Some early studies of travel impacts of CW exist. Two of these were conducted in the U.S.. A TC center project in Washington state showed that the number of VMT decreased from 63.25 miles per person-day on non-TC days to 29.31 miles on TC center days, mainly driven by reduced commuting, and no significant change in non-commute-related VMT. The study concludes that "center-based telecommuters behave as conventional commuters in terms of their number of trips, but are more similar to home-based telecommuters in terms of VMT reductions" (Henderson & Mokhtarian, 1996, p. 29).

Balepur et al. (1998) use data from the Neighborhood Telecenter Project (a project which established 15 telecenters in California) to assess travel impacts of TC centers and find the following:

— Average weekday VMT decreased by 17%.
— Non-commute trips on TC days decreased, but VMT increased because telecommuters switched from other modes to driving alone on TC days.
— On TC days, telecommuters drove shorter distances, but made more trips due to lunch breaks at home.

A study conducted in the same project also finds that walking and biking shares increased on TC days compared to no-telecommute days (Mokhtarian & Varma, 1998).

A recent study applying an agent-based model to the case of workplace sharing in Aberdeenshire, Scotland finds that allowing employees to work remotely, i.e. not at the employer office, has the potential to reduce commute times (Ge et al., 2018). The largest reductions in commuting are possible if all workers can choose their work location freely. If physical interaction between colleagues is required, a "culture where team members collectively decide on the common worksite is necessary" in order to reduce commuting (p. 96).

14.2.4 Energy impacts of activities

Environmental assessments of TC have been conducted for decades and usually focus on energy or emission impacts of the changes in travel behavior (Glogger et al., 2008; Mokhtarian et al., 1995; O'Keefe et al., 2016; Shabanpour et al., 2018). However, non-travel activities are also associated with energy requirements and energy-related emissions. Every activity has direct and indirect energy requirements. While direct energy requirements are caused by the direct consumption of electricity or fuels during the activity, indirect energy requirements are embedded in the goods and services used to perform an activity, such as the energy required to produce a car or an electronic device (Bieser & Hilty, 2020; Jalas, 2002). Energy assessments of TC provide a complete picture only if they consider both the direct and the indirect energy requirements of the goods and services consumed by individuals before and after adopting TC (Bieser & Hilty, 2020).

Various researchers investigate direct and indirect energy requirements of everyday activities (Aall, 2011; De Lauretis et al., 2017; Jalas, 2002; Jalas & Juntunen, 2015; Nässén & Larsson, 2015). Comparisons of the results of such studies are limited by differences in the time periods and regions investigated, the set of activities analyzed, aggregation of activities to activity categories, and the scope of energy requirements considered (direct vs. indirect). Still, most studies conclude that the direct and indirect energy requirements of travel are much higher than the energy requirements of most other activities (Aall, 2011; De Lauretis et al., 2017; Jalas & Juntunen, 2015). However, the energy requirements of transport modes differ significantly. While the direct energy requirements of car travel are high, they are lower for public transport and zero for walking and biking (mobitool, 2016).

Jalas and Juntunen (2015) recognize that the relationship between time use and energy inputs is linear for some activities (e.g. driving a car longer increases fuel consumption), but for other activities there is no direct correlation between the energy inputs and the time spent on an activity (e.g. playing the piano). Thus, if TC leads to an increase in time spent on non-travel activities, the net energy impacts depend on the marginal energy requirements of these activities with respect to the time allocated to them.

An early study of the direct and indirect energy impacts of changes in money and time expenditure due to changes in work time considers that only some energy requirements are proportional to the amount of time spent on an activity (Nässén & Larsson, 2015). The results show that reducing work time by 1% increases energy use by 0.06% due to the reallocation of time to other activities and by 0.8%

due to the reallocation of money to other goods and services. This indicates that time rebound effects of TC are lower than income rebound effects.

14.2.5 Research gaps and research questions

To summarize, three main research gaps exist:

(1) Most studies focus on travel impacts of TC, and only very few studies consider non-travel activities.
(2) Only a few studies on impacts of working from local CW spaces exist, indicating that CW can lead to a reduction of transport time and distance. However, these studies are relatively old, focus mainly on the U.S. and do not consider non-travel activities.
(3) Existing studies on energy impacts of activities do not consider the marginal energy impacts of non-travel activities.

This study contributes to closing the first two research gaps by answering the following research questions:

RQ 1: When people save time for commuting by working from home or from the co-working space, to what activities do they allocate the time saved?

RQ 2: What transport modes are used on employer office, co-working, and home office days?

We also briefly discuss TC impacts on the marginal energy requirements of travel and non-travel activities and thereby address the third research gap to some extent.

14.3. Materials and methods

We use time-use diary survey results from 20 participants in the CW living lab in Stockholm to investigate travel and non-travel impacts of working from the CW space and from home and compare the results with time-use and travel patterns of individuals of a larger sample of Swedish residents taken from the Swedish Time Use Survey.

14.3.1 Co-working time-use data

Co-working living lab

The CW living lab is a CW space in Tullinge, south of Stockholm, which offers 14 workplaces plus conferencing facilities (e.g. telephone booths, meeting rooms). The aim of the living lab is to investigate the effects of having a professional CW space near the participants' homes on their travel behavior. The space started operation in January 2019 and as of February 2020, 44 people regularly work from there. Most of these participants are employed by an IT company which has its headquarters in Kista, north of Stockholm. Since living in proximity to the CW space was a requirement for participating, all participants from this company save commute time on days when they work from the CW space instead of the headquarters (Figure 27). The following analysis is based on the data collected from this specific group of participants.

Figure 27: Location of headquarters of IT company in Kista and the co-working space in Tullinge.

Analysis of time-use diaries

During three weeks between September and November 2019, 20 participants of the IT company kept time-use diaries on weekdays and weekends. Participants had to indicate which activities they performed in 15-min intervals and how much time they spent in 11 different transport modes during the diary day. The diary distinguished the following activities:

- work (differentiated into work from the CW space, from home, the employer office, and 'meetings outside the office')
- travel
- everyday chores
- leisure

We excluded diary days if the total recorded time was less than 8 h (low-quality record), days for which work was less than 4 h or travel was more than 4 h (atypical workdays), and days with more than one work location. The resulting dataset includes 244 diary days from 20 diarists.

Some answers are inconsistent because travel time by transport modes and total daily travel time were covered by different questions in the survey. We calculated the 'share of travel time by transport mode' based on responses to 'travel time by transport mode' and calculated 'absolute time spent in transport modes' based on the 'share of travel time by transport mode' and responses to 'total daily travel time'.

We also compared preferred commute transport modes[6] on employer office and CW days. Due to the fact that time-use diaries only asked for daily time spent in transport by mode, we had to infer the preferred commute transport modes. Since we know that diarists live relative far away from their employer's office (at least 40 min one-way commute), we could identify the commute transport mode on most employer office days. It was not always possible to distinctly identify the commute transport mode on CW days. While this approach introduces some uncertainty, it allows us to observe some major trends about impacts of CW on commute transport modes among diarists.

[6] We defined the preferred transport mode as the transport mode which is used on more than 25% of commuting days. If no preferred transport mode could be identified, we listed all transport modes.

We used the data to compare numbers of workdays by work location, average time allocation, travel time by transport mode, and commute transport modes when people worked exclusively from the employer office (long commute), from the CW space (short commute), or from home (no commute) (see 14.4.1).

Parts of the analysis of time allocation and time spent in transport modes—which we complemented with more detailed data analysis—have been used in another study to develop and demonstrate a conceptual framework of environmental effects of CW (Vaddadi et al., 2020).

14.3.2 Swedish Time Use Survey

We compared findings in the CW living lab with time-use and travel patterns observed in a larger sample of Swedish residents from the Swedish Time Use Survey 2010/11, which is a country-wide collection of time-use diaries of Swedish residents (Statistics Sweden, 2012). In contrast to the time-use diaries of the CW living lab, diarists recorded just one workday and one weekend day. To investigate interrelationships between commute time and time spent on other activities, we compared time allocation on workdays with relatively short commute time on the one hand with workdays with relatively long commute time on the other. To do so, we plotted the average time spent on commuting (aggregated to 'commute' classes) and on other activities on a bar graph (see 14.4.2).

Some data selection and preparation of data from the Swedish Time Use Survey was necessary in order to align the sample to the sample of individuals in the CW living lab.

As the Swedish Time Use Survey investigates time use in general, it distinguishes significantly more activities. We clustered 17 of these into the main activities 'commute', 'private travel', 'work', 'leisure', and 'everyday chores'.

We removed the following data because we wanted to focus on the behavior of employees comparable to the participants in the CW living lab on typical workdays:

- people not living in larger cities
- people aged below 20 or above 65 years
- people who were unemployed, who were not employees (e.g. entrepreneurs, farmers), who indicated that they worked part-time or less than 30 h per week, who had several jobs or unusual working hours (e.g. night work)
- weekend days, sick days, vacation days, and other days when people did not work
- days for which 'travel' was longer than 4 h and 'business travel' was longer than 2 h per workday
- days for which 'work' was shorter than 4 h per workday

The variable 'commute' is discrete because the survey recorded time use in 10-minute intervals. To further reduce complexity, we clustered 'commute' into seven daily 'commute' classes. The final dataset contains 650 workdays from 650 diarists. Figure 28 shows the number of observations by commute class.

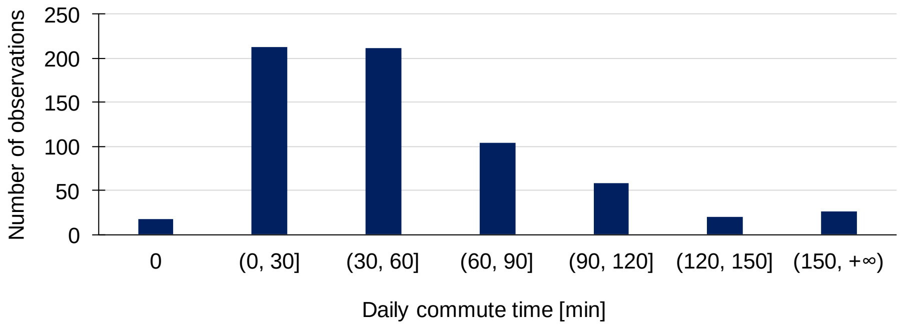

Figure 28: Number of observations (workdays) by commute class.

14.4. Results

In the following, we present the analysis of the data gathered in the CW living lab (14.4.1) and, for comparison, the analysis of the data from the Swedish Time Use Survey (14.4.2).

14.4.1 Analysis of travel diaries from the co-working living lab

Number of workdays by work location

Table 18 shows the number of days worked from different work locations. On roughly 2.8 days per week participants worked from the employer office, on 0.9 days per week from the CW space, and on 0.6 days per week from home. On other workdays, people worked from other places, from multiple locations (mainly 'home office and employer office', 'home office and CW space', or 'employer office and meetings at other places'), or did not work (e.g. vacation).

Work location	**Employer office** (long commute)	**Co-working space** (short commute)	**Home** (no commute)	**Other**
Number of diary days	167	51	36	45
Days per week	2.8	0.9	0.6	0.8

Table 18: Number of diary days by work location on the day recorded. These figures also include atypical workdays (e.g. short work time) and low-quality diary days to show the adoption of CW across all workdays (299 diary days). 'Other days' are workdays with several work locations or diarists did not work (e.g. vacation).

Table 19 shows the number of workdays by work location and diarist. While all diarists worked from the employer office in the diary period, CW and home office adoption varied across diarists:

— 7 diarists worked full days from the CW space and from home.
— 7 diarists worked full days from the CW space and not from home.
— 4 diarists worked full days from home and not from the CW space.
— 2 diarists did not work any full days from the CW space or from home.

Of the 6 diarists who did not work full days from the CW space, 5 worked parts of some days from the CW space; only one diarist never worked from the CW space in the diary period.

Diarist ID	Number of full workdays		
	Employer office	Co-working space	Home office
1	6		
2	8	2	1
3	7		7
4	8		2
5	4	11	
6	10	1	
7	10	4	
8	8	6	
9	9	3	2
10	3	6	
11	10	3	2
12	13	1	
13	9	1	3
14	14		
15	8		3
16	6	1	4
17	8		2
18	5	2	4
19	9	3	2
20	8	5	

Table 19: Number of workdays by diarist and work location, excluding workdays with multiple work locations, atypical workdays (e.g. short work time) and low-quality diary days.

Time spent on activities by work location

Figure 29 shows the average time spent on activities by work location.

On CW days, people spent roughly half as much time traveling as on employer office days. On home office days, people spent even less time traveling.

On employer office days, people spend the most time on 'work', followed by home office and CW days. However, the differences are small.

The time spent on 'everyday chores' and 'leisure' is greatest on home office days and roughly equal on employer office and CW days.

When interpreting these results, we have to consider that the time-use diaries showed that diarists indicated 'travel' and 'work' time more carefully than time spent on 'everyday chores' and 'leisure'.

Average travel time across modes by work location

Figure 30 shows the average daily travel time ('commute' + 'private travel') across transport modes.

The time spent on public transport is longest on employer office days, significantly shorter on CW days, and almost zero on home office days.

Car travel is also the longest on employer office days and shorter on CW days. On home office days, car travel is longer than on CW days. Since there is no commute on home office days, car travel is for private purposes only.

The time spent on 'biking and walking' is roughly equal on employer office and CW days and shorter on home office days.

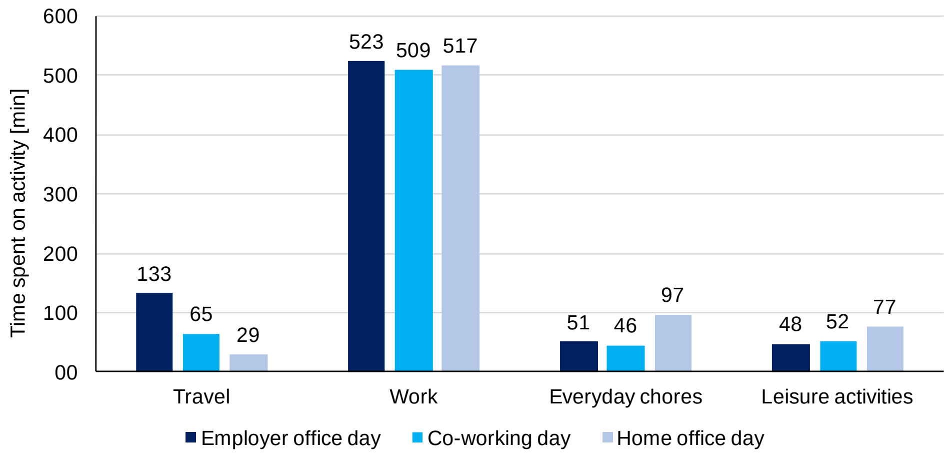

Figure 29: Daily time spent on activities by work location. The sum of time spent on all activities differs on employer office, co-working and home office days because time-use diarists often did not fill out diaries completely.

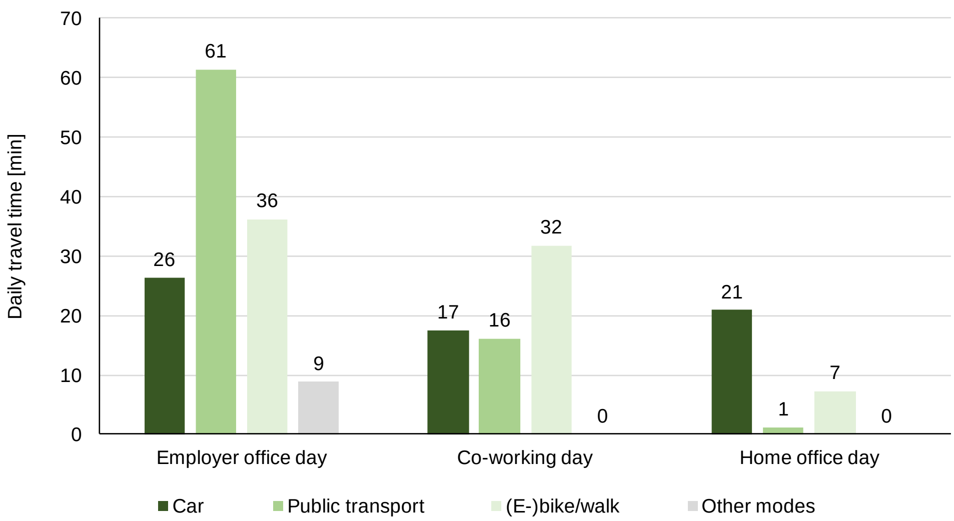

Figure 30: Daily travel time per workday across transport modes by work location.

Commute transport modes by diarist

Table 20 shows the preferred commute transport modes by diarist on employer office and CW days (there is no commute on home office days). The data reported on some diary days did not permit clear identification of the preferred transport mode. These observations are indicated as 'mix'. The data reported on some diary days merely showed that the car was not used; however, it was not clear whether the diarists commuted by public transport, (e-)bike, or foot to the CW space because they reported relevant amounts of time for all these modes. These observations are indicated as 'no car'.

When comparing transport modes on employer office and CW days, we observed the following patterns:

- 1 diarists used the car on EO and CW days.
- 1 diarists used the car both on EO days and on CW days or switched to public transport, biking or walking on CW days.
- 1 diarist switched from car on EO days to biking or walking on CW days.
- 2 diarists switched from public transport on EO days to biking or walking on CW days.
- 3 diarists used public transport both on EO days and on CW days or switched to biking or walking on CW center days.
- For 5 diarists, the change of commute transport modes from EO to CW days could not be uniquely identified. Further data analysis showed that 2 of these diarists reduced car use, 2 increased car use, and 1 did not change car use on CW days. All 5 reduced use of public transport.
- 7 diarists did not work full days from the CW in the diary period or used other transport modes.

Diarist ID	**Commute transport mode**	
	Employer office	Co-working space
1	Car, public transport	n.a.
2	Public transport, mix	No car, mix
3	Public transport, (e-)bike/walk	n.a.
4	Public transport	n.a.
5	Public transport	(E-)bike/walk
6	Car	(E-)bike/walk
7	Car	Car, mix
8	Public transport	(E-)bike/walk
9	Public transport	No car, mix
10	Public transport	No car
11	Public transport	No car, mix
12	Other	No car
13	Public transport	No car
14	Public transport	n.a.
15	Public transport, mix	n.a.
16	Car	Car
17	Public transport	n.a.
18	Public transport	No car, mix
19	Public transport	No car
20	Public transport	(E-)bike/walk, mix

Table 20: Preferred commute transport mode by diarist and work location. If a diarist did not work a full day from the co-working space in the diary period, this is indicated by 'n. a.'. 'No car' means the diarist commuted by public transport, (e-)biked, or walked to the CW space. 'Mix' means that considerable transport times were reported for 'car', 'public transport' and/or '(e-)bike/walk' on the diary day.

14.4.2 Analysis of data from the Swedish Time Use Survey

Figure 31 shows the average time spent on an activity and the commute time on a workday clustered into 'commute' classes.

There seems to be an interrelation between time spent on 'commute' and time spent on other activities; that is, time spent on other activities is greater on days with less time spent on 'commute'. Differences in time spent on 'everyday chores' and 'leisure' across commute classes are greater than differences in time spent on 'work' and 'private travel'.

Total travel time ('commute' + 'private travel') is shorter on days with less time spent on 'commute' because the increase in time spent on 'private travel' is shorter than the decrease in time spent on 'commute'.

The 'no commute' class differs from all other classes. On 'no commute' days, people spend less time on 'work' and on 'leisure' than on days with 0-30 min 'commute'.

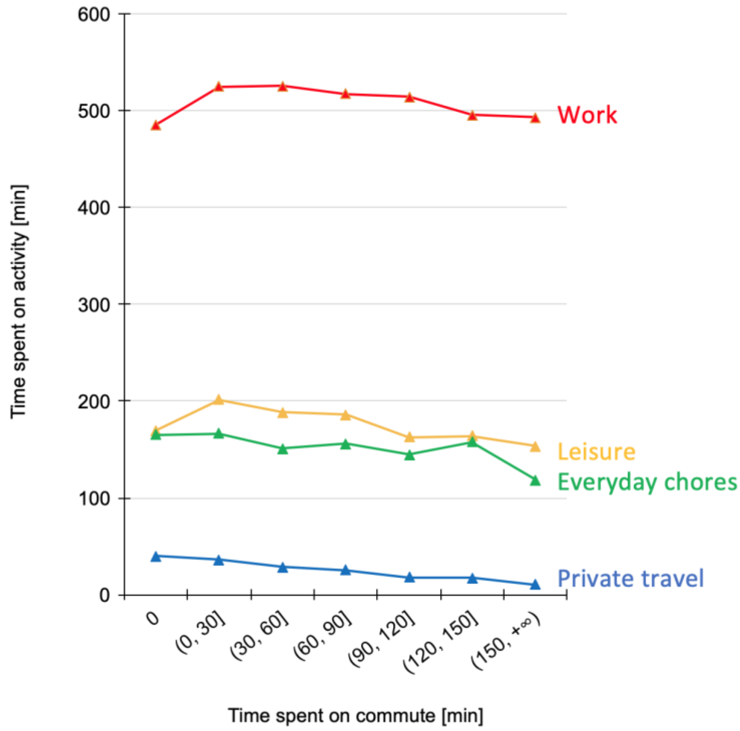

Figure 31: Average time spent on an activity on a workday by 'commute' class. We do not show time use for 'sleeping', 'studying', 'business trips', 'study-related travel', 'eating and drinking' and 'undefined activities' because they were not captured in the time-use diaries of the CW living lab. Thus, the sum of activities in the figure does not equal 24 h (= 1440 min).

14.5. Discussion

In the following, we discuss time allocation on days with different work locations, transport modes used, energy impacts of changes in time allocation, and limitations of this study.

14.5.1 Time allocation on employer office, co-working and home office days

The results of the CW living lab and the analysis of data from the Swedish Time Use Survey both show that total travel time is shorter on days when people spend less time on 'commute', which indicates that individuals compensate saved commute time with 'private travel' only to a small extent. This result is in line with the previous studies of travel impacts of working from CW spaces (Balepur et al., 1998; Ge et al., 2018; Henderson & Mokhtarian, 1996) and with results of studies of home-based TC, which find a reduction of total daily travel time on TC days and only a slight increase of non-commute travel (Lachapelle et al., 2018). Our study is not directly comparable with studies considering associations between TC, residential location, and travel (Kim et al., 2012; Zhu, 2012), nor with studies considering the travel of telecommuters' household members (Kim et al., 2015) because our data is from 3-week time-use diaries and does not include data on locations and distances, and we did not collect data from other household members.

With respect to ‘everyday chores’, the results of our two analyses differ slightly: Based on the data from the Swedish Time Use Survey, we found that time spent on ‘everyday chores’ is greater on days with less ‘commute’ time. In contrast, the CW living lab data suggests that ‘everyday chores’ time is greater on employer office days (long commute) than on CW days (short commute). Still, the most time is spent on ‘everyday chores’ on home office days (no commute). A possible explanation for this is that telecommuters intentionally shift ‘everyday chores’ to home office days. Both analyses consistently show that ‘leisure’ time is greater on days with less time spent on commuting.

In the CW case study, ‘work’ time is similar on all types of days, whereas in the analysis of the Swedish Time Use Survey ‘work’ time tends to be longer on days with less time spent on ‘commute’. Both analyses show that the differences in ‘work’ time are smaller than the differences in time spent on other activities, potentially because work times are determined in employment contracts.

The result that less ‘commute’ time is associated with more time spent on non-travel activities confirms the results of most studies of non-travel impacts of TC (He & Hu, 2015; Kuppam & Pendyala, 2001; Paleti & Vukovic, 2017), except for one which finds that the commute time saved is mainly used for additional work and not leisure (Rhee, 2008).

When interpreting the results, we have to consider that the CW living lab was based on time-use data from a very specific group of people and that time reallocation due to TC can be different for individuals with different demographic and socio-economic characteristics (e.g. presence or absence of children in the household). Impacts on other time-use categories (e.g. ‘sleep’) are possible but were not within the scope of this study. These and other limitations of our study are discussed in 14.5.4.

14.5.2 Transport modes used

Total daily travel (‘commute’ + ‘private travel’)

The time spent in all transport modes was the longest on employer office days, shorter on CW days, and the shortest on home office days; except for car travel, which was greater on home office days than on CW days. A possible explanation for this is that people shift activities which induce car travel to home office days (e.g. going shopping). This hypothesis is also supported by the fact that telecommuters spend the most time on ‘everyday chores’ and ‘leisure’ on home office days (see previous section). One approach to counteract this effect would be to actively offer sustainable transport options (e.g. ride sharing, bike sharing) or delivery services to telecommuters.

Still, we have to consider that we did not consider interdependencies between weekdays and weekends, because only few diarists carefully filled out time-use diaries on weekends. In principle, people could shift activities which induce car travel from weekends to weekdays (e.g. going shopping). This would reduce the car use on weekends, but total car use per week would not change.

Commute transport mode

On employer office days, public transport was the preferred commute transport mode, followed by car transport. Compared to employer office days, some diarists switched to less energy-intensive transport modes (from car to public transport, biking, or walking; or from public transport to biking or walking) on CW days or used the same transport modes. There is no indication that CW induced a major shift to more energy-intensive transport modes (e.g. from public transport to car).

In contrast, the TC center study in California showed that telecommuters increasingly used drive-alone modes on TC days (Balepur et al., 1998). Also, the TC center study in Washington showed that center-based telecommuters only used private vehicles to commute to the TC center (Henderson & Mokhtarian, 1996). A possible explanation is that both studies were conducted in the U.S., where the average distances from the diarists' homes to the centers were much greater than in our case. The CW space in our case study is located close to the diarists' homes, which makes walking or biking from home to the CW space possible.

14.5.3 Energy impacts

In our study, the commute time saved is spent on travel for other purposes only to a small extent. Since various studies have shown that the direct energy requirements of most non-travel activities are lower than those of travel activities (Aall, 2011; De Lauretis et al., 2017; Jalas & Juntunen, 2015), there seems to be a potential for net energy savings through working from the CW space or from home.

However, the energy impacts of TC also depend on the transport modes because car transport has very high direct energy requirements, whereas the direct energy requirements of public transport are lower and zero in the case of biking (unless e-bikes are used) and walking (mobitool, 2016). Many studies are conducted in regions such as the U.S. where cars are the prevailing transport mode; thus, any travel reduction yields high direct energy savings. Obviously, the direct energy savings that can be achieved by reduced commuting are lower for public transport users and zero for bikers (not considering e-bikes) or pedestrians. The results may be different in regions with higher shares of public transport users, bikers, and pedestrians (e.g. central or northern Europe).

In that case, the net energy impacts of TC depend even more on the energy requirements of the substitute activities. In the case of travel, the direct energy requirements are proportional to the time spent on the activity (e.g. driving a car longer increases fuel consumption). The direct energy consumption of non-travel activities, however, increases only if they involve use of energy-consuming appliances or other devices (e.g. surfing the Internet requires electricity for powering computers, taking a walk in the woods does not consume energy). Thus, the energy impacts of TC on non-travel activities must be derived from the *marginal* energy requirements of these activities, which are difficult to quantify.

To demonstrate the relevance of the modal split for the energy impacts of TC, we roughly estimated direct energy requirements per hour (MJ/h) of travel using different assumptions about the modal split (Figure 32):

— Car only
— Public transport only
— Biking and walking only (not considering e-bikes)
— Modal split as in the CW case study on employer office, CW, and home office days

We used the energy requirements of transport modes according to mobitool (2016) and the average speed across transport modes (Johnson et al., 2016). For estimating energy requirements of travel in the CW case study, we had to work with average speeds of transport modes because mobitool provides energy requirements per distance covered and the time-use diaries documented the time spent on transport.

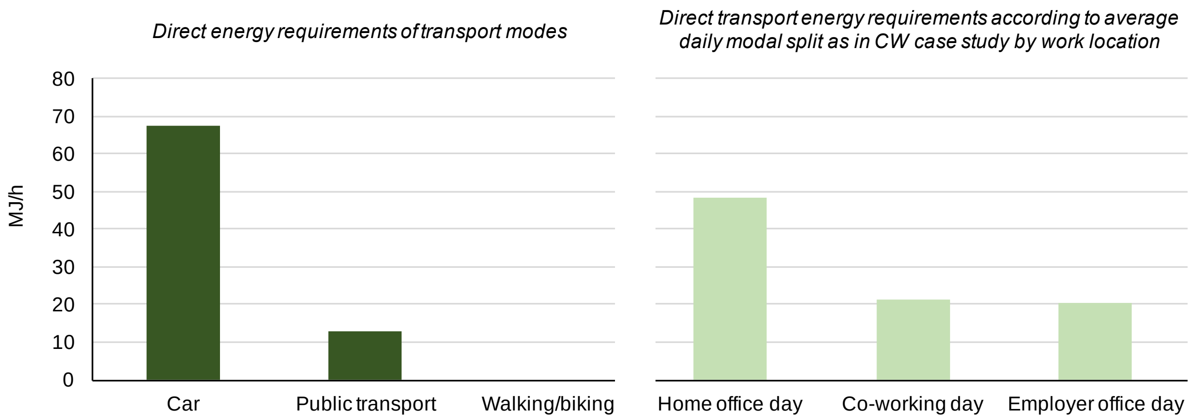

Figure 32: Direct energy requirements per hour of travel for car, public transport, biking/walking (left) and according to the average modal split in the co-working case study by work location (right). Energy requirements of transport modes based on mobitool (2016).

Car travel has by far the greatest direct energy requirements per hour, followed by public transport and walking or biking. In the CW case study, travel on home office days has the greatest energy requirements per hour because the car has by far the highest modal share on these days.

For people who exclusively commute by car, the direct energy savings due to reduced commuting are higher than for public transport commuters, as commuting is associated with greater direct energy requirements. For bikers and pedestrians, the travel-related energy savings due to working from home or the CW space would be zero, as the direct energy requirements of this transport mode are zero. Thus, any increase in energy requirements due to more time spent on other activities would lead to a net increase in energy requirements. Therefore, TC strategies should aim at reducing motorized transport and encourage telecommuters to switch to non-motorized transport modes (as some diarists in our case study did).

Comprehensive assessments of the energy impacts of TC have to include further effects such as energy consumption for heating and cooling at CW spaces, at home, and at the employer office; income rebound effects, and systemic effects of TC adoption (e.g. lifestyle changes through TC) (Vaddadi et al., 2020).

14.5.4 Methodological reflections

Our analysis is based on cross-sectional data on workdays; thus, the datasets do not enable us to draw conclusions on full-week time allocation before and after the adoption of CW or working from home. The analysis does not control for the diarists' demographic or socio-economic characteristics, which can influence their behavioral responses to changes in commute time. The CW case study is based on a small sample of people with similar jobs (office workers in an IT company). Thus, results may not be generalizable to a larger population with more diverse jobs. However, the additional analysis of data from the Swedish Time Use Survey indicated that the interrelationship between commute time and time spent on other activities is similar in the larger Swedish population. Still, it is important to consider that the countrywide Swedish time-use data was not collected for investigating impacts of a change in commute time on time spent on other activities (as done in the CW living lab).

Although the diarists kept the travel diaries carefully, quality differences between diaries do exist. For example, the sum of time spent on all activities differs on employer office, CW and home office days because time-use diarists often did not fill out diaries completely (e.g. see Figure 29). Also, individuals might have different understandings of the activity categories.

Further limitations are due to constraints in data collection: We had to exclude days with multiple work locations from the analysis of the diaries and the study does not cover full 24-hour days.

Systemic effects of TC were outside the scope of this work, but can be relevant (Ge et al., 2018). For example, some studies show that TC can increase travel in the long term due to telecommuter households relocating further away from work (Zhu, 2012). More research on the systemic effects of CW adoption, especially regarding transport demand and space use, is required to help exploit the potential of CW for environmental benefits.

14.6. Conclusion

TC is a promising ICT use case with the potential to reduce commute-related environmental impacts. To explore how CW impacts commuting, we conducted a case study of time-use, travel, and energy impacts of TC using data from a CW living lab in a residential neighborhood in Stockholm. Our results show that when diarists worked from the local CW space or from home, their total daily travel time was significantly shorter than on days when they worked from the more distant employer office. This is because telecommuters did not compensate the commute time saved with travel for private purposes; instead, they spent it on other activities such as 'leisure' or 'everyday chores'. As most non-travel activities have lower direct and indirect energy requirements than travel, this substitution has the potential to yield net energy savings.

A central variable in assessments of TC energy impacts is the modal split since the energy requirements of various transport modes differ. In the CW living lab, some diarists used the same commute transport modes or switched to less energy-intensive ones (e.g. from car to biking or walking) on CW days and we could not find any indication that CW led to a shift to more energy-intensive transport modes (e.g. from public transport to private car). This shows that offering workplace facilities in a local neighborhood can facilitate energy-efficient transport, as co-workers can walk and bike to work.

An effect that could lead to increasing energy use is switching to energy-intensive transport modes for private purposes. We observed that on home office days, people reduce total travel time, but increase car travel for private purposes. Further effects that can lead to increased energy use, but were outside the scope of this study, include a potential increase in (heated or cooled) floor space (e.g. due to the CW space) and that money not spent on commuting is spent on other energy-intensive activities (income rebound effect).

Whether TC brings about energy savings depends largely on TC-induced changes to:

(1) telecommuters' time spent in transport and their use of transport modes,
(2) space requirements at all work locations (employer office, CW, and home office space),
(3) substitute activities and their energy impacts (time and income rebound effects).

Thus, organizations adopting TC or providing TC services (in particular CW space providers) should advise telecommuters on their preferences regarding work location and transport modes. All stakeholders should work together to find strategies to reduce total office space required.

Since we conducted an exploratory study based on data from a small sample, the results should be generalized only with great caution. However, the analysis of the existing time-use data collected from a larger sample of residents of Sweden also indicated that shorter daily commute times are associated with shorter daily travel times. Thus, it would be interesting to see further, more systemic analyses of travel and non-travel impacts of working in local CW spaces and home office. This future research could reveal under what conditions TC can be a viable model to reduce work- and travel-related environmental impacts, take pressure off transport systems, and increase the well-being of workers at a larger scale.

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15 Towards a conceptual framework of direct and indirect environmental effects of co-working

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Abstract: Through virtual presence, ICT allows employees to work from places other than their employer's office and reduce commuting-related environmental effects (TC). Working from a local CW space, as a form of TC, has the potential to significantly reduce commuting and is not associated with deficits of working from home (e.g. isolation, lack of focus). However, environmental burden might increase through CW due to the infrastructure required to set-up and operate the CW space and potential rebound effects. In this paper, we (1) develop a framework of direct and indirect environmental effects of CW based on a well-known conceptual framework of environmental effects of ICT and (2) apply the framework to investigate the case of a CW living lab established in Stockholm. Based on interviews and surveys conducted with co-workers in the living lab and infrastructure data of the CW space, we roughly estimate associated energy impacts. Results show that energy requirements associated with operating the CW space can counterbalance commute-related energy savings. Thus, in order to realize energy savings CW should be accompanied with additional energy saving measures such as a net reduction of (heated) floor space (at the CW space, at the employer's office and the co-workers home) and use of energy-efficient transport modes.

***Keywords*:** ICT, co-working, telecommuting, energy consumption, commuting, flexible workplace.

15.1. Introduction

As cities continue to expand, people have started to move further away from city centers due to housing shortages and ever-increasing rents making commuting a physical and mental burden. Due to an often unreliable transportation system and heavy dependence on private vehicles, millions of people spend long hours commuting to and from work (Lam, 2017).

In 2011, roughly 38% of commuters in Stockholm were using private vehicles to commute to and from work while 25% used public transport (Transport analysis, 2011). In addition, car ownership and vehicular travel is ever increasing (Moriarty & Honnery, 2008). Besides its environmental impacts, commuting causes congestion during peak hours and has significant effects on individuals' well-being (Ye & Titheridge, 2015). Hence, there is a dire need to adopt sustainable travel practices.

ICT has transformed our existing patterns of production and consumption with consequences for the environment (Arvesen et al., 2011; Berkhout & Hertin, 2004; Bieser & Hilty, 2018b; Hilty & Aebischer, 2015). TC, working remotely and collaborating with colleagues and partners by means of ICT, has the potential to reduce commute-related environmental impacts. A specific case of TC centers are CW spaces. CW "describes any situation where two or more people are working in the same place together, but not for the same company" (DTZ, 2014, p. 3). CW spaces are "shared workplaces utilized by different sorts of knowledge professionals […] working in various degrees of specialization in the vast domain of the knowledge industry" (Gandini, 2015, p. 194). CW holds the potential to significantly reduce environmental impacts associated with commuting and is not associated with deficits of working from home (e.g. isolation, lack of focus). In order to realize these benefits, the choice of location of the CW space is in particular critical (Kramers et al., 2015, 2018; Ringenson et al., 2018).

However, CW can also increase environmental burdens, for example through required infrastructure to set-up and operate the CW space. It can also lead to rebound effects, if employees spend time and money saved on commuting on other activities, goods and services that are associated with environmental impacts (Bieser & Hilty, 2018a). In order to draw more specific conclusions about whether CW can contribute to an overall reduction in resource consumption, and which factors are particularly relevant, a more precise analysis is necessary (Börjesson Rivera et al., 2014; Horner et al., 2016; Kramers et al., 2015; Pohl, Hilty, et al., 2019).

One approach that has gained momentum in sustainability research is to test potentially sustainable innovations in living labs (Liedtke et al., 2015). In living labs, data can be collected in a real-life setting and later be used for environmental assessment (Pohl, Suski, et al., 2019). Within Mistra SAMS, a research project on sustainable transport in Sweden, a living lab CW space has been set up in the south of Stockholm (in the suburb Tullinge) and is in operation since January 2019. As of February 2020, out of 60 recruited participants, about 44 employees who live close to the CW space regularly work from there and can potentially avoid lengthy commutes to their employers' offices.

In this paper, we (1) develop a conceptual framework of the diverse environmental impacts of CW, and (2) apply the framework to investigate environmental impacts associated with the CW living lab in Stockholm. Thereby, we provide a systematic overview of potential positive and negative environmental impacts of CW. We hope this can provide first insights on environmental impacts of CW and stimulate further research on CW and other promising ICT applications, which is required to harness the potential to avoid environmental burdens and mitigate negative impacts of increasing ICT use.

The paper is organized as follows: Materials and methods are described in section 15.2. The conceptual framework of environmental effects of CW is presented in section 15.3, followed by the application of the framework to the CW case in Stockholm in section 15.4. We end with a discussion and conclusion and identify potential for future research in section 15.5.

15.2. Material and methods

To develop a conceptual framework reflecting the environmental effects of CW, we use the framework of environmental effects of ICT by Hilty and Aebischer (2015) and adapt it to the specific case of CW. The well-known and frequently applied taxonomy of environmental effects of ICT was introduced by Berkhout and Hertin (2004) at first and has been revised several times since then (Hilty & Aebischer, 2015; Horner et al., 2016; Pohl, Hilty, et al., 2019). The framework distinguishes three layers of environmental effects of ICT:

(1) Direct environmental effects through production, use and disposal of ICT
(2) Enabling effects of ICT use through the application of ICT also in other sectors (the effects result from changes in production and consumption patterns)
(3) Systemic impacts through ICT-induced changes of existing socio-economic structures and institutions

This framework is useful to investigate the specific case of CW for the following reasons:

- CW is a specific use case of ICT as explained in the introduction.
- CW requires production, operation and disposal of infrastructures (e.g. CW space, ICT equipment), processes which cause environmental impacts (layer 1).
- CW can change existing production and consumption patterns (e.g. avoiding work-related travel or changing collaboration methods among colleagues—layer 2).
- CW can fundamentally affect the nature and location of work as well as transport habits at a societal level if it is adopted at a larger scale (e.g. through diminishing of central business districts—layer 3).

To adapt the framework, we applied the universally defined environmental effects of ICT to the specific case of CW (Hilty & Aebischer, 2015; Horner et al., 2016).

In a second step, we apply the framework to roughly estimate energy impacts associated with the CW living lab in Stockholm. Wherever possible we use actual data collected in the CW living lab.

We (1) collected technical data of the CW space, such as floor space and equipment used, (2) interviewed participants on their everyday life, travel and work patterns and (3) collected daily time-use data (time spent on 'travel', 'work', 'everyday chores' and 'leisure'; use of transport modes) for three succeeding weeks by asking participants to fill out time-use diaries.

Data collection took place from September until November 2019. As the living lab is still in operation and data collection is still ongoing, we cannot estimate some effects and in some cases have to use publicly available statistics or make reasonable assumptions.

15.3. Conceptual framework of environmental effects of co-working

The framework, which describes direct, indirect and systemic environmental effects of CW, is shown in Figure 33. The first layer, 'Technology: Co-working infrastructure', describes the environmental effects of building, operating and maintaining infrastructures required for CW (e.g. CW space, video conferencing systems, parking places, etc.).

The second layer, 'Application: Working at the co-working space', describes the environmental effects due to individual co-workers or organizations adopting to working at the CW space instead of the employer's office or from home. This directly affects the use of office space, transport infrastructure, and ICT equipment. In addition, behavioral changes, due to changing work and travel practices are possible. For example, employees might spend money and time not spent on commuting on other activities that are associated with their own environmental impacts (patterns known as income and time rebound effects) (Bieser & Hilty, 2020; Sorrell & Dimitropoulos, 2008).

The third layer, 'Structural change: Large-scale co-working adoption', describes the environmental effects of a system transformation towards CW. It leaves the level of individual co-workers or organizations and focuses on environmental consequences of a transformation towards a society-wide CW culture. This means that factors such as place of residence are decisive for the place of work, regardless of the actual location of the employer. Such a transformation includes changes to working cultures, ways of communication, lifestyles or land use patterns, which only occur if a critical mass of society switches from conventional working habits to CW.

In the following, we describe each layer in some detail. In the framework, we included effects described in literature and observed during operation of the CW living lab. Still, effects beyond the ones we describe can exist.

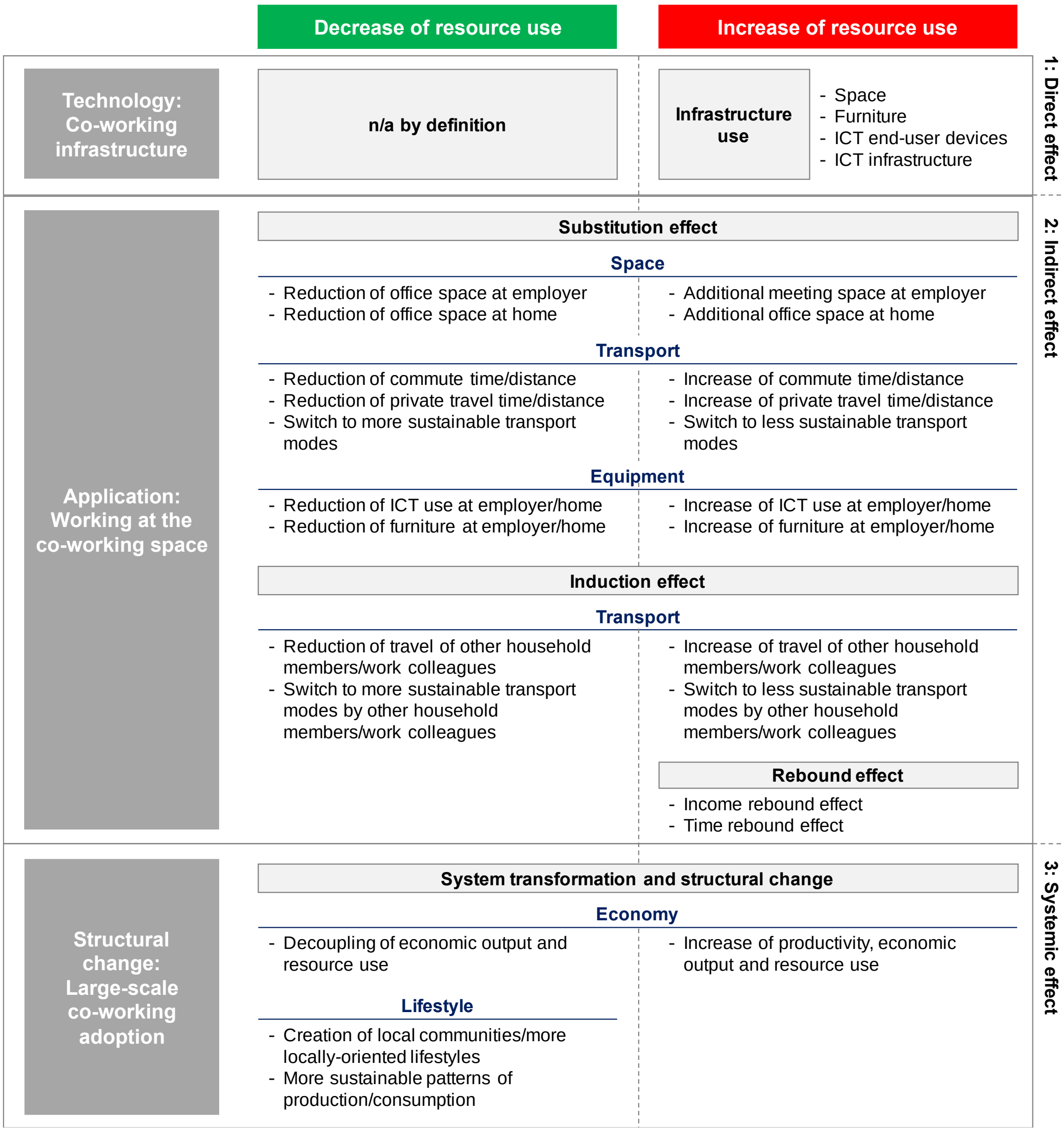

Figure 33: Framework of environmental effects of co-working (based on Hilty & Aebischer (2015) and Horner et al. (2016)).

15.3.1 Technology layer

Direct environmental effects of building, operating and maintaining CW spaces are by definition unfavorable environmental effects as they all require resources, energy and cause emissions, but do not avoid anything yet. Main environmental impacts associated with building and operating a CW space (Table 21) are caused by facilities (main offices, auxiliary rooms, parking) and equipment (ICT end-user devices and infrastructure, office furniture).

Environmental impacts caused throughout the life cycle of facilities and equipment are caused by the construction of facilities and production of equipment (production phase), the operation of these (use phase) and processes at their end-of-life (EoL phase). As for the production phase, the construction of CW spaces and production of ICT equipment, furniture and other required equipment cause environmental impacts.

With regard to facilities, energy consumption during the operational phase is of great relevance (Krimmling & Flanderka, 2017) and can be divided into energy for heating, cooling and lighting. Use phase energy demand in office buildings can be estimated proportional to office space (Knissel, 2004). With increasing adoption of energy-efficient building technologies (e.g. improved insulations) the relative importance of the construction phase increases.

With regard to ICT end-user devices, the relevance of the production phase depends on the type of the device, the service life and energy efficiency of the devices. The smaller and more energy efficient the devices, the more important is the production phase (Wäger et al., 2015).

With regard to ICT infrastructure, communication infrastructure (e.g. networks) as well as servers (or data centers) are most relevant. Overall, the total number of equipment used, their production impacts and their energy consumption during operation is decisive for the total environmental impacts.

The main target on this layer is to reduce the relative effects per co-worker that stem from constructing, operating, and maintaining CW facilities and equipment. Amongst others, this means to minimize required CW office space and to aim for high occupancy rates.

Facilities	Main use area	- Workplaces - Meeting rooms - Telephone rooms - Event space
	Auxiliary areas	- Kitchen - Bathrooms - Parking space
Equipment	ICT end-user devices and infrastructure	- End-user devices (screens, printers, white boards) - Infrastructure (e.g. network, servers) - Conferencing equipment
	Office furniture	- Desks - Chairs
	Other	- Coffee machine - Cleaning equipment - …

Table 21: Facilities and equipment in the co-working space.

15.3.2 Application layer

The environmental effects resulting from running and using the CW space can work in both directions—reducing and increasing resource use. Main environmental impacts of CW are caused by changes to the process/use of space, transport and office equipment. The main drivers of environmental impacts on this layer are changes to the floor space at the employer’s office and the reduction of commuting.

As discussed in the introduction, CW spaces that are close to the employees’ homes can contribute to a reduction in commute time and distance. This is the case, if trips to the CW space replace commute trips to work. If working from the CW space replaces working from home, commute time and commute distance increase instead.

If, before the adoption of CW, private activities such as library visits, meeting friends or shopping had been combined with commute trips, CW can also induce additional trips. Further, changes in commuting can lead to a change in transport modes used (modal split). For example, for shorter commutes people might consider taking the bike instead of the car. However, people might also increase their use of cars for shorter commute trips, because the opportunity cost of taking the car instead of public transport are less significant (in public transport people can do other activities).

Working from CW spaces has the potential for a reduction of space at the employer's office and the employee's home (e.g. by implementing desk sharing at the employer's office). However, if these office spaces are not sufficiently reduced, CW can have a net increasing effect on office space due to the CW space. Also, CW might increase demand for meeting space at the employer's office, which is required to communicate with co-workers. Employers adopting CW might also require additional ICT equipment (e.g. for video conferencing).

Furthermore, the saved travel costs can be used for other purposes (income rebound effects) and thus contribute to an increased use of resources (Börjesson Rivera et al., 2014). Finally, co-workers can spend saved commute time on other activities that are associated with environmental impacts (time rebound effects (Bieser & Hilty, 2018a)).

The main target on this layer is to promote desired and mitigate undesired effects. The effect of CW on (heated) floor space (at the employer and at the co-worker's home), the average change in commute distance of co-workers, thus, the location of the CW space (central, sub-urban, close to the co-workers houses), and the transport modes used, seem to be the most important drivers of the environmental impacts on the application layer.

15.3.3 Structural change layer

Structural effects of CW are effects that occur if CW is adopted at a larger scale. For example, given that CW reduces time spent commuting and adds flexibility to time and place of work, it may influence families' decisions regarding where to live, jobs, and investments in their dwellings (Salomon, 1986; Schiff, 1983). In the long-term this can also change land-use patterns, e.g. towards "more decentralized and lower-density land use patterns" (Mokhtarian, 2009, p. 12). CW from local CW spaces at a larger scale can also change the nature of work and would reduce demand for major office buildings in business districts, which then could be used for other purposes. Finally, CW can also change traffic streams and demand for transport in general.

Rebound effects occur also on the structural layer. For example, if CW increases the productivity of an industry and stimulates growth; this can lead to an increase in resource consumption and emissions (economy-wide rebound effect) (Bieser & Hilty, 2018c; Börjesson Rivera et al., 2014).

Structural effects of CW depend on many variables in the broader societal and economic system and are therefore difficult to predict. A long-term CW strategy at a larger scale needs to identify potential structural effects and promote CW schemes that foster environmentally favorable structural effects and mitigate unfavorable ones.

15.4. Case study: environmental effects of a co-working space in Stockholm

15.4.1 Introduction to the co-working space in Stockholm

Situated in Tullinge, a suburb in the south of Stockholm, the CW space is an experimental living lab set up to observe a wide range of effects of having a workplace close to the home of the participants. The CW space integrates various accessibility and mobility services to participants that allow them to book, plan, and travel. It offers an activity-based workplace close to co-workers' homes, gives access to 3 electric bikes (2 electric bicycles and 1 electric cargo bicycle) for free and a peer-to-peer carpooling scheme.

It is equipped with 14 workplaces, which can be booked via an online application, a well-equipped conference room for eight people, as well as three rooms for telephone or video calls. This experimental CW space acts as a platform to bring together a range of actors such as citizens, researchers, business and public authorities to create, validate, and test new mobility and accessibility technologies and services in a real-life context. The CW space has been in operation since January 2019 and as of February 2020 44 out of 60 participants regularly work there.

15.4.2 Co-working impacts on time-use and travel

We used the results of the time-use diaries of 20 co-workers who work for an IT company in Kista, north of Stockholm to compare their daily time-use including travel. Because living close to the CW space in the south of Stockholm was a requirement for participating, these co-workers significantly reduced their commute time and distance on CW days compared to employer office days. We compare time spent on 'travel', 'work', 'everyday chores' and 'leisure' on days, when people work from the employer's office, from the CW space or from home (Figure 34).

We also compared the (share of) time people spent in different transport modes on these days (Figure 35). We did not consider days, when people worked from other locations or from several locations on one day. We also excluded low quality data entries and untypical work days (work time lower than 4 hours; total recorded time lower than 8 hours; time difference between the recorded time spent on 'travel' and recorded time in specific transport modes is higher than 100 min; these were two separate questions). This results in time-use data from 244 workdays.

Time spent on activities

Of all diary days, 56% are employer office days, 17% CW days, 12% home office days and 15% other types of workdays (e.g. various work locations).

Average 'travel' time is highest, when people work from the employer's office (133 min) and decreases by 68 min on CW days and 104 min on home office days. Average working time is also slightly higher on days, when people work from the employer's office (523 min) and marginally lower on home office (-6 min) and CW days (-14 min). One possible explanation for slight differences in work time is that on home office or CW days employees spend less time socializing with work colleagues who are not physically present.

Average time spent on 'everyday chores' and 'leisure' is highest on home office days and lower on days when people work from the employer's office or the CW space. Differences in time spent on other activities (e.g. sleep) are also possible, but were not collected in the time-use diaries.

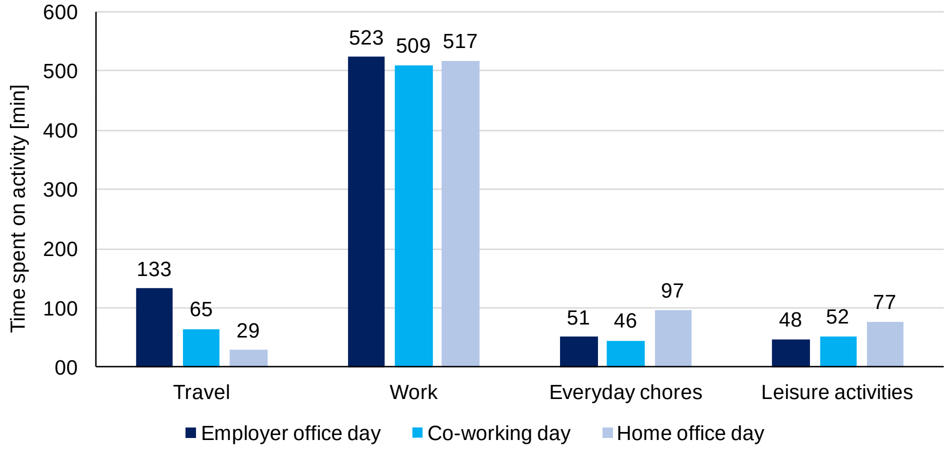

Figure 34: Average time spent on an activity by work location on that day. The sum of time spent on all activities differs on employer office, co-working and home office days because time-use diarists often did not fill out diaries completely.

Used transport modes (modal split)

On employer office days, average time spent in public transport is highest (61 min) and significantly lower on CW days (16 min) and is close to zero on home office days.

Average time spent traveling by car is also highest on employer office days (26 min) and slightly lower on CW days (17 min). Interestingly, on home office days, co-workers spend on average more time in car transport (21 min) than on CW days. One explanation for this could be that individuals shift activities which induce car transport to home office days (e.g. going shopping)

Average time spent (e-)biking and walking is of the same order of magnitude on employer office and CW days and significantly lower on home office days.

In the interviews, we asked participants about their commute transport modes specifically. The results indicate that public transport is the preferred commute transport mode, followed by car transport. This confirms the patterns observed in the time-use data.

Interviews also showed that biking and walking is rather done for private purposes. This is one possible explanation why no large differences in average time spent on biking or walking can be observed between employer office and CW days; however, on home office days, average time spent biking or walking is comparatively low. This could indicate, that that bike or foot travel is somehow related to work routines outside the home (potentially due to walking or biking between home, public transport stops and the office). Thus, further research is required to investigate this relationship.

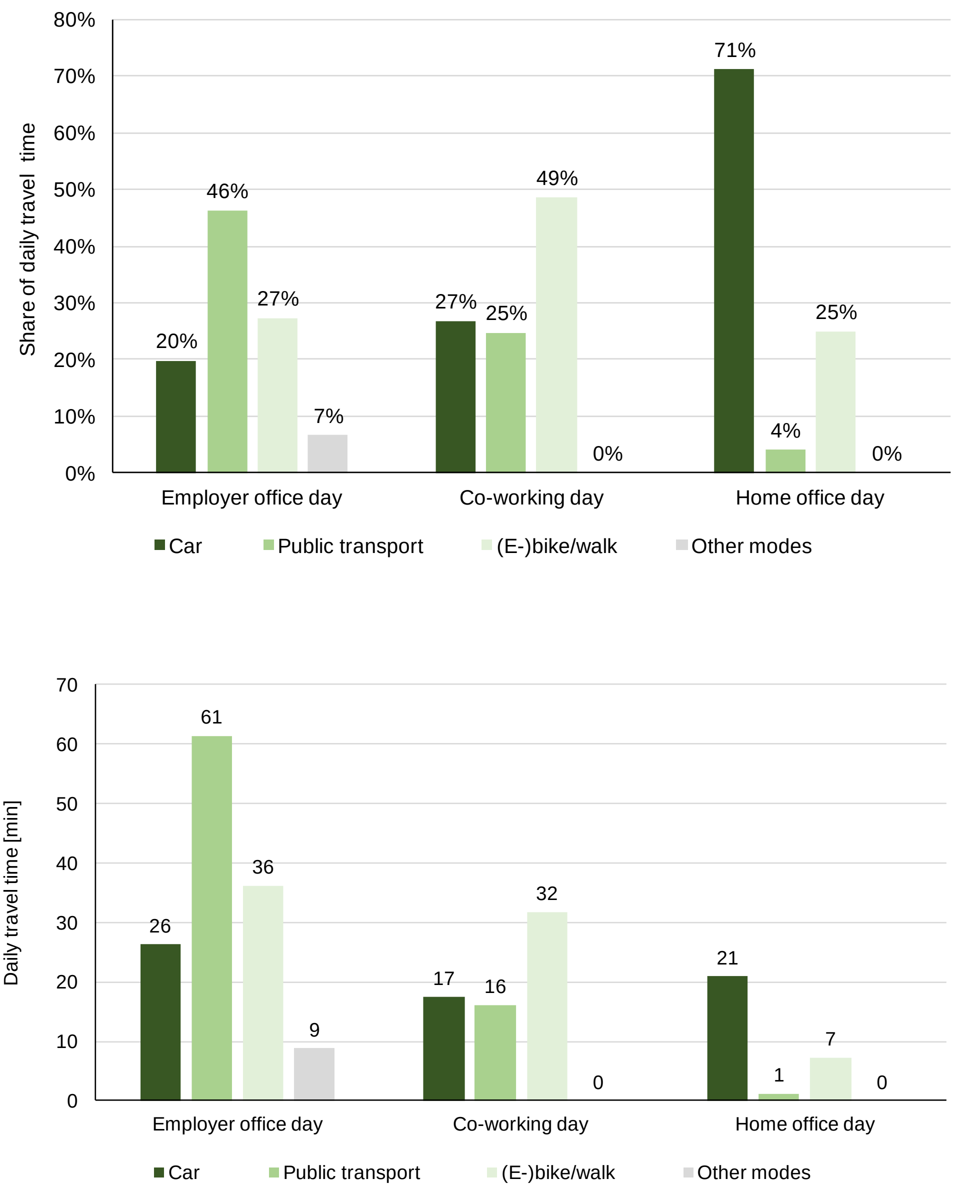

Figure 35: Average share of travel time (top) and average absolute time (bottom) spent in different transport modes by work location on that day (other modes are for example boats).

15.4.3 Energy impacts

In the following we apply the framework of environmental effects of CW to roughly estimate energy impacts of the CW living lab.

Estimation approach

We estimate energy requirements associated with…

- heating, cooling and lighting of the CW space (direct effect),
- ICT equipment operated in the CW space (direct effect) and
- changes in travel time (indirect effect), on employer office, CW and home office days.

Due to lack of data, we do not consider furniture or changes in space use at home or the employer office; neither effects on behavior of other household members or work colleagues (e.g. changes in travel) nor systemic effects. To some extent, changes in travel time include income and time rebound effects, as people spend saved commuting cost and time on travel for other purposes.

All calculations are performed for one CW day of one co-worker. Calculations focus on the use phase (energy requirements associated with the operation of the CW space and fuel consumption for transport). Energy impacts associated with production of goods and services (e.g. production of cars, construction of office buildings, and production of ICT equipment) are out of scope.

Inventory data

Table 22 provides an overview of data on floor area, ICT equipment and the number of people working in the CW space.

Building	Floor area co-working space [m^2]	170
ICT equipment	Number of workplaces	14
	Number of screens	18
	Number of desktop computers	1
	Number of printers	1
	Number of TV sets	1
Co-workers	Number of co-workers regularly working in the co-working space	44
	Number of co-workers from IT-company in Kista for whom time-use diaries are available	20

Table 22: Co-working space floor area, amount of ICT equipment used in the co-working space and number of co-workers.

To estimate energy impacts of heating, cooling and lighting of office space we used the floor space of the CW space and yearly energy requirements of standard office buildings according to the "Institut Wohnen und Umwelt" (EnWiPo, 2017; Knissel, 2004). We divided energy impacts of heating, cooling and lighting of office space by the number of people working in the CW space and the number of workdays per year to estimate impacts per co-worker and CW day. Thereby, we assume that co-workers who work for other companies have the same CW patterns (number of CW days) as the co-workers working for the IT company in Kista.

For operation of ICT equipment, we used the number of devices in operation in the CW space and daily device energy requirements according to ecoinvent (2005). To estimate impacts per co-worker and CW day, we divided ICT equipment energy consumption by the number of workplaces at the CW space. We did not include network devices and one videoconferencing system due to lack of data.

To estimate energy impacts of changes in travel time, we used the results of the time-use diaries (Figure 34, Figure 35), direct energy requirements of fuel consumption and provisioning of transport modes according to mobitool (2016) and average speed of transport modes (Johnson et al., 2016). We needed to estimate the distances driving with each transport mode using average speed of transport modes, because in the travel diaries co-workers recorded the time spent in transport modes.

Estimation results

Figure 36 shows the estimated average difference in energy consumption between one person working from the CW space for one day, the employer's office or home. It shows that much energy consumption is caused by heating, cooling and lighting (mainly heating and lighting, only few cooling) of CW office space (24.0 MJ) and only few energy consumptions is caused by operation of ICT equipment (2.0 MJ).

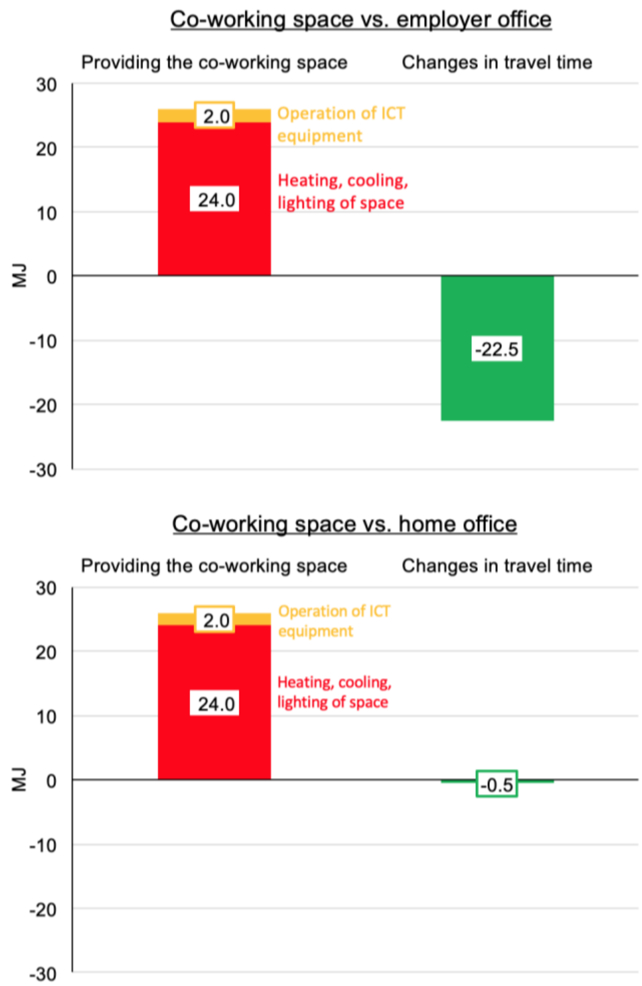

Figure 36: Difference in average energy requirements on a co-working day compared to a workday at the employers' office (top) or at home (bottom) across co-workers.

Compared to employer office days, average reduction in travel leads to a reduction of travel-related energy impacts of 22.5 MJ; thus, energy impacts of reduction in travel and energy required for heating, cooling and lighting of office space roughly cancel each other out. Compared to home office days, co-workers spend on average more time traveling on CW days; still travel-related energy consumption is slightly lower. This is because on home office days, people use the car on average more than on CW days. However, travel-related energy savings on CW days compared to home office days are much lower than the energy required to operate the CW space. The total energy required for heating, cooling and lighting the CW space does not increase proportionally with increasing utilization of the CW space. That is, because buildings do not require much more heating energy if occupancy increases or vice versa. However, the number of avoided employer office days (long commute) is proportional to total commute-related energy savings, specifically for car commuters (e.g. one CW or home office day avoids one long commute, two CW or home office days avoid two long commutes,…). Thus, substituting additional employer office days with CW or home office days is a good strategy to increase travel-related energy savings.

When interpreting the results, we have to consider that this estimation did not consider changes in energy consumption at home or at the employer's office. For example, CW could enable employers to reduce their office space and associated energy consumption for heating, cooling and lighting the space. Plus, working from home can increase residential energy consumption (e.g. for cooking, heating or cooling). Mokhtarian et al. (1995) summarize early studies which consider household energy impacts of TC and conclude that increases in residential energy consumption account for 11-25% of travel energy savings. Such effects have to be considered in comprehensive energy assessments of TC.

We also did not consider interdependencies between weekdays and weekends, because only few diarists carefully filled out time-use diaries on weekends. In principle, CW can also impact time-use on weekends. For example, people could systematically shift activities for which they require the car (e.g. shopping) from weekends to home office days. This would reduce the car use on weekends, but total car use per week would not change.

15.5. Discussion and conclusion

CW from a local CW space is a promising ICT use case to reduce transport demand and associated environmental impacts, while having a positive effect on well-being of employees (e.g. more time for family and friends). However, CW also causes environmental impacts, for example through infrastructure required to operate CW spaces or through time rebound effects.

Based on an existing framework of environmental effects of ICT, we developed a conceptual framework of environmental effects of CW. The framework distinguishes environmental effects of CW on three layers: (1) direct effects through the infrastructure required to operate CW spaces, (2) indirect effects due to individual co-workers or organizations adopting CW (e.g. avoided commutes) and (3) structural effects through a system transformation towards CW (e.g. fundamental changes in demand for transport and office space).

While direct effects are environmentally unfavorable by definition (they increase resource use), indirect effects and systemic effects can increase but also reduce resource use (e.g. by avoiding commute time or inducing additional travel for other purposes). Thus, net environmental effects depend on the magnitude of effects on all three layers and institutions should consider them when developing and adopting CW schemes.

In our case study of a CW living lab in Stockholm, we found that co-workers on average traveled most on employer office days, less on CW days and least when they worked from home, leading to travel-related energy savings. However, changes in transport mode can counterbalance this effect, as we found in our case study: On home office days, participants spent on average more time traveling by car than on CW days, leading to higher travel-related energy use on home office days than on CW days.

A rough estimation shows that the energy required to operate the CW space and travel-related energy savings roughly counterbalance each other on employer office and CW days. Thus, CW does not lead to energy savings per se, but should be accompanied by additional energy savings measures, such as reduction of office space at the employer's office. One way to reduce employer office space is to, instead of having fixed workplaces, adopt shared workplaces which can be booked by employees for days when they work from the employer's office. This can increase the utilization of workplaces at employer offices and allow for reduction of total office space; however, in companies with traditional work environments a transformation of working culture, tools and regulations as well as support for employees who struggle with such a change might be required. Other companies (e.g. start-ups) might not even rent or build larger office spaces and establish CW in the first place.

The main levers to realize energy savings through CW are a reduction of total travel time and distances (e.g. by choosing CW spaces close to home), use of sustainable transport modes, a net reduction of (heated) floor space (at the CW space, at the employer's office and the co-workers home) and a high number of CW or home office days (increasing the number of avoided commutes to employer offices).

Our calculations have limitations and uncertainties regarding the extent of daily activities captured, the energy requirements of travel and buildings, and the consideration of structural effects. We focused on operational energy requirements, thus environmental effects related to the production, construction and disposal of buildings, devices, vehicles and roads are not included in our estimation.

Working mainly remotely and communicating with colleagues virtually can also impact productivity of teams and well-being of individuals (Janisch & Hilty, 2017). Thus, when increasing the number of CW or home office days, possible impacts on productivity and well-being of employees have to be taken into account.

The co-workers investigated in this case study all work for the same IT Company. Thus, the possibility to adopt CW and behavioral changes of individuals through CW can be different for individuals working for different companies, in different sectors with different job requirements. Calculations are based on averages across all co-workers. Investigating individual co-workers can reveal further insights on changes in time-use patterns which depend on characteristics of individuals (e.g. preferred commute pattern). We also excluded weekends, because time-use diaries kept on weekends are of lower quality than those kept on workdays. Thus, we could not assess associations between CW patterns, time use on weekends and total weekly travel.

Furthermore, we presented our results in terms of energy impacts of adopting CW. Environmental impacts beyond energy use (e.g. global warming potential or human toxicity) exist and need to be investigated to provide a full picture.

Finally, we did not collect time-use data of participants before they adopted CW. Thus, whether CW leads to a net reduction in travel cannot be assessed with the available data. Still, the calculation demonstrates, that CW does not necessarily lead to energy savings and that non-travel related environmental impacts of CW matter.

Future research should take a broader perspective in terms of effects and activities included in the calculations and environmental impact categories and life cycle stages considered. If CW is adopted at a larger scale, systemic effects can lead to fundamental transformation of transport systems and land use. These effects are difficult to estimate and further research is required. We encourage companies and researchers to experiment with CW and find ways to use CW for reducing environmental effects of transport, work and everyday life. The framework developed in this paper and the findings of the living lab can provide guidance for this.

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