Next generation mobile networks

Problem or opportunity for climate protection?

Jan Bieser
Beatrice Salieri
Roland Hischier
Lorenz M. Hilty

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Authors

Jan Bieser, Beatrice Salieri, Roland Hischier, Lorenz M. Hilty

In cooperation with

Swisscom AG:
Marius Schlegel
Res Kindler
Res Witschi

swisscleantech:
Christian Zeyer

Sounding board

Doris Fiala
Edith Graf-Litscher
Jürg Grossen

Contact information

University of Zurich
Prof. Dr. Lorenz M. Hilty, Dr. Jan Bieser
Informatics and Sustainability Research Group
Department of Informatics
Binzmuehlestrasse 14
CH-8050 Zurich
jan.bieser@ifi.uzh.ch

Empa
Dr. Roland Hischier, Dr. Beatrice Salieri
Advancing Life Cycle Assessment Group
Technology and Society Laboratory
Lerchenfeldstrasse 5
CH-9014 St. Gallen
roland.hischier@empa.ch

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Vorwort

Der Klimawandel ist eine der grössten Herausforderungen unserer Zeit – für die Gesellschaft und auch für die Wirtschaft. Um die Ziele des Pariser Klimaabkommens zu erreichen, müssen die CO_2-Emissionen bis 2050 auf netto-null gesenkt werden. Der Wirtschaft kommt auf diesem Weg eine entscheidende Rolle zu, wenn Wohlstand und Gesundheit der Bevölkerung sowie der Schutz des Klimas gleichermassen sichergestellt sein sollen.

Swisscleantech und Swisscom verbinden dieselben Werte und Zielsetzungen, nämlich sich für die Nachhaltigkeit in der Schweiz einzusetzen und Verantwortung zu übernehmen – für die Umwelt und den Wirtschaftsstandort Schweiz. Die Digitalisierung hat ein grosses Potential für den Klimaschutz, davon sind wir überzeugt. Digitalisierung betrifft dabei nicht nur die ICT-Branche, sondern alle Wirtschaftszweige, die dank ICT nachhaltiger werden können.

Die Infrastruktur bildet das Rückgrat der Digitalisierung. Datennetze und Rechenzentren wollen einerseits zuverlässig betrieben werden. Gleichzeitig gilt es bereits heute, die Infrastruktur für die nächsten Jahrzehnte zu planen. Diese Weiterentwicklung bedarf klarer Rahmenbedingungen und dafür einer breiten Akzeptanz bei den Stakeholdern auf allen föderalistischen Ebenen.

Mit Blick auf den Ausbau neuer Mobilfunknetze in der Schweiz wollen wir mit dieser gemeinsamen Studie darlegen, welche Beiträge leistungsfähige Netze für den Klimaschutz leisten können. So möchten wir den Dialog über die Bedeutung künftiger Mobilfunkinfrastrukturen für den Klimaschutz ermöglichen.

Die vorliegende Studie wurde während der Erstellung durch eine politische Begleitgruppe begleitet. Die Gruppe hat dabei insbesondere folgende Rolle und Aufgaben wahrgenommen: Mitsprache bei der Auswahl der Anwendungsfälle, deren Auswirkungen aufs Klima vertieft analysiert wurden, sowie Prüfung der Erkenntnisse mit Bezug auf Nutzbarkeit im politischen Dialog.

Wir bedanken uns ganz herzlich bei der Begleitgruppe für ihr Engagement und bei den Autoren der Universität Zürich und der Empa für die umfassende Analyse, die mit dieser Studie entstanden ist.

Bopp Carsten

Carsten Bopp
Co-Präsident swisscleantech

Stefan Nünlist
Leiter Unternehmenskommunikation und
Nachhaltigkeit, Swisscom

Sounding board

Doris Fiala
Nationalrätin FDP

„Der Einsatz neuer Technologien ist immer mit einer Güterabwägung verbunden. Dies gilt auch für 5G. Die vorliegende Studie zeigt exemplarisch, dass diese Technologie für Klimaschutz und Nachhaltigkeit Vorteile haben kann. Der Verzicht auf die Technologie hätte voraussichtlich auch negative Folgen auf Arbeitsplätze und die Stärke der schweizerischen Wirtschaft. Auf der anderen Seite steht das Vorsorgeprinzip. Es ist wichtig beide Ebenen ins Gleichgewicht zu bringen. Einseitige Vorverurteilung ist ebenso wenig im Interesse der Schweiz wie blindes Vorauseilen".

Edith Graf-Litscher
Nationalrätin SP

„Unser Wohlstand basiert nicht zuletzt darauf, dass wir immer bereit waren auf Innovation zu setzen und rechtzeitig in Infrastrukturen investiert haben. Deshalb können wir heute von unserer Wasserkraft und dem gut ausgebauten Eisenbahnnetz profitieren. Ob eine Innovation zielführend ist, muss sich daran messen, ob die Volkswirtschaft insgesamt davon profitieren kann. Die vorliegende Studie hilft, diese Frage besser zu beurteilen. Sie zeigt für mich: 5G ermöglicht Schritte in die richtige Richtung. Während Smart Work unsere Arbeitsmobilität optimieren wird und auch die Vereinbarkeit von Familie und Beruf auf neuer Art ermöglicht, kann Precision Farming helfen sicher zu stellen, dass unsere Nahrungsmittel in bester Qualität und optimaler Menge aber mit reduzierten Umweltschäden hergestellt werden. Beides geht besser mit 5G. Dies sind nur zwei Beispiele. Wer nüchtern überlegt, gibt 5G eine Chance".

Jürg Grossen
Nationalrat GLP

„Die Digitalisierung ist ein zentraler Eckpfeiler für ein modernes, komfortables Leben, das auch dem Umwelt- und Klimaschutz gerecht wird. Digitalisierung braucht Daten – verlässlich, schnell und in Echtzeit. Ein optimales Netzwerk von mobilen und leitungsgebunden Kommunikationsnetzen stellt sicher, dass diese Daten zur Verfügung stehen. Im Mobilen Bereich steht nun der Schritt von 4G zu 5G an. Die vorliegende Studie zeigt, dass 5G dabei hilft, eine optimale Vernetzung sicher zu stellen und Dank den neuen Anwendungen das Klima zu schützen. Es spricht deshalb alles für diesen wichtigen Technologieschritt".

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Summary

5G mobile networks and greenhouse gas emissions

Requirements placed on mobile networks in terms of number and types of connected devices, data volumes and types of supported applications are increasing. 5G mobile networks, the roll-out of which is currently discussed in politics, industry and academia, are intended to meet these increasing requirements.

Rolling out network infrastructure is not only capital-intensive, it is also associated with significant energy requirements and greenhouse gas (GHG) emissions caused by producing and operating the network infrastructure. On the other hand, each generation of mobile network technologies has shown to enable additional types of applications so far. This enabling effect can have an impact on patterns of production and consumption and therefore on the related GHG emissions. For example, 5G technology is expected to be an enabler for automated driving, a use case which is expected to have substantial impacts on GHG emissions caused by transport in the long term.

As Switzerland has ratified the Paris Agreement and aims at being climate-neutral by 2050, it is important to assess the impact of 5G mobile networks on GHG emissions in Switzerland and to identify the main factors that influence the net GHG effect of this technology. For these reasons, the present study investigates the following research questions:

(1) How much GHG emissions will be caused by the production and operation of 5G network infrastructure in Switzerland in 2030?

(2) What are use cases which will benefit significantly from 5G mobile networks and what is their potential to contribute to the reduction of GHG emissions in Switzerland in 2030?

The aim of this study is not to provide justifications for or against the roll-out of 5G mobile networks in Switzerland, but to shed light on one specific aspect of 5G: the expected effect on GHG emissions. Other aspects, such as security or health, are explicitly excluded from this research.

GHG footprint of mobile networks

Based on life cycle assessment, our results show that the production and operation of 5G mobile network equipment installed in the Swisscom network are expected to cause 0.018 Mt CO_2e/year in Switzerland in 2030, 57% of which are caused by producing the network infrastructure and 43% by providing the electricity required for operating the infrastructure. A comparison of the GHG emissions caused by 2G-4G and 5G mobile networks per unit of data transmitted shows that today's mobile networks cause 30.3 g CO_2e/GB, while 5G mobile networks in 2030 are expected to cause 4.5 g CO_2e/GB, or 85% less than today's mobile networks.

GHG-reduction potential of 5G-supported use cases

5G networks are designed to enable enhanced mobile broadband, massive machine-type communications and ultra-reliable, low-latency communication. The IMT-2020 standard by the International Telecommunication Union defines requirements that have to be met by 5G mobile networks (e.g. ultra-low latency, high data rates, high capacity). Each of these requirements represents a significant improvement over older mobile network generations. In a literature review, we identified use cases across various sectors that benefit from 5G mobile network capabilities. These sectors are transportation (e.g. automated driving), manufacturing (e.g. remote maintenance), farming (e.g. precision fertilization), energy (e.g. smart grids), buildings (e.g. remote home monitoring), entertainment and media (e.g. augmented reality), health (e.g. remote surgery) and the public sector (e.g. infrastructure monitoring). 4G mobile networks do not provide the capabilities to support all of these use cases. The reasons differ from use case to use case; they can be related, e.g., to capacity, latency or availability. Although some use cases can potentially be realized with (a combination of) communication technologies other than 5G (e.g. WiFi-based automated driving, LoRaWAN-based precision farming), there is an advantage in meeting the requirements of many use cases with one mobile network technology and infrastructure, as in the case of 5G mobile networks.

Out of the identified use cases, we selected four with a promising potential to reduce GHG emissions in Switzerland:

- flexible work
- smart grid
- automated driving, and
- precision farming.

As a result of our assessment, we estimate that these 5G-supported use cases can avoid up to 2.1 Mt CO_2e/year in 2030 in an optimistic scenario, 0.6 Mt CO_2e/year in the expected scenario and 0.1 Mt CO_2e/year in a pessimistic scenario. The largest potentials can be attributed to the following use cases: flexible work (by reducing business travel and commuting through enhanced virtual collaboration), smart grids (by increasing the share of renewable energies in the electricity supply system), and precision farming (by reducing use of agricultural inputs such as fertilizers and increasing productivity in livestock farming). In comparison, the reduction potential of automated driving is low in 2030. The adoption of all four use cases is expected to be still relatively low by 2030, which implies that the future potential of the use cases to contribute to climate protection can increase after 2030.

There are two risks that counteract the GHG abatement potential of the 5G-supported use cases. First, rebound effects can compensate, if not overcompensate, for the expected GHG-reductions. This means that increased GHG-efficiency can also create an increase in demand for certain services, which leads to additional emissions. Second, there is additional (non-5G) equipment required for enabling these use cases (e.g. laptops for flexible work, sensors, drones or robots for precision farming), whose production and operation causes additional GHG emissions. We estimate these additional emissions up to 0.16 Mt CO_2e/year over all four use cases by 2030, i.e., clearly higher than the total footprint of the 5G infrastructure.

Conclusions

If 5G network capabilities are systematically utilized to support use cases with high GHG abatement potentials, significant GHG abatements can be realized by 2030. The overall reduction potential of the use cases investigated in this study is clearly larger than the GHG footprint of 5G networks (even if we roughly include the 5G networks of other telecommunication network operators) plus the GHG footprint of additional (i.e., not 5G-specific) ICT equipment required for enabling the use cases.

In order to put 5G at the service of climate protection, measures should be taken in two fields. First, the GHG footprint of the ICT sector should be kept small. Here, it is important to address all ICT equipment because 5G infrastructure will be responsible for less than 3% of the footprint of the whole ICT sector, but the use of 5G will need additional ICT equipment that is not specific to 5G. Second, the GHG abatements enabled by use cases in the transportation, energy and farming sectors should be unleashed by creating framework conditions that are conducive to flexible work models, new mobility services, renewable and decentralized energy sources, and forms of farming that target the reduction not only of CO_2, but also CH_4 and N_2O emissions, and that benefit more from digitally enabled precision than from economies of scale.

In order to put 5G at the service of climate protection, it is therefore necessary to systematically exploit the climate protection potential of 5G-supported use cases and to mitigate risks that could lead to an increase in GHG emissions (additionally required ICT equipment, rebound effects).

Zusammenfassung

5G-Mobilfunknetze und Treibhausgasemissionen

Die an Mobilfunknetze gestellten Anforderungen hinsichtlich der Anzahl und Art der verbundenen Geräte, der Datenvolumina und der unterstützten Anwendungen nehmen weiter zu. Mobilfunknetze der 5. Generation (5G), deren Einführung derzeit in Politik, Industrie und Wissenschaft diskutiert wird, sind darauf ausgelegt, diesen wachsenden Anforderungen zu entsprechen.

Der Aufbau von Netzinfrastrukturen ist nicht nur kapitalintensiv, sondern führt auch zu einem erheblichen Energieeinsatz und damit verbundenen Treibhausgasemissionen durch Herstellung und Betrieb der Netzinfrastruktur. Andererseits hat bisher jede neue Mobilfunkgeneration zusätzliche Anwendungen ermöglicht. Diese Innovationswirkung kann Produktions- und Verbrauchsmuster und somit auch die damit verbundenen Treibhausgasemissionen beeinflussen. Beispielsweise ist davon auszugehen, dass die 5G-Technologie eine der Grundlagen des automatisierten Fahrens sein wird, einer Anwendung, die langfristig erhebliche Auswirkungen auf die verkehrsbedingten Treibhausgasemissionen haben kann.

Angesichts der Ratifizierung des Pariser Klimaschutzübereinkommens durch die Schweiz und des erklärten Ziels der Schweiz, bis zum Jahr 2050 klimaneutral zu werden, müssen auch die Auswirkungen der 5G-Mobilfunknetze auf die Treibhausgasemissionen der Schweiz betrachtet werden. Die vorliegende Studie untersucht daher folgende Fragestellungen:

(1) Wie hoch sind die Treibhausgasemissionen infolge des Aufbaus und des Betriebs der 5G-Netzinfrastruktur im Jahr 2030 in der Schweiz?

(2) Welche Anwendungsfälle profitieren erheblich von 5G-Mobilfunknetzen und welches Potenzial zur Verringerung von Treibhausgasemissionen ergibt sich im Jahr 2030 in der Schweiz aus diesen Anwendungsfällen?

Das Ziel dieser Studie ist nicht, Argumente für oder gegen den Aufbau von 5G-Mobilfunknetzen in der Schweiz zu liefern. Vielmehr soll ein spezifischer Aspekt von 5G beleuchtet werden: die zu erwartenden Auswirkungen auf die Treibhausgasemissionen. Andere Aspekte, wie Sicherheit oder Gesundheit, werden durch diese Studie ausdrücklich nicht betrachtet.

Treibhausgas-Fussabdruck von Mobilfunknetzen

Unsere auf einer Ökobilanz basierenden Ergebnisse zeigen, dass die Herstellung und der Betrieb der für 5G-Mobilfunknetze erforderlichen Netzinfrastruktur von Swisscom im Jahr 2030 in der Schweiz voraussichtlich 0,018 Mt CO_2e pro Jahr verursachen wird. 57% davon entstehen bei der Herstellung der Netzinfrastruktur, die verbleibenden 43% durch die Erzeugung der elektrischen Energie für den Betrieb dieser Infrastruktur. Pro übertragenem Datenvolumen wird durch 2-4G-Mobilfunknetze heute Emissionen von etwa 30,3 g CO_2e/GB verursacht. Für 5G-Mobilfunknetze erwarten wir im Jahr 2030 Emissionen von etwa 4,5 g CO_2e/GB und somit 85% weniger als bei den heutigen Mobilfunknetzen.

Treibhausgas-Reduktionspotenzial durch 5G-unterstützte Anwendungen

5G-Mobilfunknetze sind auf schnellere mobile Breitbandverbindungen, datenintensive Kommunikation zwischen Maschinen und hochzuverlässigen Datenaustausch mit geringer Latenz ausgelegt. Die durch die Internationale Fernmeldeunion festgelegte Norm IMT-2020 legt die Anforderungen fest, die 5G-Mobilfunknetze erfüllen müssen (z. B. extrem geringe Latenzzeiten, hohe Datenraten, hohe Bandbreiten). Jede dieser Anforderungen bedeutet eine signifikante Verbesserung gegenüber den Mobilfunknetzen früherer Generationen. Wir konnten im Rahmen einer Literaturrecherche Anwendungen in folgenden Sektoren identifizieren, die von diesen Möglichkeiten profitieren würden: Verkehr (z. B. automatisiertes Fahren), Produktion (z. B. Fernwartung), Landwirtschaft (z. B. Präzisionsdüngung), Energie (z. B. Smart Grids), Gebäude (z. B. Fernüberwachung der Wohnung), Unterhaltung und Medien (z. B. Augmented Reality), Gesundheit (z. B. Telechirurgie) und der öffentliche Sektor (z. B. Infrastrukturüberwachung). 4G-Mobilfunknetze sind nicht in der Lage, all diesen Anwendungsfällen gerecht zu werden. Die Gründe dafür sind je nach Anwendungsfall unterschiedlich und können beispielsweise die Bandbreite, die Latenz oder die Verfügbarkeit betreffen. Auch wenn manche Anwendungsfälle potenziell mit anderen Kommunikationstechnologien als 5G (oder deren Kombinationen) möglich wären (beispielsweise automatisiertes Fahren auf WLAN-Basis, Präzisionslandwirtschaft auf LoRaWAN-Basis), ist die Nutzung einer einzigen Mobilfunktechnologie und -infrastruktur für gleichzeitig viele verschiedene Anwendungsfälle vorteilhaft. Dies wäre mit 5G-Mobilfunknetzen möglich.

Wir haben aus den identifizierten Sektoren vier vielversprechende Anwendungen ausgewählt, mit denen sich die Treibhausgasemissionen in der Schweiz senken liessen:

- flexibles Arbeiten
- Smart Grid
- automatisiertes Fahren
- Präzisionslandwirtschaft

Unsere Berechnungen zeigen, dass sich im Jahr 2030 durch die genannten Anwendungen mit 5G-Unterstützung in einem optimistischen Szenario bis zu 2,1 Mt CO_2e/Jahr einsparen liessen. Im erwarteten Szenario ergeben sich 0,6 Mt CO_2e/Jahr und in einem pessimistischen Szenario noch immer 0,1 Mt CO_2e/Jahr. Die grössten Potenziale liegen im flexiblen Arbeiten (durch Vermeidung von Geschäftsreise- und Pendlerverkehr aufgrund besserer virtueller Zusammenarbeit), Smart Grids (durch einen höheren Anteil erneuerbarer Energien in den Elektrizitäts-Versorgungsnetzen) sowie Präzisionslandwirtschaft (durch geringeren Einsatz landwirtschaftlicher Betriebsstoffe wie Düngemittel sowie Produktivitätssteigerungen in der Viehzucht). Das Potenzial des automatisierten Fahrens ist im Jahr 2030 vergleichsweise klein. Die Verbreitung aller vier Anwendungsfälle wird im Jahr 2030 voraussichtlich noch relativ gering sein. Dies legt nahe, dass das Klimaschutzpotenzial der Anwendungsfälle nach 2030 weiter zunehmen wird.

Zwei Risiken wirken der potenziellen Verringerung von Treibhausgasemissionen durch die genannten 5G-Anwendungsfälle entgegen. Erstens können Rebound-Effekte die erwarteten Treibhausgaseinsparungen kompensieren. Damit ist gemeint, dass die höhere Treibhausgaseffizienz auch zu einer höheren Nachfrage nach bestimmten Dienstleistungen und damit zu zusätzlichen Emissionen führen kann. Zweitens ist für die betreffenden Anwendungen zusätzliche (nicht 5G-spezifische) Informations- und Kommunikationstechnik (IKT) erforderlich (z. B. Laptops für flexibles Arbeiten; Sensoren, Drohnen oder Roboter für die Präzisionslandwirtschaft), deren Herstellung und Betrieb zusätzliche Treibhausgasemissionen verursacht. Wir schätzen diese zusätzlichen Emissionen über alle vier Anwendungsfälle hinweg auf bis zu 0,16 Mt CO_2e/Jahr im Jahr 2030. Dieser Wert liegt somit deutlich über den gesamten durch die 5G-Infrastruktur verursachten Treibhausgasemissionen.

Schlussfolgerung

Durch eine gezielte Nutzung der Möglichkeiten des 5G-Netzes für Anwendungen mit grossem Treibhausgas-Reduktionspotenzial lassen sich die Treibhausgasemissionen bis zum Jahr 2030 in der Schweiz erheblich verringern. Das gesamte Einsparpotenzial im Rahmen der in dieser Studie untersuchten Anwendungen ist deutlich höher als die durch die 5G-Netze verursachten Treibhausgasemissionen (auch wenn wir die 5G-Infrastruktur anderer Telekommunikationsunternehmen grob mit einbeziehen) plus die Emissionen durch die zusätzliche (also nicht 5G-spezifische) IKT, die für die untersuchten Anwendungen benötigt wird.

Um die 5G-Technologie für den Klimaschutz einzusetzen, sind Massnahmen auf zwei Gebieten erforderlich. Erstens sollten die durch die IKT verursachten Treibhausgasemissionen niedrig gehalten werden. Dabei ist es wichtig, die gesamte IKT zu berücksichtigen, da die 5G-Infrastruktur für weniger als 3% der Treibhausgasemissionen des gesamten IKT-Sektors verantwortlich sein wird und der Einsatz von 5G zur Emissionsvermeidung zusätzliche, nicht 5G-spezifische IKT-Ausrüstung erfordert. Zweitens sollte die Vermeidung der Treibhausgasemissionen durch die untersuchten Anwendungen im Verkehr, in der Energieversorgung und der Landwirtschaft durch geeignete Rahmenbedingungen unterstützt werden. Diese sollen flexible Arbeitsmodelle, neue Mobilitätsdienstleistungen, erneuerbare und dezentrale Energiequellen sowie landwirtschaftliche Methoden (mit geringeren Ausstoss nicht nur von CO_2, sondern auch von CH_4 und N_2O) fördern, die eher von digitalisierungsgestützter Präzision als von Skaleneffekten profitieren.

Um 5G in den Dienst des Klimaschutzes zu stellen ist es daher notwendig Klimaschutzpotenziale durch 5G-untersützte Anwendungen systematisch zu erschliessen und Risiken die zu einer Erhöhung der Treibhausgasemissionen führen können (zusätzlich benötigte IKT, Rebound-Effekte) zu vermeiden.

Résumé

Réseaux mobiles 5G et émissions de gaz à effet de serre

Les exigences auxquelles doivent répondre les réseaux mobiles en matière de nombre et de types d'appareils connectés, de volumes de données et de types d'application prises en charge ne cessent d'augmenter. Les réseaux mobiles 5 G, dont le déploiement fait actuellement l'objet de discussions dans les milieux politiques, industriels et universitaires, sont destinés à satisfaire ces exigences croissantes.

Le déploiement d'une infrastructure de réseau est non seulement une activité à forte intensité de capital mais il s'accompagne également de besoins énergétiques importants et d'émissions de gaz à effet de serre (GES) causées par la construction et l'exploitation de l'infrastructure. Par ailleurs, jusqu'à présent, chaque génération de technologie de réseau mobile a apporté avec elle de nouveaux types d'application. Cet effet d'activation peut avoir un impact sur les modes de production et de consommation et, par conséquent, sur les émissions de GES. Par exemple, la technologie 5G devrait rendre possible la conduite automatisée, un cas d'utilisation qui à long terme aura des incidences significatives sur les émissions de GES dues au transport.

Comme la Suisse a ratifié l'Accord de Paris et vise à atteindre la neutralité climatique à l'horizon 2050, il est essentiel d'évaluer l'impact des réseaux mobiles 5G sur les émissions de GES en Suisse et d'identifier les principaux facteurs qui influence l'effet net de cette technologie sur les GES. Pour ces raisons, la présente étude examine les questions de recherche suivantes :

(1) Quelle quantité d'émissions de GES sera causée par la construction et l'exploitation de l'infrastructure du réseau 5G en Suisse en 2030 ?

(2) Quels cas d'utilisation bénéficieront de manière significative des réseaux mobiles 5G et dans quelle mesure peuvent-ils contribuer à la réduction des émissions de GES en Suisse en 2030 ?

L'objet de cette étude n'est pas de fournir des justifications en faveur ou contre le déploiement des réseaux mobiles 5G en Suisse mais d'éclairer un aspect spécifique de la 5G : son effet attendu sur les émissions de GES. D'autres aspects tels que la sécurité ou la santé sont explicitement exclus de cette étude.

Empreinte GES des réseaux mobiles

Sur la base d'une analyse du cycle de vie, nos résultats montrent que la construction et l'exploitation des équipements du réseau mobile 5G pour le réseau de Swisscom en Suisse devraient engendrer 0,018 Mt CO_2e/an en 2030, dont 57% résultent de la construction de l'infrastructure du réseau et 43% de la production de l'électricité nécessaire à l'exploitation de cette infrastructure. Une comparaison des émissions de GES dues aux réseaux mobiles 2G-4G et 5G par unité de données transmises montre que les réseaux mobiles actuels émettent 30,3 g de CO_2e/GB, tandis que les réseaux mobiles 5G devraient produire 4,5 g de CO_2e/GB en 2030, soit 85 % de moins que les réseaux mobiles actuels.

Potentiel de réduction des GES des cas d'utilisation de la 5G

Les réseaux 5G sont destinés à permettre l'ultra haut débit mobile, l'Internet des objets massif (Massive Machine Type Communication) et des communications ultra fiables et à faible latence. La norme IMT-2020 de l'Union internationale des télécommunications définit les exigences auxquelles doivent répondre les réseaux mobiles 5G (par exemple, latence ultra-faible, débits de données élevés, capacité élevée). Chacune de ces exigences représente une amélioration significative par rapport aux générations précédentes de réseaux mobiles. Dans une analyse documentaire, nous avons identifié dans divers secteurs des usages qui bénéficieront des capacités des réseaux mobiles 5G. Ces secteurs sont les transports (conduite automatisée), la fabrication (télémaintenance), l'agriculture (fertilisation de précision), l'énergie (réseaux intelligents), le bâtiment (télésurveillance domestique), les loisirs et les médias (réalité augmentée), la santé (téléchirurgie) et le secteur public (surveillance des infrastructures). Les réseaux mobiles 4G ne sont pas capables de prendre en charge tous ces usages. Les raisons diffèrent d'un usage à l'autre ; elles peuvent être liées, par exemple, à la capacité, à la latence ou à la disponibilité. Bien que certains usages puissent être réalisés avec d'autres (combinaisons de) technologies de communication que la 5G (par exemple, la conduite automatisée basée sur le WiFi, l'agriculture de précision basée sur LoRaWAN), il y a un avantage à répondre aux exigences de nombreux usages avec une technologie et une infrastructure de réseau mobile unique, comme dans le cas des réseaux mobiles 5G.

Parmi les usages identifiés, nous en avons sélectionné quatre qui offrent un potentiel prometteur de réduction des émissions de GES en Suisse :

– le travail flexible,
– les réseaux intelligents,
– la conduite automatisée,
– l'agriculture de précision.

Suite à notre évaluation, nous estimons que ces usages de la 5G peuvent éviter jusqu'à 2,1 Mt CO_2e/an en 2030 dans un scénario optimiste, 0,6 Mt $CO2_e$/an dans le scénario escompté et 0,1 Mt CO_2e/an dans un scénario pessimiste. Les potentiels les plus importants résident dans les usages suivants : le travail flexible (grâce à la réduction des déplacements professionnels et des trajets domicile-travail résultant d'une collaboration virtuelle renforcée), les réseaux intelligents (grâce à l'augmentation de la part des énergies renouvelables dans le système de fourniture d'électricité) et l'agriculture de précision (grâce à la réduction de l'utilisation d'intrants agricoles tels que les engrais et à l'augmentation de la productivité dans l'élevage). Comparativement, le potentiel de réduction de la conduite automatisée est faible en 2030. L'adoption de ces quatre usages devrait être encore relativement faible en 2030. Par conséquent, leur potentiel pour contribuer à la protection du climat peut continuer à augmenter après 2030.

Deux risques peuvent contrebalancer le potentiel de réduction des émissions de GES des usages de la 5G. Premièrement, des effets de rebond peuvent compenser, voire surcompenser, les réductions de GES attendues. En effet, une augmentation de l'efficience en matière de GES peut également entraîner une augmentation de la demande pour certains services, causant des émissions supplémentaires. Deuxièmement, ces usages nécessitent des équipements complémentaires (n'utilisant pas la 5G) dont la production et l'exploitation génèrent des émissions de GES supplémentaires (par exemple, des ordinateurs portables pour le travail flexible, des capteurs, des drones ou des robots pour l'agriculture de précision). Nous estimons que pour les quatre usages ces émissions supplémentaires pourraient atteindre 0,16 Mt CO_2e/an d'ici 2030, soit nettement plus que l'empreinte totale de l'infrastructure 5G.

Conclusions

Si les capacités du réseau 5G sont systématiquement utilisées pour permettre des usages offrant un fort potentiel de réduction des émissions de GES, une dimension significative des GES pourra être réalisée à l'horizon 2030. Le potentiel de réduction global des usages examinés dans cette étude est clairement plus élevé que la somme des empreintes GES des réseaux 5G (même si on inclut approximativement les réseaux 5G d'autres fournisseurs de réseaux de télécommunications) et des équipements TIC supplémentaires (c'est-à-dire non spécifiques à la 5G) nécessaires pour permettre les usages.

Pour pouvoir mettre la 5G au service de la protection du climat, des mesures doivent être prises dans deux domaines. Premièrement, l'empreinte GES du secteur des TIC doit rester faible. Il est important à cet égard de tenir compte de tous les équipements TIC car l'infrastructure 5G sera responsable de moins de 3% de l'empreinte de l'ensemble du secteur des TIC, mais son utilisation nécessitera des équipements TIC supplémentaires qui ne sont pas spécifiques à la 5G. Deuxièmement, les réductions des émissions de GES rendues possibles par les usages dans les secteurs des transports, de l'énergie et de l'agriculture devraient être libérées par la création de conditions cadres qui favorisent des modèles de travail flexible, de nouveaux services de mobilité, des sources d'énergie renouvelables et décentralisées et des formes d'agriculture visant à réduire non seulement les émissions de CO_2, mais aussi celles de CH_4 et de N_2O, et bénéficiant davantage de la précision apportée par le numérique que des économies d'échelle.

A fin de mettre la 5G au service de la protection du climat, il est donc nécessaire d'exploiter systématiquement le potentiel de protection du climat des cas d'utilisation soutenus par la 5G et d'atténuer les risques qui pourraient conduire à une augmentation des émissions de GES (équipements TIC supplémentaires nécessaires, effets de rebond).

1 Mobile networks and climate protection

1.1 Introduction

Requirements placed on mobile networks in Switzerland and globally are increasing. The share of Internet users in Switzerland who access the Internet on-the-go increased from 43% in 2010 to 91% in 2019 (FSO, 2020). Cisco expects that the monthly mobile data traffic per user in Western Europe is expected to increase from 2.4 GB in 2017 to 12 GB in 2022 (Cisco, 2019b) and the global number of mobile connections to increase from 8.6 in 2017 to 12.3 billion in 2022 with an increasing share of IoT connections (Cisco, 2019a). At the same time, new mobile network applications are being developed which have a variety of specific requirements.

To meet the growing demand for mobile connectivity, mobile network technology has continuously been enhanced. To date, 4 generations of mobile networks (1G-4G) have been rolled out. In recent years, the fifth generation of mobile networks (5G) has been developed and partially implemented. To date, first 5G networks are already available in more than 8’000 cities worldwide (Ookla, 2020).

Rolling out mobile network equipment is not only capital-intensive but also associated with high energy requirements and greenhouse gas (GHG) emissions caused by producing and operating the network equipment. The environmental impact of mobile communication infrastructure in general has been known to be relevant for a long time (Scharnhorst et al., 2006). In 2018, almost 19’000 mobile communication installations were in operation in Switzerland alone (FOEN, 2018). Chapter 2 of this study presents an assessment of the prospective GHG impact of 5G infrastructure in the year 2030.

At the same time, each generation of mobile network technologies supports new types of applications, which enable society’s patterns of production and consumption to change. Such changes have consequences for GHG emissions as well. For example, 4G network data rates provide the possibility for mobile work (e.g. in cafes or trains), something that was unthinkable with 2G networks. 5G mobile networks are expected to support several use cases which have the potential to change the GHG emissions, in particular in the transport, energy and agriculture sectors. Chapter 3 of this study presents an assessment of such use cases with regard to their potential to reduce GHG emissions in 2030.

In August 2019, the Federal Council of Switzerland decided upon the 2050 climate target for Switzerland, which aims at net zero greenhouse gas (GHG) emission by 2050 (FOEN, 2020).

As 5G mobile networks have consequences for GHG emissions and Switzerland has to significantly reduce its GHG footprint, the question arises whether 5G will in the coming decades contribute to increasing GHG emissions (e.g. due to electricity consumption of network equipment) or foster new applications which can substantially contribute to climate protection. This study aims to investigate both sides by providing answers to the following research questions:

(1) How much GHG emissions are caused by production and operation of 5G network equipment in Switzerland in 2030?

(2) What are use cases which will benefit significantly from 5G mobile networks and what is their potential to contribute to the reduction of GHG emissions in Switzerland in 2030?

To answer research question (2), we consider mechanisms that lead to a reduction of GHG emissions (so-called GHG abatement levers) as well as rebound effects (which counteract the abatements).

The aim of this study is not to provide justifications for or against the roll-out of 5G mobile networks in Switzerland, but to shed some light on one specific aspect of 5G: the expected effect on GHG emissions. Other aspects, such as security or health, are explicitly excluded from this research.

1.2 Mobile network evolution

A communication network is "a group of devices connected to one another" (Grigorik, 2013, p. 80) and can be used to transmit data between devices. In wireless networks, devices are not connected by cables; instead radio communication is used for data transmission, enabling "the desired convenience and mobility" for users (Grigorik, 2013, p. 79). Wireless networks can be distinguished according to their geographic range into personal area networks (e.g. based on Bluetooth), local area networks (e.g. based on WiFi), metropolitan area networks (e.g. based on WiMAX) and wide area networks (e.g. based on cellular networks) (Grigorik, 2013). This study focuses on cellular networks, which we call *mobile networks*, as it is common.

The first commercial mobile network (1G) was established in 1979. Since then, 4 major generations of mobile networks (1G to 4G) have been rolled out globally, each providing different capabilities for voice or data transmission and related services. Table 1 provides an overview of mobile network generations including two relevant performance characteristics: data rate and latency. Data rate refers to the amount of data which can be send via a network per unit of time (e.g. measured in Kilobits/second or Megabits/second), latency refers to the time a data packet requires for travelling from the sender to the receiver (usually measured in milliseconds) (Grigorik, 2013).

Mobile network generation	**Launch/ release**	**Description**	**Data rate**	**Latency**
1G	1979	Analogue system for voice transmission	Voice only	
2G	1991	First digital system including data transmission (e.g. for text messaging, SMS) and mobile Internet access (for text-based websites)	100–400 Kbit/s	300-1'000 ms
3G	~1999	First broadband Internet allowing for multimedia websites and audio and video streaming.	0.5–5 Mbit/s	100-500 ms
4G	2008-2011	Fast broadband Internet allowing, for example allowing for HD audio and video streaming.	1–50 Mbit/s	<100 ms

Table 1: Evolution of mobile network generations based on Grigorik (2013). The data rates and latency provided in the table are approximations of an average active mobile connection in a real-world setting. These differ from the peak data rate and the lowest possible latency, which can only be achieved under ideal conditions. The launch/release years vary by reference and by country and only provide a rough indication for the timeline.

Mobile network performance (e.g. with respect to data rates and other characteristics) increased with each generation, enabling new types of applications. While 1G and 2G mobile networks were mainly used for phone calls and transmission of limited amounts of data (e.g. 2G only allowed for sending SMS), 3G and 4G mobile networks provide access to the Internet as we know it today, enabling applications such as web surfing, audio and video streaming. Along with the roll-out of 3G mobile networks, the first smartphones were introduced to the market (Blackberry in 2002 and iPhone in 2007).

In the past, mainly consumer devices were connected to mobile networks (e.g. smartphones); thus, the number of devices was linked to the number of mobile network subscribers (which is still growing until today). In recent years, mobile networks are increasingly used to connect objects which transmit data (e.g. household appliances, sensors in street lights, or in cars), a trend called the Internet of Things (IoT). Cisco (2019a) estimates that by 2022 globally, mobile networks will support more than 8 billion personal mobile devices and 4 billion IoT connections. As a consequence of the increasing number of connected devices as well as the increasing use of data-intensive applications such as video streaming, the amount of data transmitted via mobile networks in 2022 is expected to increase to 930 Exabytes globally, which is a factor 113 above the level of 2012 (Cisco, 2019a).

As the variety of applications and devices supported by mobile networks as well as the volume of data transmitted increases, so do the requirements for mobile network performance, even beyond data rates. For example, sensors (a key element of the IoT) are often not connected to a fixed electricity supply and powered by batteries with small capacity; thus, the energy required to send and receive needs to be minimized. Another source of more stringent requirements is the fact that mobile networks will be play an increasing role in (safety-)critical infrastructures and connect vehicles or control electricity grids, which leads to increasing demands for reliability and security. For these reasons, the International Telecommunications Union developed a new standard for 5G mobile networks – setting various requirements for next generation mobile networks (ITU, 2017).

1.3 Opportunities and risks of mobile networks for climate protection

Information and communication technology (ICT) is the entirety of technologies to store, process and transmit information. There is a growing interest in direct and indirect impacts of ICT on GHG emissions (Bieser et al., 2020; GeSI & Accenture Strategy, 2015; Hilty & Bieser, 2017; Malmodin & Bergmark, 2015).

Direct effects refer to the emissions caused by producing, operating and disposing of ICT hardware. These effects are by definition unfavorable for climate protection, as they contribute to GHG emissions. They 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" (Bieser & Hilty, 2018b; ISO, 2006, p. 2).

Indirect effects refer to the changes caused by applying ICT and the consequences for other processes and their GHG emissions. These effects can be favorable or unfavorable for climate protection (Hilty & Aebischer, 2015). For example, ICT allows us to work from home and have virtual meetings, thus avoiding travel-related GHG emissions. However, ICT (e.g. through intelligent transport systems) can also make transport more convenient and cheaper, leading to an increase in transport and associated GHG emissions.

In the last two decades, various studies have been conducted to assess direct and indirect effects of ICT on climate protection (Bieser et al., 2020; Bieser & Hilty, 2018c; Horner et al., 2016; Williams, 2011). For example, a study on opportunities and risks of ICT for climate protection in Switzerland showed that ICT applications have the potential to make a relevant net contribution to climate protection by 2025 (Hilty & Bieser, 2017). All of the studies mentioned have focused on ICT in general (e.g. considering end user devices, data centers, and communication networks). As 5G mobile networks are currently the subject of intense debate in politics and industry, the question arises if and how these networks can contribute to the reduction of GHG emissions.

As for ICT in general, 5G mobile networks have direct effects on GHG emissions, because network equipment needs to be produced, installed, powered with electricity while being used and disposed of at the end of its service life. On the other side, 5G mobile networks provide new opportunities for applications which can contribute to climate protection, i.e., they may have positive indirect effects.

This report is structured as follows: Section 2 presents the analysis of direct effects of 5G mobile networks on GHG emissions (RQ 1). Section 3 presents the analysis of 5G-supported use cases and their expected indirect effects on GHG emissions (RQ 2). Details on the applied methods are provided in the respective sections. Section 4 presents a synopsis of direct and indirect effects of 5G mobile networks on GHG emissions. We end with a conclusion in section 5.

2 Direct effects

2.1 Goal and scope

The direct effects, the resources consumed and the emission caused by producing and operating ICT hardware, are assessed by means of Life Cycle Assessment (LCA). LCA is a "tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e. from raw material acquisition, via production and use stages, to waste management" (ISO, 2006). The related ISO standard distinguishes between four different phases within an LCA study, as shown in Figure 1.

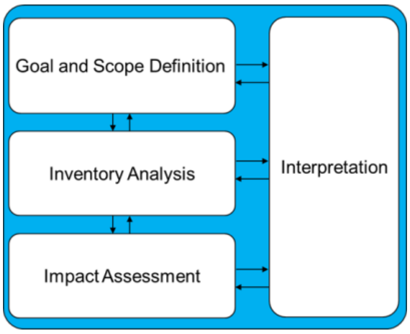


Figure 1: The different steps of a Life Cycle Assessment (LCA) study (ISO, 2006).

The first phase of an LCA study is the goal and scope definition, which defines the general context of the study. This includes the reasons for carrying out the study, the intended application, the applied functional unit, the impact assessment method chosen, as well as the system boundaries of the study.

The goal of this LCA study is to assess direct effects of 5G mobile networks on climate change in Switzerland. For this, a comparative investigation is conducted, comparing the new 5G mobile network with today's mobile network technologies (i.e. with 2-4G mobile networks). Thereby, we develop two scenarios, representing the mobile network configurations for the years 2020 and 2030.

The LCA study has "cradle-to-gate" system boundaries, comprising the production of mobile network infrastructure and its use in Switzerland. Office and technical buildings of Swisscom and their energy demand are excluded from the study due to their low relevance (Malmodin et al., 2012). The end-of-life of the mobile network infrastructure is also excluded from the LCA study, as previous results indicated that the production and use phase together dominate the environmental impacts along the entire life cycle (Scharnhorst et al., 2006).

Within the study, the following three main components of the mobile network system are distinguished: (i) the access, (ii) the core and (iii) the transport network (Figure 2). The functional unit is "1 GB of data transferred by the mobile network".

In phase 2 of this LCA study (i.e. Life cycle Inventory, LCI), we compile and quantify the inputs and outputs of the investigated product and/or service throughout the life cycle. In this phase, data regarding the raw material needs, energy consumption and emission into the environment are collected. For this study, we collected primary data (e.g. data traffic, energy consumption, infrastructure data of the access, core and transport network) from Swisscom and its technical partner Ericsson. We used secondary data from literature to characterize the material composition of the various components and devices within the three network parts. Ecoinvent version v3.5 has been used for all the upstream processes. The results of this step are reported in the next section (see 2.2).

Phase 3 (i.e. Life cycle Impact Assessment, LCIA) is the "phase aimed at understanding and evaluating the importance of the potential environmental impacts of a product system" (ISO, 2006). In other words, within the LCIA phase, the environmental impacts associated with the quantified inventory flows are assessed. This study has the goal to identify the effects of 5G mobile networks on climate change. Therefore, the impacts assessment in this study is reduced to the global warming potential (GWP) using IPCC 2013 factors.

2.2 Used data

The inventory data for the mobile network infrastructures, i.e. the access, core and transport network components and their related energy consumption, have been collected in close collaboration with technical experts from Swisscom and Ericsson, and complemented with information from existing literature. With this data we estimate the amount of GHG emissions caused during production of network infrastructure equipment (production phase) and during generation and transmission of electricity required to operate the infrastructure (use phase).

The mobile network system of Swisscom has been modelled separately for the access, core and transport network. For the access network, we started by describing an "average mobile network site". For the core and transport network, we modeled the entire system. The individual components of these three network parts are summarized in Figure 2.

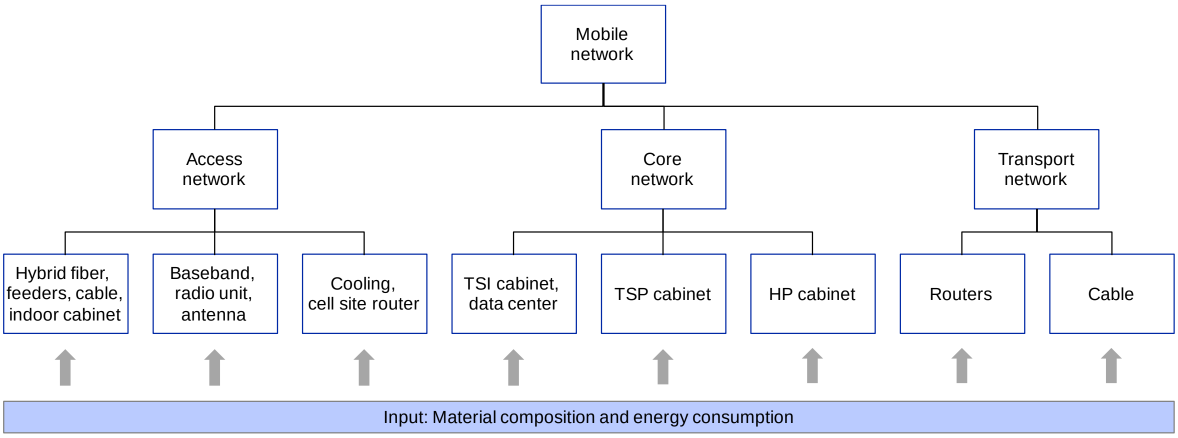


Figure 2: System boundaries and investigated components of the mobile network.

2.2.1 Access network

Each site of the access network contains the following components: baseband units, radio units, beamforming antennas, passive antennas, indoor cabinet, cooling equipment, routers, feeders, jumpers and hybrid fibers. For each of these components, the average quantity (in kg) at such an access site is calculated, as

$$Mass_{x,i,t} = m_x * qty_{x,i,t} * \%_{i,t} \ (Eq. 1)$$

where

m_x is the mass of the component x (e.g. a baseband unit weighs 1 kg), $qty_{x,i,t}$ is the average quantity per site of component x for the mobile network i (i.e. 2-4G or 5G) in the year t (2020 or 2030) and $\%_{i,t}$ represents the split of the component between the 2-4G and 5G mobile network. The shared part of components is equally split between the technologies. The resulting inventory data for an average access network site for 2-4G and 5G in 2020, and 4G and 5G in 2030 (2G and 3G networks will all be decommissioned before 2030) are reported in Table 2.

Component	2020		2030		Unit
	2-4G	5G	4G	5G	
Baseband units	21	9	7	13	kg
Radio units	210	22	89	109	kg
Indoor cabinet	60	22	16	33	kg
PSU	20	12	12	20	kg
Batteries	8	5	5	8	kg
Beamforming antennas	-	21	-	79	kg
Passive antennas	20	15	56	70	kg
Feeders	3’097	2’434	3’097	2’434	m
Jumpers	38	31	40	80	m
Hybrid fibers	600	480	360	720	m
Cooling: air conditioners	5	3	0.7	12	kg
Cooling: flexibox	24	14	29	48	kg
Routers	1	6.8	1	7.2	kg

Table 2: Inventory data for an average site of the access network in 2020 and 2030, respectively. For each year, the split into the various network technologies (i.e. 2-4G resp. 4G and 5G) is shown. 2G and 3G networks will all be decommissioned before 2030.

The energy consumption of each component of the access network is calculated based on information provided by Ericsson. As the provided values are nominal values a correction factor of 0.8 has been applied. The energy consumption for the components of the access network is calculated as:

$$Energy_{x,i,t} = (0.8 * energy_{x}) * qty_{x,i,t} * \%_{i,t} \ (Eq. 2)$$

where

energy_x is the nominal energy consumption (in Watt, W) for the component x , $\text{qty}_{x,i,t}$ is the average quantity per site of the component x for the mobile network i (2-4G or 5G) in the year t (2020 or 2030); $\%_{i,t}$, represents the split of the components between the 2-4G and 5G mobile network. Again, the shared components are equally split between the technologies.

The value of the energy consumption of each component expressed in Watt are then transformed in kWh, assuming an operation time of 24h on 365 days. As above, the values represent an average access network site. The resulting values for 2-4G, 4G and 5G in 2020 and 2030 are reported in Table 3.

Component	2020		2030		Unit
	2-4G	5G	4G	5G	
Baseband	3’877	1’120	880	1’706	kWh
Radio	11’788	1’306	5’835	6’826	kWh
Cabinet (PSU)	618	371	428	714	kWh
Beamforming antenna	-	1’671	-	5’179	kWh
Cooling	681	371	142	237	kWh
Router	130	893	79	943	kWh

Table 3: Energy consumption for an average site of the access network for 2-4G and 5G in 2020 and 4G and 5G technologies in 2030. 2G and 3G networks will all be decommissioned before 2030.

2.2.2 Core and transport network

For the core and the transport network, the collected data represent the entire network system. We collected the data regarding the infrastructure and the energy consumption of the core network with support from Ericsson. Within the infrastructure of the core network in the year 2020 it can be distinguished between (i) the telco cloud infrastructure (TCI) – further split into TCI cabinet and GW cabinet – and (ii) the blade server platform (BSP) – further split into TSP subrack, two types of EPG cabinets, and the HP cabinet, respectively. The core network changes substantially between 2020 and 2030 and the infrastructure comprises only the first element (i.e. the TCI), again split into TCI cabinet and the GW cabinet. For the material composition of the elements of the core network, we distinguish between “electronic components” and “mechanical components”. Table 4 shows the material input and energy consumption for 2020 and 2030.

Component	2020	2030	Unit
Telco Cloud Infrastructure (TCI)			
TCI cabinet			
Electronic component	957	24’340	kg
Mechanical component	818	20’448	kg
Gateway cabinet			
Electronic component	181	1’116	kg
Mechanical component	177	1’091	kg
Blade Server Platform (BSP)			
TSP subrack			
Electronic component	3’880	-	kg
Mechanical component	3’177	-	kg
EPG cabinet, type 1			
Electronic component	1’576	-	kg
Mechanical component	660	-	kg
EPG cabinet, type 2			
Electronic component	788	-	kg
Mechanical component	330	-	kg
HP cabinet			
Electronic component	524	-	kg
Mechanical component	660	-	kg
Energy consumption			
Electricity (AC)	41.77	675.24	kW
Electricity (DC)	202.50	-	kW

Table 4: Inventory data for the core network in 2020 and 2030.

We collected infrastructure and energy consumption data of the transport network with the support of various experts from Swisscom. The transport network is split into three parts, called RAMP, Pentacon and SONATE. While the first two elements (RAMP, Pentacon) represent the nodes that connect the mobile network to the backbone, SONATE represents this actual backbone of all the communication systems of Swisscom, consisting of some (further) access devices/nodes as well as a (national-wide) glass fiber network. This glass fiber network can be split into several parts, where one part represents the connections to the mobile base stations (33’000 km in 2020, 41’000 km in 2030), one part the connections to all other elements of the Swisscom network (24’000 km in 2020), and one part a common backbone (including the metro core and metro access network, about 70’000 km in 2020 and 2030). From the very last part – based on the actual amount of transferred data – about 10% or 7’000 km are allocated to the 2-4G and 5G mobile networks here for 2020 and 2030. With a similar split (10%), the access devices/nodes of SONATE are allocated to the mobile network infrastructure modelled here.

All the nodes (RAMP, Pentacon) and further access devices (SONATE) are aggregated as “routers” in Table 5 below. We used the weights of the various devices provided in the data sheets of the producers of these components (i.e. Cisco, Ericsson, Huawei, and Juniper respectively).

Component	2020	2030	Unit
RAMP Network part 1 (EN,CO,BG)	9’412	-	kg
RAMP Network part 2 (RR)	236	236	kg
RAMP Network part 3 (SUMO)	24’050	-	kg
Pentacon part 1 (MAU,MAN-S/L)	19’600	63’142	kg
Pentacon part 2 (MEN,MRR)	1’944	2’520	kg
Pentacon part 3 (S-MEN,MCN,MDN)	1’800	5’296	kg
SONATE part 1 (Core-Metro)	23’474	23’474	kg
SONATE part 2 (Core-Backbone)	4’739	4’739	kg
Total Nodes/Routers	**85’255**	**99’407**	**kg**
Optical Fiber	40’000	48’000	km
Energy consumption	1.09E+07	1.54E+07	kWh/year

Table 5: Inventory data for the transport network in 2020 and 2030.

2.2.3 Life cycle inventories

The inventory data for each of the component of the mobile network (Figure 1) have then been translated into respective LCI datasets as described below.

Life cycle inventory of the access network

The material composition of each component of the access network has been identified in close collaboration with the experts from Swisscom and Ericsson, using available information in literature and in the technical documentation of the components. The details are reported in the subsequent tables (Table 6).

Component	Material composition	Data source(s)
Baseband unit	See Table 8	Streicher-Porte et al. (2015), technical data sheets
Radio unit	See Table 9	Aleksic (2013), technical data sheets
Indoor cabinet (PSU)	See Table 10	Expert input, technical data sheets
Lead acid battery	See Table 11	Sullivan and Gaines (2012)
Antennas (passive & beamforming)	See Table 12	Expert input, technical data sheets
Cooling (flexibox part)	See Table 13	Expert input, technical data sheets
Cooling (air conditioner part)	See Table 13	Hischier et al. (2020)

Table 6: Overview of the material composition data for the components of mobile networks.

For modelling the elements Jumper, Hybrid fiber, Router and PSU, already existing datasets from the database ecoinvent have been used as proxies (Table 7).

Component	Used ecoinvent dataset
Jumper	Cable, network cable, category 5, without plugs {GLO}
Hybrid fiber	Cable, data cable in infrastructure {GLO}
Router	Router, internet {GLO}
PSU (in indoor cabinet)	Power adaptor, for laptop {GLO}

Table 7: Used ecoinvent dataset for the jumper, hybrid fiber, router and PSU.

To characterize the material composition for the “Baseband unit”, we used the description of a "Rackserver" device by Streicher-Porte et al. (2015) (Table 8). For each element of a rackserver (plastics, aluminum, steel, electronic components), we calculated its share of the total mass of the Rackserver of and used the shares as a “proxy” to estimate the share of plastics, aluminum, steel, copper and electronic components within a single “Baseband unit” with a mass of 1kg.

Rackserver	g
Aluminum	752
Steel	14’675
Plastics	473
PSU	1’360
Storage device	1’900
Main board	1’400
RAM	80
CPU	43
Fans	8
Cable	260
Total weight	**21’051**

→

Baseband Unit	
Amount	**Applied ecoinvent datasets**
3%	– market for aluminium, wrought alloy {GLO} – market for sheet rolling, aluminium {GLO}
70%	– market for steel, low-alloyed {GLO} – market for sheet rolling, steel {GLO}
2%	– market for polyethylene, high density, granulate {GLO} – market for acrylonitrile-butadiene-styrene copolymer {GLO} – market for injection moulding {GLO}
16%	– market for printed wiring board, mounted mainboard, laptop computer, Pb free {GLO}
1%	– market for copper [GLO] – market for wire drawing, copper {GLO}

Table 8: [Left] Material composition (in g/device) of a Rackserver, used as proxy for the inventory data for the baseband unit. [Right] Composition (in % of materials) of the baseband unit and the used ecoinvent dataset to model the materials.

To characterize the material composition for the “Radio unit”, we used data describing a “UMTS Radio Network Contoller” according to Aleksic (2013) in a similar manner as for the “baseband unit”. The inventory data and the used ecoinvent dataset for the “Radio Unit” are reported in Table 9.

UMTS-RNC	%
Housing	76
Fan	10
Switches	2
Processors	7
Timing board	1
Network interface	3
Cable	1

→

Radio Unit	
Amount	**Applied ecoinvent datasets**
5%	– market for aluminium, wrought alloy {GLO} – market for sheet rolling, aluminium {GLO}
70%	– market for steel, low-alloyed {GLO} – market for sheet rolling, steel {GLO}
10%	– market for polyethylene, high density, granulate {GLO} – market for acrylonitrile-butadiene-styrene copolymer {GLO} – market for injection moulding {GLO}
14%	– market for printed wiring board, mounted mainboard, laptop computer, Pb free {GLO}
1%	– market for copper [GLO] – market for wire drawing, copper {GLO}

Table 9: [Left] Material composition (in g/device) of the UMTS radio network controllers (UMTS-RNC), used as proxy for the inventory data of the radio unit. [Right] Composition (in % of materials) of the radio unit and used ecoinvent dataset to model the materials.

We estimated the inventory of the indoor cabinet (Table 10) with the support of Ericsson experts and the information provided in the technical datasheet of the Power 6210 unit from Ericsson. The modelled infrastructure represents a capacity rack (for batteries), combined with a power rack and a power connection unit (PCU) on the top. The authors assumed that 2% of the weight represent the (internal) connection cables. The remaining weight of the indoor cabinet represents the batteries and the power supply (PSU) units. While the PSU units have been approximated by using the ecoinvent dataset “power adaptor, for laptop {GLO}, market for, Cut-off, U” (as stipulated in Table 7 above), the batteries have been modelled according to the information provided by Sullivan and Gaines (2012) (Table 11).

Component	Material composition	Used ecoinvent dataset
7% PCU/power connection unit	71% Steel 29% Plastic	– market for steel, low-alloyed {GLO} – market for sheet rolling, steel {GLO} – market for polyethylene, high density, granulate {GLO} – market for acrylonitrile-butadiene-styrene copolymer {GLO} – market for injection moulding {GLO}
55% Battery rack	100% Steel	– market for steel, low-alloyed {GLO} – market for sheet rolling, steel {GLO}
36% Power rack	100% Steel	– market for steel, low-alloyed {GLO} – market for sheet rolling, steel {GLO}
2% Electronic cables	100% Copper	– market for copper {GLO} – market for sheet rolling, copper {GLO}

Table 10: The main components (share of total weight) of an indoor cabinet, material composition of each component and the used ecoinvent datasets.

Material composition	Used ecoinvent dataset
69% Lead	– market for lead {GLO}
11% Sulfuric acid	– market for sulfuric acid {GLO}
4% Plastic (PP)	– market for polypropylene, granulate {GLO}
12% Water	– market for water, deionised, from tap water, at user {Europe without Switzerland}
4% Glass fiber	– market for glass fibre {GLO}

Table 11: Material composition (share of total weight) and ecoinvent dataset used for the lead acid battery.

The material composition for both types of antennas (i.e. beamforming antenna units and passive antenna units) were provided by experts from Ericsson (Table 12).

Material composition	Used ecoinvent dataset
70% Metal	– market for steel, low-alloyed {GLO} – market for sheet rolling, steel {GLO}
5% Plastic	– market for polyethylene, high density, granulate {GLO} – market for acrylonitrile-butadiene-styrene copolymer {GLO} – market for injection moulding {GLO}
24% Electronics	– market for printed wiring board, mounted mainboard, laptop computer, Pb free {GLO}
1% Copper	– market for copper {GLO} – market for wire drawing, copper {GLO}

Table 12: Material composition and ecoinvent dataset applied for both types of antennas (i.e. beamforming antenna and passive antenna).

The cooling unit is composed of two sub-components – the “flexibox unit” (a passive cooling system) and the classical air conditioner unit (also called split unit). For the “flexibox unit”, the material composition has been provided by experts from Swisscom. For the air conditioner, we used data provided in Hischier et al. (2020). The material composition and the ecoinvent dataset used to model the cooling unit are listed in Table 13.

Unit	Material composition	Used ecoinvent dataset
Flexibox unit	90% Steel	– market for steel, low-alloyed [GLO] – market for sheet rolling, steel {GLO}
	10% Electronic	– market for printed wiring board, mounted mainboard, laptop computer, Pb free {GLO}
Air conditioner unit	8.35% Plastic	– market for polyethylene, high density, granulate {GLO} – market for polypropylene, granulate {GLO} – market for synthetic rubber {GLO} – market for polystyrene, general purpose {GLO} – market for polyethylene terephthalate, granulate, amorphous {GLO} – market for acrylonitrile-butadiene-styrene copolymer {GLO} – market for injection moulding {GLO}
	3.69% Electronic	– market for printed wiring board, mounted mainboard, laptop computer, Pb free {GLO}
	9.04% Iron	– market for cast iron {GLO}
	44.50% Steel	– market for steel, low-alloyed {GLO} – market for sheet rolling, steel {GLO}
	1.86% Stainless steel	– market for steel, chromium steel 18/8 {GLO} – market for sheet rolling, chromium steel {GLO}
	7.91% Aluminium, sheet extrusion	– market for aluminium, wrought alloy {GLO} – market for sheet rolling, aluminium {GLO}
	21.64% Copper wire	– market for copper {GLO} – market for wire drawing, copper {GLO}
	3.01% Refrigerant	– market for refrigerant R134a {GLO}

Table 13: Material composition and used ecoinvent dataset for the cooling unit.

Life cycle inventory of the core and transport network

We created the inventory dataset for the core network with the technical support Ericsson experts, who provided a composition of the mechanical and electronic parts for various components. Due to the lower relevance of this part (Malmodin et al., 2012), we modelled these two parts as 100% steel sheets for the mechanical part and 100% printed wiring boards for the electronic part. The exact datasets used are listed in Table 14.

Network component	Used ecoinvent dataset
Electronic components	– market for printed wiring board, mounted mainboard, laptop computer, Pb free {GLO}
Mechanical components	– market for steel, low-alloyed {GLO} – market for sheet rolling, steel {GLO}

Table 14: Components and the applied ecoinvent datasets for the core network.

The transport network has been modelled based on inputs from Swisscom experts and technical datasheets of exemplary nodes and access devices. We used the weight of these devices provided in the data sheets to calculate the total weight (listed in Table 5 above). For their composition, we used the router dataset from ecoinvent. However, as the original router dataset in ecoinvent 3.5 is erroneous (showing wrong amounts for the actual electronics part), the router has been "re-modelled" for this study according to the dataset provided in Table 15 below.

Also for the optical fiber, no respective dataset is available in ecoinvent 3.5. Therefore, we used information provided by Pinto et al. (2017) to model 1 m of optical fiber. The details are reported in Table 15.

Component	Mass [kg]	Used ecoinvent dataset
Fiber [1 m]	0.01975 0.00124 0.00124	– market for glass fibre {GLO} – market for extrusion, plastic pipes {GLO} – market for polymethyl methacrylate, sheet {GLO}
Router [1 kg]	0.47 0.265 0.265	– market for chassis, internet access equipment {GLO} – market for printed wiring board, surface mounted, unspecified, Pb containing {GLO} – market for printed wiring board, surface mounted, unspecified, Pb free {GLO}

Table 15: Components and used ecoinvent datasets for 1 m of optical fibre (top), and 1 kg of router (bottom) in the transport network.

Life cycle inventory of the Swiss electricity mix 2030

For the year 2020, the electricity mix of Switzerland, available in ecoinvent 3.5, has been applied in this study. For the electricity mix of Switzerland in the year 2030, in total five different future scenarios have been modelled, called "business as usual" (BAU), "pessimistic", "expected, "optimistic and "theoretical" in the following (see 3.5.2, page 49, for detailed assumptions). Table 16 reports – for each of these five scenarios – the contribution of the different primary energy sources, both for the generation in Switzerland and the imported electricity generated in other countries. We used, the "expected" scenario as the baseline scenario for 2030.

Swiss generation	**BAU**	**Pessimistic**	**Expected**	**Optimistic**	**Theoretical**
Water power (without pump electricity)	46.40%	46.40%	46.40%	46.40%	46.40%
PV	9.53%	9.67%	10.20%	12.55%	35.73%
Wind	4.76%	4.83%	5.10%	6.27%	17.87%
Biomass (wood)	0.31%	0.31%	0.31%	0.31%	-
Biogas	0.33%	0.33%	0.33%	0.33%	-
Biomass (waste incinerator)	0.99%	0.99%	0.99%	0.99%	-
Nuclear energy	16.30%	16.30%	16.30%	16.30%	-
Natural gas thermal power station	0.06%	0.06%	0.06%	0.06%	-
Waste incinerator	1.35%	1.35%	1.35%	1.35%	-
Total generation in Switzerland	**80.04%**	**80.25%**	**81.04%**	**84.57%**	**100%**

Foreign generation	**BAU**	**Pessimistic**	**Expected**	**Optimistic**	**Theoretical**
Water power (without pump electricity)	4.34%	4.34%	4.34%	4.34%	-
PV	0.01%	0.01%	0.01%	0.01%	-
Wind	0.45%	0.45%	0.45%	0.45%	-
Nuclear energy	2.12%	2.09%	1.97%	1.48%	-
Crude oil	0.01%	0.01%	0.01%	0.01%	-
Natural gas	0.21%	0.20%	0.19%	0.14%	-
Black coal steam turbine	0.01%	0.01%	0.01%	0.01%	-
Waste incinerator	0.04%	0.04%	0.04%	0.04%	-
from non-verifiable sources	12.78%	12.60%	11.93%	8.96%	-
Total foreign generation	19.96%	19.75%	18.96%	15.43%	-

Table 16: Share of energy consumption in Switzerland by energy source, inland generation and foreign generation for the five scenarios of the electricity mix in 2030.

2.3 Results and interpretation

The mobile data traffic in Switzerland of Swisscom for 2020 and 2030 is reported in Table 17. In 2020, 99% of data is transferred by 2-4G and 1% by 5G networks. From 2020 until 2030, we expect an increase of mobile data traffic from 544 mn GB in 2020 to 5042 mn GB. In 2030, 80% of this data traffic will be transferred over the 5G network.

Data traffic	2020	2030
Total data volume	544	5`042
Data volume transferred by 2-4G	539	1`008
Data volume transferred by 5G	5	4`033

Table 17: Mobile data traffic (mn GB) in Switzerland transferred by Swisscom 2-4G and 5G mobile networks in 2020 and in 2030.

The global warming potential (in kg CO_2e) of 2-4G and 5G networks in 2020, and 4G and 5G networks in 2030 (2G and 3G networks will all be decommissioned before 2030) per unit of data (1 GB) and per year are reported in Table 18.

Mobile network generation	2020		2030	
	per GB	per year	per GB	per year
2-4G (2020) / 4G (2030) network	0.03	1.63E+07	0.008	8.09E+06
5G network	1.01	5.50E+06	0.004	1.81E+07

Table 18: Global warming potential (GWP 100a, in kg CO_2e) for the 2-4G and 5G networks in 2020, and 4G and 5G networks in 2030 (2G and 3G networks will all be decommissioned before 2030). The impacts are shown for 1GB of transmitted data, as well as for the total amount of data transmitted in the respective networks per year.

Table 18 and Figure 3 show that in 2030, 5G mobile networks are expected to cause 85% less GHG emissions per unit of transmitted data than 2-4G mobile networks in 2020.

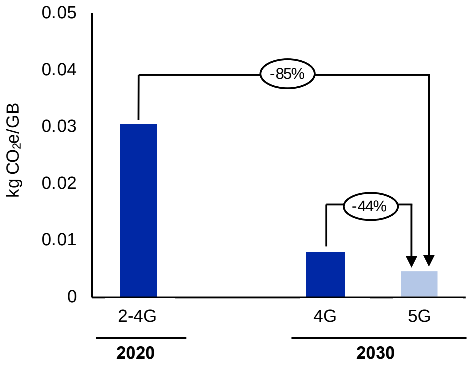


Figure 3: Global warming potential (kg CO_2e) of 2-4G in 2020, 4G and 5G in 2030 per GB of transmitted data.

However, if we consider the amount of GHG emissions caused by each network technology per year, 5G networks in 2030 will cause 11% more GHG emissions than 2-4G networks in 2020 (Figure 4). This increase is due to the increase in mobile data traffic between 2020 and 2030 (+650%). If the expected data traffic in 2030 would be transmitted only via 4G mobile networks, it can be assumed that GHG emissions caused by mobile networks in Switzerland would be higher (see 2.4).

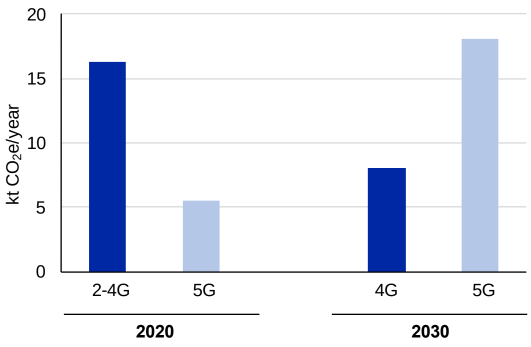


Figure 4: Global warming potential (kt CO_2e) of 2-4G and 5G mobile networks in 2020, and 4G and 5G mobile networks in 2030 per year.

A contribution analysis has been performed in order to investigate the main sources (e.g. infrastructure and energy consumption) of GHG emissions in the four configuration networks (2-4G, 5G in 2020 and 4G, 5G in 2030) (Figure 5).

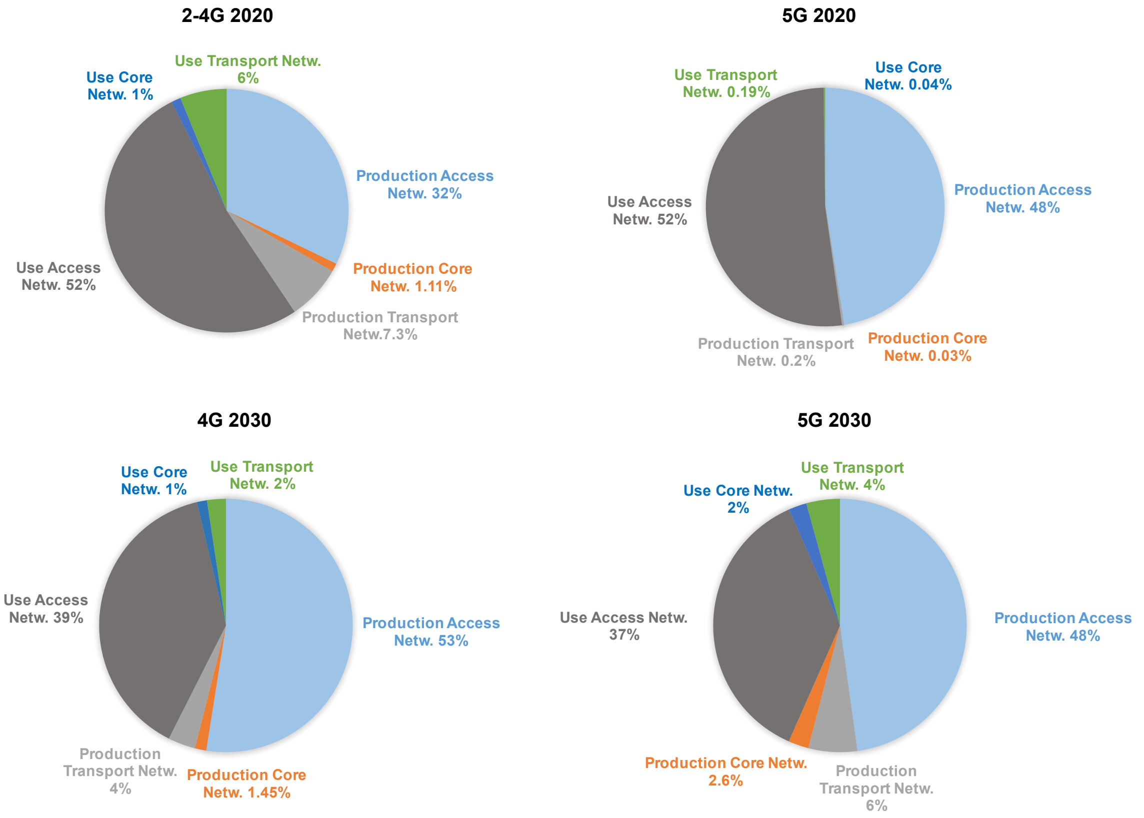


Figure 5: Contribution analysis of the mobile networks in 2020 and 2030 for the impact category climate change (GWP). The functional unit is 1 GB of data transmitted.

The contribution analysis shows that, for the 5G mobile network in 2030, the production of the infrastructure (access, core and transport network infrastructure) contributes to 57% to the GHG emissions, while 43% are caused by energy consumption during the use phase. A similar trend can be seen also for the 4G network in 2030.

For the mobile networks (2-4G and 5G) in 2020 however, more GHG emissions are caused by energy required to operate the network infrastructure (use phase, 60%) than by producing the network infrastructure (40%).

2.4 Sensitivity analysis

We investigated a hypothetical scenario in which the total volume of data in 2030 is allocated to the 4G network; meaning that no 5G technology will be available in 2030. For comparison, we also investigated the opposite scenario – i.e. all the volume of data is transferred by the 5G network, and no 4G network is needed anymore. It shows that in this “5G only” scenario, mobile networks would in 2030 cause roughly 15% less GHG emissions than in the “4G only” scenario (Figure 6).

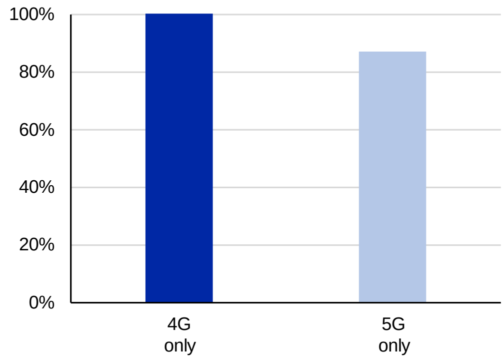


Figure 6: Global warming potential assuming all mobile data traffic in 2030 is transmitted via 4G networks (“4G only”, set to 100%) or via 5G networks (“5G only”) in 2030.

The global warming potential of 5G networks in 2030 per GB of transmitted data was estimated to be 0.0045 $kgCO_2e/GB$ using the “expected” electricity mix in 2030. As the electricity mix influences the LCA results (Malmodin & Lundén, 2016) a sensitivity analysis has been performed using the “BAU”, “pessimistic”, “optimistic” and “theoretical” electricity mix in (as listed in Table 16). The results of the sensitivity analysis are report in Table 19 and shown in Figure 7 (the expected scenario has been set to 100%).

Scenario	BAU	Pessimistic	Expected	Optimistic	Theoretical
GWP [$kgCO_2e$]	0.0046	0.0046	0.0045	0.0042	0.0036

Table 19: Sensitivity analysis for 5G mobile networks in 2030, for 1 GB of data transmitted.

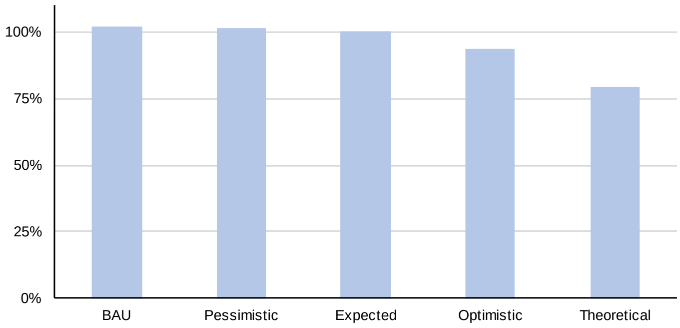


Figure 7: Potential impacts on climate change due to the use of 5G networks in 2030 operated with different electricity mixes. The impact on climate change of 5G networks operated with the electricity mix in the "expected" scenario – in this study used as baseline scenario – is set to 100%.

The sensitivity analysis performed here confirms the relevance of the “electricity mix” in assessing the environmental impact of the ICT sector (Malmodin & Lundén, 2016).

3 Indirect effects

3.1 Indirect effects of ICT on climate protection in literature

ICT is an enabler of many forms of change in all sectors of the economy. Such indirect effects can have an increasing or decreasing impact on GHG emissions, depending on the use case of ICT. Several frameworks for structuring indirect ICT effects have been proposed (for an overview see Hilty & Lohmann, 2013). Important categories are substitution effects, optimization effects, induction effects and (at the macro level) rebound effects. ICT-induced substitution and optimization effects can lead to a decrease in GHG emissions (e.g. video conferencing substitutes air travel, a smart thermostat optimizes heating). Induction effects occur if ICT use motivates additional consumption of goods or services (Bieser et al., 2020). Rebound effects occur when ICT-induced improvements in energy efficiency lead to price reductions of an energy service and increased use of the same or other energy services (e.g. ICT applications in transport can lower the cost of mobility and increase demand for transport or other activities which cause energy consumption) (Greening et al., 2000).

Indirect effects of ICT on climate protection have been researched in industry practice and academia for two decades (Bieser & Coroamă, 2020). The Global e-Sustainability Initiative (GeSI), an ICT industry association for sustainability, commissioned a series of studies to assess the climate protection potential of ICT use (GeSI et al., 2008; GeSI & Accenture Strategy, 2015; GeSI & BCG, 2012; GeSI & Deloitte, 2019). To do so, they selected a set of ICT use cases in various sectors (e.g. smart grid in the energy sector, telecommuting in the transport sector) and assessed and aggregated their impact on GHG emissions. The results of these studies postulate that the climate protection potential of applying ICT (indirect effects) is much higher than the GHG footprint of the ICT sector (direct effects). In contrast, various studies conducted by academic institutions estimate that the unfavorable effects of ICT on climate protection so far outweigh the favorable effects or at best cancel each other out. For example, a study commissioned by Swisscom and WWF Switzerland on opportunities and risks of digitalization for climate protection in Switzerland showed that by 2025 under pessimistic assumptions GHG-increasing effects of ICT will outweigh GHG-reducing effects. Only, if GHG abatement potentials are systematically explored and negative effects mitigated, digitalization can serve climate protection (Hilty & Bieser, 2017).

Many further studies of indirect effects of ICT on climate protection exist, most of which focus on ICT in general. We could not find a study which systematically assesses the GHG impacts of 5G-enabled use cases specifically.

3.2 5G network capabilities and usage scenarios

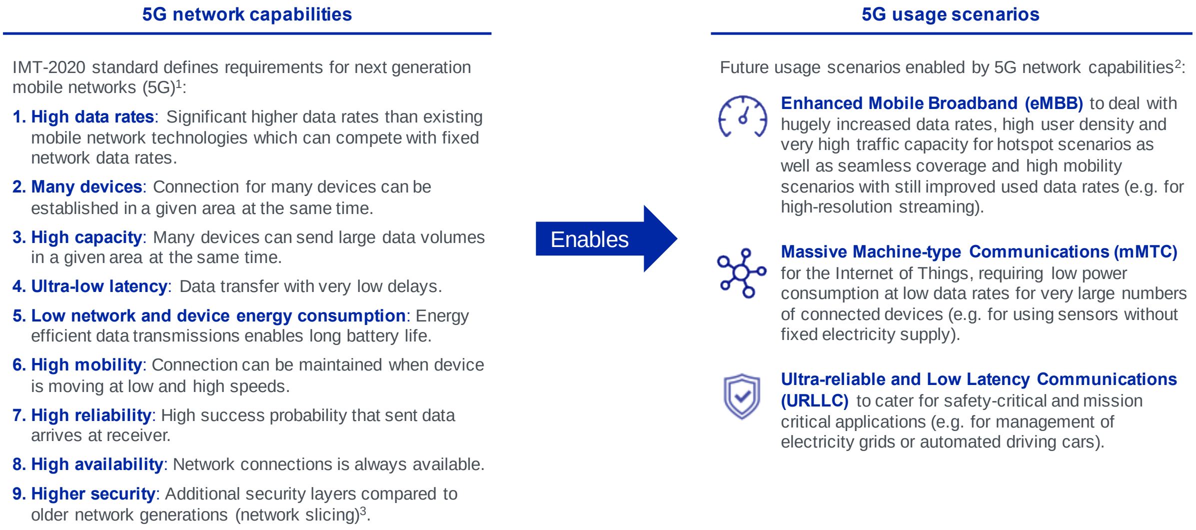
Various trends lead to increasing requirements placed on mobile networks, e.g.:

- Consumers want to access the Internet from almost anywhere at any time.
- Many data-intensive applications are developed and used (e.g. high-resolution video streaming on smartphones).
- Companies in various sectors identify potentials for process improvements based on (fully) automated and (mobile) connected production processes.
- Objects are equipped with mobile connections and transmit data amongst each other. For example, mobile networks shall be used to provide connectivity for operating and maintaining (safety-)critical infrastructures (e.g. sensors to monitor the conditions of electricity grids or streets).

To specify the requirements placed on the next generation of mobile networks, the International Telecommunication Union (ITU) developed three mobile network usage scenarios (ITU, 2015):

(1) *Enhanced Mobile Broadband (eMBB)* to deal with hugely increased data rates, high user density and very high traffic capacity for hotspot scenarios as well as seamless coverage and high mobility scenarios with still improved used data rates (e.g. for high-resolution streaming).
(2) *Massive Machine-type Communications (mMTC)* for the Internet of Things, requiring low power consumption and low data rates for very large numbers of connected devices (e.g. for using sensors without fixed electricity supply).
(3) *Ultra-reliable and Low Latency Communications (URLLC)* to cater for safety-critical and mission critical application (e.g. for management of electricity grids or automated vehicles (AVs)).

In 2017, the ITU transferred these usage scenarios into a set of minimum requirements in the IMT-2020 report (ITU, 2017), which became a standard for requirements of 5G mobile networks. We analyzed the requirements and identified eight capabilities of future 5G mobile networks which depict a significant improvement over existing mobile network technologies and can provide benefits to use cases with GHG abatement potentials (Figure 8).



5G network capabilities

IMT-2020 standard defines requirements for next generation mobile networks (5G)[1]:

1. **High data rates**: Significant higher data rates than existing mobile network technologies which can compete with fixed network data rates.
2. **Many devices**: Connection for many devices can be established in a given area at the same time.
3. **High capacity**: Many devices can send large data volumes in a given area at the same time.
4. **Ultra-low latency**: Data transfer with very low delays.
5. **Low network and device energy consumption**: Energy efficient data transmissions enables long battery life.
6. **High mobility**: Connection can be maintained when device is moving at low and high speeds.
7. **High reliability**: High success probability that sent data arrives at receiver.
8. **High availability**: Network connections is always available.
9. **Higher security**: Additional security layers compared to older network generations (network slicing)[3].

5G usage scenarios

Future usage scenarios enabled by 5G network capabilities[2]:

Enhanced Mobile Broadband (eMBB) to deal with hugely increased data rates, high user density and very high traffic capacity for hotspot scenarios as well as seamless coverage and high mobility scenarios with still improved used data rates (e.g. for high-resolution streaming).

Massive Machine-type Communications (mMTC) for the Internet of Things, requiring low power consumption at low data rates for very large numbers of connected devices (e.g. for using sensors without fixed electricity supply).

Ultra-reliable and Low Latency Communications (URLLC) to cater for safety-critical and mission critical applications (e.g. for management of electricity grids or automated driving cars).

Figure 8: 5G network capabilities according to IMT-2020 standard (2017) and 5G usage scenarios (ITU, 2015). Higher security is not part of the IMT-2020 standard. However, network slicing is a 5G feature, which provides an additional layer of security compared to existing mobile network technologies[1].

3.3 5G-supported use cases

If future 5G mobile networks provide the capabilities described above, existing mobile network use cases can be improved (e.g. improved video conferencing quality due to higher data rates and lower latency) and new use cases can be enabled (e.g. low latency communication is a vital requirement for fully automated driving). In order to identify potential 5G-supported use cases, we reviewed existing literature on 5G applications from academia, industry (e.g. network technology providers), standardization bodies (e.g. 3GPP) and industry associations (e.g. Next Generation Mobile Networks Alliance). We aggregated similar use cases, harmonized terminology across use cases and clustered these into sectors (Table 20). Use cases in the sectors transportation, manufacturing and entertainment and media were most frequently mentioned.

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[1] Network slicing is a technology which allows to provide various, individually configured, virtual networks (network slices) based on one shared network infrastructure (Li et al., 2017).

Sector	Use case
Transport	– Automated driving – Connected vehicles and transport infrastructure (e.g. connected cars or drones, traffic monitoring) – Virtual presence (e.g. video conferencing, telecommuting) – Transport information systems (e.g. infotainment systems, route optimization)
Manufacturing	– Automation of industrial production processes (e.g. robotics) – Optimization of industrial production processes (e.g. remote maintenance, zero-defect-manufacturing) – Augmented and virtual reality in industrial production (e.g. improved worker training) – Tracking of goods (e.g. inventory management, just-in-time delivery) – Remote control (e.g. mobile drones to keep workers out of dangerous areas)
Farming	– Precision fertilization and livestock farming – Agricultural robots (e.g. for weeding)
Energy	– Smart grid (e.g. real-time electricity grid management)
Buildings	– Intelligent heating and cooling – Remote home monitoring
Entertainment and media	– Smart stadiums (e.g. immersive experiences, improved operations, upselling) – Augmented and virtual reality (e.g. remote participation in events) – Immersive media (e.g. personalized video advertisement in densely populated areas) – High-resolution streaming – Wearables (e.g. smart watches, health trackers) – Collaborative gaming
Health	– Remote health services (e.g. remote surgery) – Remote health monitoring (e.g. fall detection) – Smart medication (e.g. digital medication diaries)
Public sector	– Infrastructure monitoring and control (e.g. defect detection) – Reliable communication in case of emergencies (e.g. robust communication in case of disasters) – Video surveillance (e.g. surveillance of public spaces)

Table 20: Overview of selected 5G-supported use cases by sector according to literature review.

3.4 Method

3.4.1 Selection of use cases

5G mobile network applications in almost all economic and social systems exist; thus, it is almost impossible to cover all indirect effects of 5G mobile networks on GHG emissions. For specific use cases of 5G mobile networks (e.g. AD, smart grid), however, we can estimate indirect effects on GHG emissions, e.g. by comparing a use case scenario without the adoption of 5G mobile networks (baseline) with a scenario with the adoption of 5G mobile networks (Bieser & Hilty, 2018b). Based on the results of the literature review we discussed the use cases with the study team and with a study sounding board which consisted of three members of the Swiss parliament. Finally, we selected four use cases in different sectors at different maturity levels that benefit from 5G networks and can avoid GHG emissions. Table 21 provides an overview of the selected use cases and its main levers for reducing GHG emissions.

Sector	Use case	Description	GHG abatement lever
Work & transport	Flexible work	Working from everywhere – at the employer's office, at home, on the move or from other places. Efficient virtual collaboration with colleagues and customers independent of location.	Reduction of – commuter traffic – business travel – office space
Energy	Smart grid	Optimization and monitoring of electricity supply and demand processes.	– More efficient provisioning of electricity – Reduction of electricity consumption – Increased use of electricity from (fluctuating and/or decentralized) renewable sources
Transport	Automated driving	(Partly) automating the dynamic driving task in street transport.	– Increased fuel efficiency – Reduction in vehicle-miles travelled through automated mobility and transport services
Agriculture	Precision farming	Optimization of agricultural production processes.	– Reduced use of agricultural input factors (e.g. fertilizers) – Reduced GHG emissions (including methane, CH_4, and nitrous oxide, N_2O)

Table 21: 5G-supported use cases in scope of this study and its main GHG abatement lever. Further use case GHG impacts exist.

3.4.2 Assessment of use cases

For each use case, we qualitatively analyzed which 5G network capabilities are beneficial for the use case (based on 3.2), what GHG abatement potential and rebound effects can be expected, and if there are further environmental, social and economic impacts.

In addition, a quantitative estimation of the GHG abatement potentials was conducted for Switzerland in 2030 by applying the following procedure (Bieser & Hilty, 2018c):

- identifying *GHG abatement levers* (e.g., increase of fuel efficiency of road transport vehicles through AD),
- estimating *baseline emissions*, i.e., the prospective emissions caused in 2030 with current patterns before the use case was realized (e.g. expected transport GHG emissions without significant adoption of AD),
- estimating the *level of adoption* of the use case in 2030, i.e., the share of the population that will adopt the use case (e.g. share of AVs in 2030),
- estimating the *impact on GHG emissions* per unit of adoption of the use case (e.g., fuel savings due to AD),
- estimating the expected *rebound effect* (e.g. increase in vehicle-miles travelled due to cost reductions of car transport).

We based our analysis on the data available from academic and industrial sources and additional interviews with experts from Switzerland and other countries. As the use cases depend on further ICT equipment besides 5G networks (e.g. smart grids require smart meters), we also roughly estimated the GHG emissions caused by production and operation of this additional equipment in 2030. We call this equipment "non-5G equipment" needed for the given use case. For this non-5G equipment, we estimated life-cycle GHG impacts of the devices based on the weight, lifetime and power consumption during operation using device emission factors from ecoinvent (ecoinvent Centre, 2018; Wernet et al., 2016). We extrapolated impacts per device to country-wide values using use case specific macro-economic indicators (e.g. number of commuters in 2030 for flexible work), considering expected adoption by 2030.

To deal with the uncertainty about future developments and to show the potential influence of actions taken, we developed three scenarios for the indirect effects in 2030. The scenarios differ in the assumptions made about adoption rates and GHG impacts in 2030 (Table 22). The magnitude of the differences between the scenarios reflects the uncertainty.

Scenario	Description
Pessimistic	The pessimistic scenario combines… – an adoption rate assuming that planned actions to increase penetration of the use case are not taken with – the lower boundary of the data points for the impact identified.
Expected	The expected scenario combines… – an adoption rate that can be expected according to measures currently implemented or planned with – the average of the data points for the impact identified.
Optimistic	The optimistic scenario combines… – an adoption rate assuming that actions accelerating penetration of the use case are taken with – the upper boundary of the data points for the impact identified.

Table 22: Scenarios used for the estimation of indirect effects.

3.5 Use cases in detail

3.5.1 Flexible work

Terminology

ICT relaxes space and times constraints of work (Lenz & Nobis, 2007). That means, that many activities, especially in the knowledge-intensive sector, which were originally bound to the employer's office and its opening hours can now be performed location- and time-independent by means of ICT (Bieser & Hilty, 2020). Thus, physical presence at a specific workplace or a physical meeting with a business partner is often not necessarily required for effective collaboration.

Telecommuting means "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" (Mokhtarian, 1991, p. 11). Besides working from home, telecommuting can also be performed from a telecommuting center (Mokhtarian, 1991, p. 11), e.g. in co-working spaces, or on-the go (e.g. in trains). If telecommuting leads to a shift of work locations to the worker's homes or to places, which are closer to the worker's home, it can lead to a reduction of commuter traffic and associated GHG emissions. Plus, employers can reduce their office space and reduce energy consumption and GHG emissions caused by heating, cooling and lighting office space.

Besides telecommuting, video conferencing technology provides the possibility to conduct business meetings at a distance and thus to avoid GHG emissions associated with business travel. Various types of video conferencing systems exist ranging from video telephony (simplest form; person-to-person communication) to telepresence system (fixed installation in a room; best audio and video quality) (Kubrak, 2019).

Flexible work in Switzerland

In the following we describe current (tele-)commuting, video conferencing and business travel practices in Switzerland.

(Tele-)commuting

The larger part of work in Switzerland is conducted at employer's offices, causing significant amounts of commuting. In Switzerland, in 2017, roughly 4.0 million people commuted to work, 33% more than in 2000. Between 2010 and 2017 the one-way commute length in Switzerland increased from 13.8 km to 15.0 km and the average time spent on a one-way commute was 30.6 minutes in 2017 (FSO, 2019b). Figure 9 shows that in 2017 the car was by far the preferred commute transport mode followed by trains and public street transport. This causes significant amounts of GHG emissions because motorized transport is associated with high GHG emissions. Besides its environmental impacts, commuting causes congestion during peak hours and has significant effects on individuals' well-being (Ye & Titheridge, 2015).

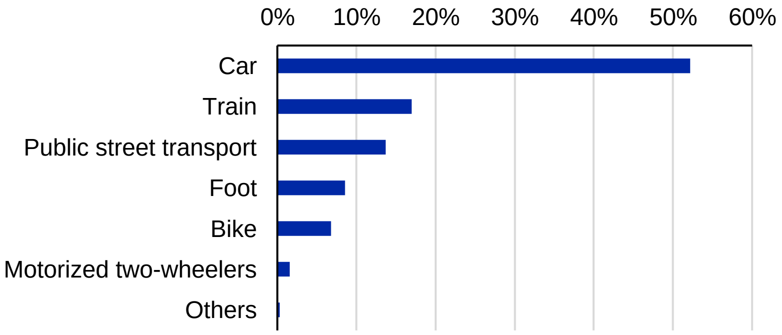

Figure 9: Share of commuters by main commute transport mode in Switzerland in 2017 based on FSO (2019a).

In Switzerland, an increasing share of work can potentially be performed outside of the employer's office. The number of people working in the tertiary (service) sector in Switzerland increased from roughly 2.2 million 1992 to 3.0 million in 2019. In the same period, the share of those people who work on knowledge-intensive services increased from 46% to 57% (FSO, 2020f). From 2001 until 2018 the share of the Swiss working population who occasionally or regularly work from home increased from 6.6% to 23.8% (FSO, 2020e). The number of co-working spaces in Switzerland is expected to increase from 6 in 2011 to 300 in 2022 and the number of co-workers is expected to increase from 250 to 22'000 in the same period (immodea, 2019).

Even though, there is a limit to the amount of work which can be conducted remotely without face-to-face interaction, there is still unexploited potential to avoid commute- and office-space related GHG emissions through remote work. A survey on telecommuting in Switzerland showed that 30% of economically active people wish to do more remote work, whereas less than 10% of people wish to do less or no remote work (Weichbrodt et al., 2016). The fact, that a large part of the Swiss workforce can continue to work for from home during the currently ongoing COVID-19 pandemic is an impressive example of the possibilities for remote work. It will be interesting to see mid- to long-term effects COVID-19 on adoption of flexible work.

Video conferencing and business travel

In 2015, Swiss residents conducted on average 64 business trips (one leg) per person, out of which 61% were conducted by motorized individual transport, 25% by slow transport (bike, foot), 11% by public transport and 3% by other means of transport (FSO, 2017). The World Travel & Tourism Council estimates that business tourism spending in Switzerland increased from roughly 2.5 billion CHF in 1995 to 7.4 billion CHF in 2019 (WTTC, 2020) and that global business tourism spending will increase from 1'374 billion US-$ in 2020 to 2'029 billion US-$ in 2029 (cited from Statista (2020b)). The International Civil Aviation Organization predicts that until 2050 fuel consumption of international aviation could grow by more than 300% compared to 2015 (ICAO, 2019) and could make up 22% of global CO_2 emissions (Cames et al., 2016). Thus, there is a significant potential to avoid GHG emissions by substituting physical business trips with video conferencing, which is even increasing in the future.

Substitution rates of video conferencing for business travel are still low (Arnfalk, 2002). Despite significant improvements in video conferencing technology, it cannot "fully replace the power of direct interaction" (Janisch & Hilty, 2017, p. 9). Face-to-face meetings have some advantages over virtual meetings, which are (Janisch & Hilty, 2017; Le Quéré et al., 2015) that personal interaction helps to build commitment and trust, that reaching agreements in decision-making processes is more likely in face-to-face meetings (Hiltz et al., 1986) and that performance of face-to-face teams is higher due to more effective information exchange and higher satisfaction of team members (Warkentin et al., 1997). However, it must be taken into account that these advantages are cultural and that culture can change.

5G and flexible work

Important challenges in adopting flexible work in Switzerland are that team collaboration is more effective in person, that company policies do not allow for remote work or no remote work culture exists, that no ICT tools for effective communication and collaboration are available and that existing ICT infrastructure of employer's and at employee's homes does not allow for access to the employers networks (Weichbrodt et al., 2016). Thus, if ICT solutions for effective communication and collaboration are further enhanced at least one of these challenges is addressed. Important ICT-based flexible work solutions are virtual meetings as well as data sharing solutions (Brodsky, 2017).

Virtual meetings

A study by Forrester (2018) showed that 96% of companies face challenges when managing video conferencing solutions and that most common challenges in conducting video conferences are difficulties in establishing a connection, long connection times at the start of the meeting and poor call quality. Thus, there is still potential to improve the video conferencing experience through improved technology and thereby increase substitution rates with regard to business travel.

A central aspect in video conferencing quality is the delay of audio and video, which must be very short (low latency) and exactly the same for audio and video. Hilty and Labhart (2017) state that a central requirement of video conferencing is that end-to-end delay is below 150 ms. Table 23 shows the user experienced latency of an active mobile network connection by generation.

Mobile network generation	Latency
2G	300-1'000 ms
3G	100-500 ms
4G	<100 ms

Table 23: Latency of an active mobile connection by mobile network generation (Grigorik, 2013).

While 2G and 3G latency is too high, latency of 4G mobile networks is small enough even for high-quality video conferencing. For example, to date, many people use 4G mobile networks to conduct video calls using Apple FaceTime or Whatsapp on smartphones. Still, latency is highly variable, depending on the current performance and utilization of the mobile network (Grigorik, 2013). Thus, even when using 4G mobile networks, audio and video quality can suffer from high latency. Since 5G mobile networks provide a significant latency improvement over existing mobile network generations, user experience in video calls can be expected to improve significantly.

Other important determinants of video conferencing quality are video resolution and sound clearness (Hilty & Labhart, 2017), which depend on data rates. Table 24 shows the user experienced data rates of an active mobile connection by network generation.

Mobile network generation	Data rate
2G	100-400 Kbit/s
3G	0.5-5 Mbit/s
4G	1-50 Mbit/s

Table 24: Data rates of an active mobile connection by mobile network generation (Grigorik, 2013).

Although 4G mobile networks allow for transmission of high-quality video and audios signals, users often face problems with respect to video and audio quality caused by low data rates. Even in video conferences run on fixed networks, video and audio quality is often insufficient. Some video conferencing technology providers therefore recommend participants to switch off their cameras in such cases (BlueJeans, 2019) in order to free up bandwidth for audio transmission. In comparison, 5G mobile networks are supposed to enable a user experienced data rate of 100 Mbit/s for downlink and

50 Mbit/s for uplink data transfer. Peak data rates of 5G networks (20 Gbit/s for downlink and 10 Gbit/s for uplink data transfer) can easily compete with today's data rates provided on modern fiber optical networks (ITU, 2017).

Another critical aspect in video conferencing quality is reliability, which refers to the probability that a sent data package actually arrives at the receiver and is not lost during transmission (ITU, 2017). Network requirements in two video conferencing standards (H.323 and SIP) are that the packet loss rate is below 0.5% (VidyoConnect, n.d.). The requirement in 5G mobile networks is that the packet loss rate is not higher than 10^{-5} or 0.001% (ITU, 2017), which is a significant improvement over existing mobile network generations and also over WiFi-networks (Chen et al., 2012).

It must be taken into account that not all future video conferences will run on mobile networks. For example, state-of-the-art telepresence systems are usually permanently installed in dedicated rooms and run on fixed networks which provide high data rates, low latency and high reliability. However, such installations are often the exception from the rule and a large part of video conferences is not conducted with professional video conferencing systems, but with end user devices such as laptops over Wifi-networks. It is exactly the flexibility of using any devices from any place to join a high-quality video conference where 5G unfolds its potential. When people connect from their usual workplace, from their home office or from any other place, video conferencing experience can be enhanced with 5G networks.

In the future, 5G networks can enable new forms and applications of video conferencing. Virtual reality and augmented reality solutions (e.g. with smart glasses) can establish new forms of video conferencing, in which participants immerse into a shared virtual location, working together on shared 3D objects beyond text documents. Such technologies place high requirements on latency and data rate, which can potentially be met by 5G (Erol-Kantarci & Sukhmani, 2018). In the manufacturing sector, 5G networks can support increasingly complex cases of remote maintenance. For example, if a technician can inspect and repair a machine remotely using smart glasses, traveling to the construction site can be avoided (Müller et al., 2019). In the healthcare sector, 5G networks can enable new forms of patient-doctor interactions, avoiding many cases in which the patient had to go to the doctor's surgery, which also has advantages from a hygienic point of view. On the other side, highly specialized medical personal does not have to travel to other hospitals when needed, e.g., for a surgical intervention. It is obvious that such telesurgery, a surgical intervention conducted at a distance by means of robotics and communication networks, requires high reliability and reaction times, the latter being specified in the range "of about 100ms, 10ms, and 1ms […] for auditory, visual, and manual interaction" (Soldani et al., 2017). However, a broad adoption of such services is not expected in the near future.

Data access

With the increasing penetration of services provided in the cloud more data is stored on centralized servers and accessed from end-user devices via communication networks (cloud computing) (Reinsel et al., 2018). Often, whole software applications are installed on centralized servers and operated remotely via communication networks. This increases requirements placed on communication networks – not only on fixed networks, but also on mobile networks because cloud services are increasingly accessed from mobile end user devices and from various locations (Noor et al., 2018). 5G mobile networks provide a significant improvement in data rates, latency, availability and energy efficiency over existing mobile networks (Grigorik, 2013; ITU, 2017) and, thus, can play a central role in overcoming challenges associated with remote access to cloud services. 5G mobile networks are also developed to support mobile edge computing, an approach to improve user experience (e.g. lower latency, higher data rates), by moving cloud computing services closer to the user, at the edge of the mobile network (the radio access network[2]) (Hu et al., 2015).

Working on the move

Even though mobile network coverage along railways in Switzerland is higher than in its neighboring countries (Rügheimer, 2019), productivity when working on the move (e.g. on trains) can suffer from poor mobile network connection, caused by low mobile network coverage along railways and by challenges in maintaining a stable connection when the connection for many end user devices has to be handed over from one radio base station to another one at the same time (Huang et al., 2010; G. Singh & Shrimankar, 2020; Tagesanzeiger, 2013). 5G mobile networks are required to maintain a specific connection quality in different mobility scenarios covering speeds from 0 km/h up to 500 km/h for high-speed trains (ITU, 2017). Swiss Federal Railways is currently discussing and testing a 5G-based mobile network to provide better connectivity services to its clients and to optimize rail operation (Brand & Nänni, 2019; Ehs, 2019). For example, if trains exchange information on their position, acceleration and braking behavior, the distance between trains can be reduced and thus the capacity of existing rail infrastructure increase. Such applications are safety-critical and have high requirements on latency and reliability, which can potentially be met by 5G mobile networks (Brand & Nänni, 2019).

To summarize, 5G mobile networks have the potential to improve the existing remote work experience and provide the possibility to enable remote from truly everywhere, not only fixed workplaces, but also on-the-go in urban and rural areas.

GHG abatement potential and rebound

Telecommuting and video conferencing have potential to avoid commuter traffic and business travel, which causes high amounts of GHG emissions due to the fuel consumption of the transport vehicles used and the construction, operation and maintenance of transport infrastructures. If travel in Switzerland increases, especially during rush hours, this would lead an increasing demand for transport infrastructures (e.g. streets, railways) whose construction, operation and maintenance causes high amounts of GHG emissions. Flexible work provides a loophole out of continuously increasing travel demand and can reduce the need for additional transport infrastructure.

A central factor in GHG impacts of commuting and business travel is the modal split. Driving to the office or to a meeting by car is associated with higher amounts of GHG emissions than using public transport, biking or walking (mobitool, 2016). In Switzerland the car is by far the most preferred (commute) transport mode (FSO, 2019a); thus, for the average telecommuter in Switzerland commute-related GHG emission reductions can be expected.

Virtual work is also associated with GHG emissions, e.g. caused by producing and operating the equipment and for data transmission through existing networks. As an example, Figure 10 shows the GHG emissions associated with a trip from Zurich to a meeting in Paris and back (Warland & Hilty, 2016). GHG emissions caused by travelling 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 video conferencing technology. The orders of magnitudes indicated here are robust even with regard to the contested numbers on the carbon intensity of video streaming (Kamiya, 2020).

Flexible work can also enable employers to reduce their office space and the energy required for heating, cooling and lighting the space and use of accommodation services (e.g. hotels), which are also

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[2] The radio access network is the part of the mobile network which establishes a wireless connection between end-user devices (e.g. smartphones) and the core network.

associated with substantial energy requirements and GHG emissions (e.g. for space heating and cooling).

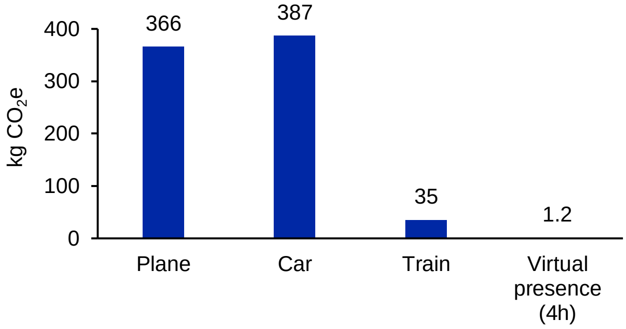

Figure 10: GHG emissions associated with a trip to Zurich and back by transport mode (Warland & Hilty, 2016). Figures are based on full life cycle assessment (e.g. including production of transport vehicles and of video conferencing equipment).

However, flexible work is also subject to various types of rebound and induction effects which counteract possible GHG emission reductions. First, time and money not spent on travel can be spent on other travel as well as non-travel activities associated with GHG emissions (Bieser & Hilty, 2018a). A study on household energy consumption in Switzerland from 2002-2005 showed that average household spending is associated with 4 MJ/CHF, but spending on electricity with 10 MJ/CHF and spending on air travel with 60 MJ/CHF (Girod et al., 2014; Girod & de Haan, 2010). Flexible work can also impact travel conducted by other household members (Hamer et al., 1991; Kim et al., 2015). On the one side, it can increase travel of other household members because the telecommuters' cars are available during the day. On the other side, it can reduce travel of other household members. For example, an early telecommuting study in the Netherlands found that telecommuter's household members reduced their travel due to an increased "hominess" feeling because the telecommuter is at home (Hamer et al., 1991).

Flexible work can also lead to an increase in space use and energy consumption for heating, cooling and lighting at home or at other locations (e.g. co-working spaces). For example, if someone expects to work a significant amount of time from home, he or she might consider investing in a larger dwelling with a separate office space. In the long run, the possibility to work from anywhere, independent of the location of employer offices, might influence a household's decision where to live (e.g. outside of city centers), which can feed back on commuting distance and transport for other activities; and thus, GHG emissions (Bieser & Hilty, 2020; Chakrabarti, 2018; Hu & He, 2016; Zhu, 2012).

Finally, virtual collaboration technology decreases the cost of setting up and conducting meetings; thus, the number of meetings and national and international collaboration in general can intensify. In addition to this rebound effect, there is a well-known induction effect of digital technology which increases the demand for travel because the technology 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). However, it is difficult to estimate to what extent this trend will be driven by the possibility for flexible work or by digitalization in general. Estimating rebound and induction effects of video conferencing is challenging as they depend on many variables which vary across sectors and socio-economic contexts.

Other use case impacts

Besides GHG impacts, avoiding transport is associated with further environmental, social and economic benefits, such as reductions of noise and air pollutants, time savings for individuals and cost savings for organizations (Forrester, 2018). Plus, a transition towards a culture of virtual collaboration can have a positive effect on the productivity of an organization and its employees (Hiltz et al., 1986; Warkentin et al., 1997). Improved hygiene should be added to the list of positive impacts, as could be observed during the COVID-19 lockdown.

If flexible work would lead to a reduction of travel demand in the long term – something which is unavoidable from a climate policy perspective – the construction of additional transport and building infrastructure and associated environmental impacts (e.g. energy requirements, space use) could also be avoided. In the long run, a larger adoption of flexible work could even lead to more dispersed and lower-density settlement, because people will be willing to live in larger distances from employer's offices which are often located in city centers (Mokhtarian, 2009).

Flexible work can also provide social benefits. For example, it can increase access to the job market for people who live far away from commercially active areas (Singh et al., 2006) or who are restricted by their personal life (e.g. caregivers). Time and location-independent work can also improve people's work-life balance, if it enables them to adjust their work schedule to their individual needs (Hayman, 2010). However, more self-reliable, time- and location-independent work bears also the risk of overworking with negative impacts on individuals' well-being (Barnett et al., 2011; Leung & Lee, 2005). A central question is also how companies can ensure occupational safety standards (e.g. minimum size of workplace, ergonomic workplaces) if people work from home (Healy, 2000).

Economic benefits of flexible work are that self-determined work can increase job satisfaction of workers (Hayman, 2010), organizations have access to a larger workforce (because the place of residence of workers is less relevant) (Bayrak, 2012) and productivity can increase when efficient collaboration with anyone at any time is possible (Weichbrodt et al., 2016). Form a business perspective, flexible work can also yield time savings, reduced travel costs and travel fatigue (Forrester, 2018). On the other side, working remotely can decrease informal exchange among employees and reduce collaboration effectiveness (Weichbrodt et al., 2016). Managing remote working teams requires different leadership and management styles and higher levels of trust among workers (Hackl et al., 2017). Finally, remote work increases an organization's dependency on well-working ICT infrastructure. This is one step further towards criticality of ICT infrastructure (Hilty, 2008). Some sources argue that potential productivity decreases due to loss of face-to-face exchange (Warkentin et al., 1997) and vulnerability to cyber risks will increase (Arnfalk et al., 2016; Hilty, 2008).

Thus, in order to realize the environmental benefits of *flexible work*, well-thought out strategies need to be developed and implemented which consider environmental aspects, the well-being of the individual and the productivity of the organization.

Estimation of GHG abatement potential

We estimate the GHG abatement potential through reduced demand for commuting, heated office space and business travel.

Reduction of commuting

In 2017, roughly 4.0 million Swiss residents commuted to work (FSO, 2019b), 52% of which by car, 17% by train, 14% by public road transport (e.g. bus, tram), 9% by foot and 7% by bicycle (FSO, 2019a). We estimated the number of commuters by transport mode in 2030 based on expected population growth until 2030 (FSO, 2020d) assuming no change in the commute modal split. Based on data from the Federal Office of Statistics on telecommuting adoption in Switzerland in 2018 (FSO, 2020e) and average degree of employment in Switzerland (80%) (FSO, 2020a), we estimated that on average Swiss workers work 0.25 days per week from home.

We estimate the GHG emissions from telecommuting using average commute distance by transport mode (FSO, 2019b) and transport-mode specific (full life-cycle) emission factors in 2030 according to

Paul Scherrer Institut (2020). We extrapolate the average commute distance in 2017 until 2030 according to the average yearly growth rate of commute distances between 2010 and 2017. To avoid double counting with the GHG emission abatement potential of the use case “AD”, we reduce the emission factors used here according to the expected fuel savings due to the (small) adoption of automated driving predicted for 2030. This yielded baseline GHG emissions caused by Swiss residents’ commuting in 2030 of 3’962 kt CO_2e.

Between 2013 and 2018, average yearly growth in the number of home office days per person was 5.6% (based on (FSO, 2020e)). In the pessimistic scenario, we assumed that growth of home office days per person slows down between 2018 and 2030 (half growth rate, 0.34 home office days per week in 2030), in the expected scenario we assumed a constant growth rate (0.48 home office days per week in 2030) and in the optimistic scenario, we assumed that growth of home office adoption accelerates (double growth rate, 0.89 home office days per week in 2030). To estimate the theoretical potential, we assumed that everyone working in the knowledge-intensive sector in Switzerland works exclusively from home, yielding 1.71 home office days per week.

We used the average of the rebound effect identified in four telecommuting studies in European countries according to Gossart (2015), which is reported to be 37.25%. This means that for every km saved through telecommuting, individuals travel 372.5 m more for other purposes. This estimated rebound only includes time and income which is reassigned from commuting to travel for other purposes. It does not consider other types of rebound effects or systemic effects of telecommuting adoption (e.g. residential relocation due to telecommuting). Table 25 provides an overview of the main assumptions.

GHG abatement lever	**Baseline GHG emissions**	**Number of home office days per week**					**Rebound effect**
		BAU	Pes.	Exp.	Opt.	Theor.	
Reduction of commuting	3’962 kt CO_2e	0.25	0.34	0.48	0.89	1.71	37%

Table 25: Main assumptions for estimating GHG abatement potential by avoiding commuting through flexible work in Switzerland in 2030 (BAU: Business As Usual).

Reduction of heated office space

In Switzerland in 2017, roughly 56 million square meters of office space existed (based on Statista (2020a)), out of which roughly 4% were unused (Martel, 2018). Based on the average annual growth of office space in Switzerland between 2011 and 2017 (1.3% p.a., based on Statista (2020a)), we estimate that by 2030, roughly 64 million square meters of office space will be heated in Switzerland. Based on a study on heating energy consumption of office space (Aiulfi et al., 2010), we estimate that by 2030 office space will use roughly 78 kWh heating energy per square meter and year. Finally, we estimate the emission factor for space heating based on expected energy consumption for space heating in Switzerland according to Kirchner (2012) and emission factors of energy carriers according to ecoinvent (ecoinvent Centre, 2018; Wernet et al., 2016) (roughly 160 g CO_2e/kWh). This yields 804 kt CO_2e caused by heating office space in Switzerland in 2030, assuming that office space reduction is proportional to the increase in home office days by scenario (0% in the BAU, 3% in the pessimistic, 6% in the expected, 17% in the optimistic scenario; 39% for the theoretical potential). Expert interviews showed that the maximum possible office space reduction a company can achieve through telecommuting and desk sharing is 40% on average**.** Therefore, we multiplied the adoption of telecommuting by scenario with 40%. This yielded office space reductions by 2030 of 0% in the BAU, 1% in the pessimistic, 2% in the expected and 7% in the optimistic scenario. For the theoretical scenario we assume a 40% reduction of office space.

Data on rebound effects from office space reduction is sparse. An older study from the Netherlands found that if occupants are always home during the day energy consumption for space and water heating increases by roughly 3% (Guerra Santin et al., 2009). Multiplying this value with the expected quotient of space heating energy consumption for residential purposes and for office space in 2030 (roughly 6.9, estimated based on Kemmler and Spillman (2019) and Kirchner (2012)) yields a rebound effect of 23%. Table 26 provides an overview of the main assumptions.

GHG abatement lever	**Baseline GHG emissions**	**Reduction of heated office space**					**Rebound effect**
		BAU	Pes.	Exp.	Opt.	Theor.	
Reduction of heated office space	804 kt CO_2e	0%	1%	2%	7%	40%	23%

Table 26: Main assumptions for estimating the GHG abatement potential by reducing heated office space in Switzerland in 2030.

Reduction of business travel

We estimate the amount of business travel conducted by Swiss residents in 2030 based on data from the Mobility and Transport Microcensus 2015 of the Federal Office for Spatial Development (2017). We extrapolate the number of business air trips (0.1 per year and Swiss resident in 2015) until 2030 according to the average yearly growth rate of business trips between 2008 and 2018 and the number of business trips by other transport modes based on expected population growth. We follow this approach because the number of air trips per resident has been increasing at a higher rate than the number of trips by motorized individual transport and public transport per resident.

We estimate the amount of GHG emissions caused by business travel of Swiss residents in 2030 using average distances of (business) trips by transport mode (ARE, 2017) and projected transport mode-specific emission factors in 2030 according to Paul Scherrer Institut (2020), which are based on a full life cycle assessment. To avoid double counting with the GHG emission abatement potential of the use case “AD”, we reduced the emission factors used here according to the expected fuel savings due to the predicted (small) adoption of automated driving in 2030. This yields baseline GHG emissions caused by Swiss residents’ total business travel in 2030 of 2’806 kt CO_2e.

Based on a project of video conferencing adoption among public agencies in Sweden (Arnfalk et al., 2016) and an expert interview with a member of this project, we estimate that the current substitution rate of video conferencing for business travel is 5% and that the substitution rate will remain stable in a pessimistic scenario, increases to 10% in an expected scenario and to 20% in an optimistic scenario in the period to 2030. To estimate the theoretical potential, we adopted the result of a recent survey in the same project, which shows that during the COVID-19 pandemic, 88% of workers in the Swedish public agencies could maintain their productivity despite the absence of business travel (Hiselius & Arnfalk, 2020).

We could not find robust data on direct rebound effects of video conferencing. Therefore, we use the expert estimate that 3% of GHG emission reduction through video conferencing are compensated through additional business air travel. This figure does not include a general increase in business travel due to increasing international collaboration due to use of ICT (induction effect). Table 27 provides an overview of the main assumptions.

GHG abatement lever	**Baseline GHG emissions**	**Substitution rate of video conferencing with business travel**					**Rebound effect**
		BAU	Pes.	Exp.	Opt.	Theor.	
Reduction of business travel	2’806 kt CO_2e	5%	5%	10%	20%	88%	3%

Table 27: Main assumptions for estimating the GHG abatement potential through the substitution of business travel with video conferencing in Switzerland in 2030.

To roughly estimate the GHG emissions caused by non-5G equipment required for flexible work, we considered laptops, computer monitors and video conferencing systems and extrapolated it to country-wide values using the expected number of commuters, the number of companies in Switzerland in 2030 and the adoption rates by scenario (result in section 3.6.3). We did not include accessory devices, the additional utilization of data centers, or other communication networks.

Figure 11 shows the estimated GHG abatement potential for the use case flexible work (incl. avoided commuting, business travel and reduction of heated office space) by scenario.

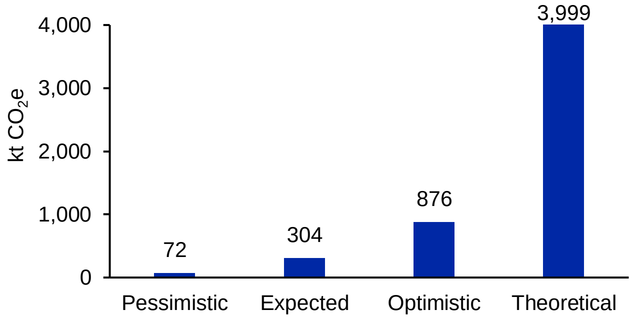

Figure 11: Estimated GHG abatement potential through flexible work by scenario.

Conclusion and recommendations

Establishing a flexible work culture does not lead to GHG emission abatements per se, but depends largely on changes to time spent in transport, use of transport modes, space requirements at all work locations (employer office, telecommuters' homes, co-working spaces, etc.) and the substitute activities, related consumption of goods and services and their GHG impacts. Thus, organizations adopting flexible work schemes should advise their workers on their preferences regarding work location, business travel and transport modes (Vaddadi et al., 2020). 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. space use at home), rebound effects, and systemic effects may compensate (if not overcompensate) for the commute-related energy savings (Vaddadi et al., 2020).

Only if the effectiveness and user experience in terms of audio and video quality, reliability and collaboration tools comes close to the effectiveness and experience of face-to-face meetings, higher adoption of flexible work can be expected. Therefore, virtual collaboration service providers should utilize the capabilities of 5G mobile networks to enhance remote work and virtual collaboration experiences and develop new solutions for virtual interaction (e.g. augmented and virtual reality). Flexible work services (including access to fast broadband Internet) should also be offered in rural areas to enable more people to work remotely.

Organizations should develop and implement systematic flexible work strategies considering various aspects:

- the organization's working culture (e.g. from hierarchical to collaborative leadership styles)
- policies (e.g. travel and meeting policies which are conducive to home office and virtual meetings)
- workers' well-being (e.g. consulting employees regarding remote work)
- office infrastructure (e.g. sharing workplaces and reducing office space)
- ICT infrastructure (e.g. remote collaboration and data security solutions).

Exemplary measures taken in the above-mentioned project in Sweden (Arnfalk et al., 2016), are: sharing of information and education materials via intranets, webinars and on-site training, commitment of top-level management and focus groups which continuously work on occurring issues. Additionally, a monitoring and reporting system was set up which allowed to measure and compare the progress across organizations and units. Monitoring systems should not only address the adoption of flexible work, but also track employee satisfaction and occurring issues in order to establish a culture and system of continuous improvement. To make this happen, travel policies should be adjusted to incentivize the reduction of commuting and business travel. To date, business travel policies often incentivize physical business travel, e.g. through bonuses provided by travel companies which can be used for private purposes. The Swedish project with more than 100 participants clearly showed that providing technology itself is not sufficient, but systematic approaches are required to increase the use of video conferencing (Arnfalk et al., 2016).

Policy makers can also support the adoption of flexible work through government-driven campaigns, by providing stakeholder platforms for collaboration on successful flexible work adoption and by establishing efficient fiscal policies which lead to the inclusion of the true external cost of travel in travel prices (e.g. the climate impacts of air travel). They should also aim at minimizing commute distances in their spatial planning and thereby take pressure off transport systems and reduce environmental loads.

3.5.2 Smart grid

Terminology

The Swiss Federal Office of Energy defines a smart grid as an "electrical system which, taking into account measurement and mostly digital information and communication technologies, ensures the exchange of electrical energy from different sources with consumers with different requirements. Such a system takes into account the needs of all market players and society. The use and operation of the system can thereby be optimized, costs and environmental impact can be minimized, and the quality and security of supply can be guaranteed" (SFOE, 2010, translated by the authors).

In a literature review on smart grids, Tuballa and Abundo (2016) found various smart grid functionalities. Through demand response, smart grids dynamically adapt electricity demand according to electricity supply. This increases reliability of electricity supply and can support the integration of electricity from fluctuating renewable energy sources (e.g. photovoltaic or wind energy) if demand is shifted according to availability of electricity from these sources. To do so, smart grids use technologies for measuring electricity consumption of consumers (e.g. smart meters) and technologies which allow to switch off electricity-consuming devices (e.g. smart fridges) when there is a risk that electricity demand exceeds supply. When electricity (e.g., from renewable sources) is abundant, smart grids store electricity in distributed electricity storages (e.g. batteries, plug-in electric vehicles) and use these capacities to meet electricity demand at demand peaks. To maintain high reliability of electricity supply, smart grids monitor electricity demand and supply, as well as grid operation at all times, optimize transmission and distribution of electricity, and automatically react to incidents.

In a smart grid, digital ICT is required to enable information exchange between electricity generators, electricity markets, electricity storage units, consumers, the electricity grid and grid operators (Office of the National Coordinator for Smart Grid Interoperability et al., 2012). Only by means of this information, electricity generation, transmission, distribution and consumption can be optimized and failures (e.g. overloading) can be avoided.

Electricity generation and consumption in Switzerland

Electricity consumption in Switzerland in 2018 equaled 62.0 TWh, out of which 4.3 TWh were transmission losses (final consumption equals 57.6 TWh) (SFOE, 2019). Total consumption (incl. transmission losses) increased by 10% between 2000 and 2018.

A study on the future electricity consumption in Switzerland from 2012 (Kirchner, 2012) estimated that in a BAU scenario, electricity consumption in Switzerland increases from 58.8 TWh in 2010 to 61.5 TWh in 2020, and to 64.4 TWh in 2035. Assuming linear development between 2020 and 2035 yields an electricity consumption of 63.5 TWh in 2030.

The Swiss Energy Strategy 2050 aims at a reduction of electricity consumption per capita of 3% between 2000 and 2020 and of 13% between 2000 and 2035. Based on electricity consumption in 2000 (Kirchner, 2012), expected population growth (FSO, 2019, 2020d), and assuming a linear reduction of electricity consumption per capita between 2020 and 2035, we estimate that this equals an electricity consumption of 61.5 TWh in 2030.

Electricity generation in Switzerland is mainly based on water and nuclear power. Electricity generation based on other renewable energies (e.g. photovoltaics, wind) has been increasing in recent years. To meet domestic electricity demand, Switzerland imports electricity from other countries, which is often generated using fossil energy carriers (e.g. in Germany). According to Pronovo AG (2020), 66% of Swiss electricity demand in 2018 was met with water power, 17% with nuclear energy, 8% with other renewable energies (e.g. photovoltaic, wind), 8% with electricity from unverified sources or fossil energy carriers (mainly imported electricity), and 1% with electricity from waste incinerators.

The Swiss Energy Strategy 2050 (SFOE, 2018) aims at a slight increase of the amount of electricity generated with water power in Switzerland to 37.4 TWh in 2035 and a large increase of the amount of electricity generated with other renewable energy sources (e.g. photovoltaics, wind) in Switzerland to 4.4 TWh in 2020 and 11.4 TWh in 2035.

The Swiss Federal Office for Energy (2015) also developed a Smart Grid Roadmap for Switzerland, in which it assumes that many technologies required for smart grids will be in operation in Switzerland by 2030.

5G and smart grids

To our knowledge, there is no systematic comparison of communication technologies with regard to the requirements of smart grids. 5G mobile networks provide various capabilities which smart grids require. The three most important of these capabilities are discussed below.

Reliable data exchange at low latency

In order to ensure reliability of electricity supply and increase use of electricity from fluctuating renewable energy sources, electricity demand has to be dynamically adjusted to electricity supply. Especially during peak demand (e.g. in evenings), which can even increase due to increasing diffusion of electric vehicles, it is a risk that electricity demand exceeds supply (Leligou et al., 2018). In order to optimize electricity demand and supply, precise state measurements (Leligou et al., 2018) and continuous data exchange among distributed sensors (which measure demand and the grid state), actuators (which allow to switch off electricity-consuming devices), grid operators, and electricity markets (which facilitate trade of electricity and flexible electricity resources[3]) is required. The Verein Smart Grid Schweiz (2015) states that synchronous measurements, important controls or protective mechanisms (e.g. power plant control) in a smart grid require response times below 1 second. Leligou et al. (2018) state that phasor management units, which help in measuring and managing demand, can refresh data between 10 to 50 times per second. 5G mobile networks can meet these requirements and have a significantly lower latency and higher reliability than existing mobile networks. The URLLC (Ultra-Reliable and Low Latency Communications) usage scenario of 5G networks (ITU, 2015) has been specifically designed to meet the requirements of such safety-critical applications.

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[3] The flexibility to switch-off an electricity-consuming device when required is a resource which can be sold on future electricity markets.

Many devices

If smart grids become reality, this also means that the number of devices sending and receiving data will increase rapidly, especially in the low-voltage area of the electricity network (Leligou et al., 2018): Households must be equipped with smart meters (Leligou et al., 2018); a large number of intelligent devices which are able to shut down upon request to dynamically reduce electricity demand need to be connected (Tuballa & Abundo, 2016); the electricity grid must be monitored with sensors; distributed electricity sources (including electric vehicles) must communicate with the grid (Tuballa & Abundo, 2016). 5G networks allow to connect more devices and provide a higher capacity than the existing mobile networks. The mMTC (massive Machine-Type Communications) usage scenario of 5G networks (ITU, 2015) has been designed to meet these requirements.

Security

As many safety-critical applications depend on reliable electricity supply (e.g. operation of transport infrastructures, data centers), the electricity grid itself is a critical infrastructure. 5G networks offer additional security layers compared to existing mobile networks (e.g. through network slicing), which can help protecting the grid against cyber attacks.

To summarize, 5G networks provide the possibility to exchange data reliably, securely, with low delay between many devices. These are communication requirements are crucial for smart grids. In Germany, a research hub of universities and industrial companies supported by the Federal Ministry of Ecomonic Affairs and Energy was founded to develop solutions which utilize the capabilities of 5G networks for smart grid applications (National 5G Energy Hub, 2020).

GHG abatement potential and rebound

Smart grids can reduce GHG emissions through various mechanisms. First, smart grids can increase the use of electricity from fluctuating renewable energy sources by managing the demand: reducing demand when the availability of electricity from renewable energy sources is low, storing electricity (e.g. in the batteries of electric vehicles) when it is abundant (Tuballa & Abundo, 2016). This reduces GHG emissions if it reduces the use of more carbon-intensive energy carriers. In Switzerland, it is crucial to reduce use of imported electricity which is based on fossil energy carriers (SFOE, 2015).

Second, transmission and distribution (line) losses occur when electricity is transported from the generating unit to the consuming device. Amongst others, line losses depend on the load of the grid and the distance over which the electricity is transported (NACAA, 2015). Smart grids can reduce line losses by operating the grid at an optimal load (e.g. through adaptive voltage control) (NACAA, 2015) and by integrating distributed electricity sources in the electricity grid and thereby shortening the distance from electricity generation to consumption (SFOE, 2015). Also, prosumer neighborhood networks will be enabled to optimize self-consumption of energy trough Customer Energy Managers (CEM) based on local low radiation 5G networks. These so-called “microgrids” shift flexibility management into the premise area and reduce energy transportation losses and associated GHG emissions.

Third, by enabling a better utilization of existing grid infrastructure, smart grids can avoid the build-out of electricity grid infrastructure (SFOE, 2015), whose construction and operation is material- and energy-intensive, thus associated with GHG emissions.

Fourth, consumers in a smart grid receive information on their electricity consumption through energy-feedback systems (e.g. smartphone apps). This can lead to a savings effect if consumers use this information to reduce their electricity consumption (Ecoplan, 2015; Pratt et al., 2010).

Fifth, smart grids can facilitate the transformation towards e-mobility, e.g. by optimizing the charging times of electric vehicles according to individual mobility needs and the availability of electricity. If this leads to a faster substitution of GHG-intensive combustion engines with GHG-efficient electric engines, GHG emissions can be saved (Pratt et al., 2010).

Further GHG reducing impacts of smart grids mentioned in literature are the use of sensor data for grid diagnostics or for monitoring the effectiveness of energy efficiency programs (Pratt et al., 2010).

Smart grids can stimulate electricity consumption (rebound effect) if increased income from energy savings is spent on increased use of electricity consuming appliances (Athavale & Knaus, 2017; Santarius, 2012) or if consumers take less care about saving electricity because they assume the grid is operating “smart” and “green” enough by itself (Santarius, 2012). Saved income can not only be spent on electricity but also on other activities which cause GHG emissions (e.g. motorized travel) (Greening et al., 2000). If the energy efficiency of a whole economy increases, relative cost of providing energy services decrease, which can have consequences for the types and quantities of goods and services produced and consumed (economy-wide rebound) (Greening et al., 2000).

Other use case impacts

Smart grids can contribute to landscape conservation and reduction of resource use if existing grid infrastructure is better utilized and less additional infrastructure needs to be built (SFOE, 2015). Still, construction, operation and disposal of infrastructures required in smart grids (e.g. PV panels, digital infrastructures) requires energy, resources and causes emissions to the environment (SFOE, 2015).

Companies in the electricity sector can reduce cost by increasing automation along the electricity value chain (e.g. through automated fault detection) and improve resilience of the electricity grid to disruption (e.g. through predictive maintenance) (SFOE, 2015). Collected electricity data can help in optimizing grid planning and operation (SFOE, 2015). Smart grids can increase competitive pressure in the electricity sector by increasing the consumers’ flexibility in choosing electricity service providers, by facilitating market entry for new electricity service providers and the development of new business models (SFOE, 2015).

A major risk of smart grids is that they increase the dependency of the critical electricity infrastructure on ICT infrastructures, thus introducing ICT-related security threats (e.g. through cyber attacks) (Gunduz & Das, 2020).

Estimation of GHG abatement potential

We estimate the GHG abatement potential of smart grids through energy feedback systems, reduction of line losses and an increased share of electricity from renewable energy sources.

For the baseline scenario, we used the business as usual scenario from a study on expected electricity consumption in Switzerland until 2050, which provides an estimate for expected electricity consumption in Switzerland in 2020 and 2035 (Kirchner, 2012). Linear interpolation of the forecasts 2020 and 2035 yields a prospective consumption of 63.5 TWh in 2030. In principle, it would be possible to use the baseline scenario based on the electricity efficiency increases according to the Swiss Energy Strategy 2050 (61.5 TWh in 2030). However, the electricity efficiency increases considered in the Energy Strategy 2050 are also considering smart grid applications (e.g. smart meters), so we cannot use this data to avoid double counting.

An impact assessment of smart meters in Switzerland estimated that an 80% rollout of smart meters can reduce electricity consumption in Switzerland by 1.8% through electricity consumption behavior changes (Ecoplan, 2015). Based on this study, we estimate that energy feedback systems in general (smart meters and other systems such as information displays) lead to a reduction of electricity consumption by 2.3%. Reduction of electricity consumption reduces final consumption of electricity and line losses, because less electricity has to be transport to electricity consumers. By 2027, in

Switzerland 80% of conventional electricity meters shall be replaced by smart meters (80%) (Stromversorgungsverordnung, 2017). However, we assume that only in combination with additional information tools and smart home applications, consumers will actually reduce their electricity consumption. Based on a survey on adoption of smart home technologies in Switzerland (ofri Internet GmbH, 2019), we assume an adoption rate of 20% for energy feedback technologies in Switzerland in 2020 and in 2030 in the BAU scenario, 30% in the pessimistic, 40% in the expected and 50% in the optimistic scenario. For the theoretical potential, we assume an adoption of 100%.

As described above, optimized transmission and distribution of electricity (e.g. adaptive voltage control) and use of DERs can reduce line losses. In a study on GHG impacts of smart grids in the USA, Hledik (2009) estimates that smart grids can reduce distribution losses by 10%. We use this value for our optimistic scenario and for estimating the theoretical potential. In the expected scenario, we assume a reduction of distribution losses of 5% and in the pessimistic scenario of 2.5%.

Still, it cannot be expected that the full potential of smart grids to reduce distribution losses will be exploited by 2030. Based on the Smart Grid Roadmap Switzerland (2015) and an expert interview we assume that by 2030 0% of this technology will be available in a BAU scenario, 10% in the pessimistic scenario, 20% in the expected scenario and 30% in the optimistic scenario. Although the Smart Grid Roadmap shows that most smart grid technology will be in operation by 2030, we use lower adoption rates because we assume some required technologies (e.g. ICT in distribution grids) and the regulatory framework required for realizing all smart grid functionalities will not be in place by then. For the theoretical potential, we assume an adoption of 100%.

There are no reliable studies quantifying the potential of smart grids to increase the share of electricity from renewable energy sources in electricity consumption. Therefore, we use a workaround to roughly estimate this potential. In 2016, total installed electricity generation capacity in Switzerland was 20.8 GW (ElCom, 2018). A study on the potential of demand side management (DSM) in Switzerland estimates the amount of electricity consumption which can be influenced through DSM technologies (e.g. electricity consumption that can be reduced or postponed) (Vossebein et al., 2019). The study estimates that a theoretical DSM-potential of 31.0-46.6 GW (>100% of installed capacity), a technical potential of 1.1-2.6 GW and a socio-technical potential of 0.6-1.0 GW exists. To derive a rough estimate of the potential increase in electricity from renewable energy sources through smart grids, we use the quotient of the DSM-potential in Switzerland and the installed electricity generation capacity in Switzerland. For the optimistic scenario, we use the average of the lower and upper boundary of the technical potential (8.9% of installed capacity) and for the expected scenario the average of the lower and upper boundary of the socio-technical potential (3.8% of installed capacity). For the pessimistic scenario, we assume half of the potential assumed in the expected scenario (1.9%). For the theoretical potential, we assume that in 2030 smart grids allow to manage the grid in a way that whole Swiss electricity consumption is met with electricity from renewable energy sources (water, photovoltaic, wind) in Switzerland.

Based on expert interviews, we assume that these potentials can only partly be realized by 2030 (adoption of 0% in the BAU scenario, 10% in the pessimistic scenario, 25% in the expected scenario, 50% in the optimistic scenario, 100% for the theoretical potential). Please note that these values are rough estimates and the large differences across scenarios reflect the uncertainty. According to this estimate, the share of electricity consumption from renewable energy sources in 2030 increases by 0.2%-points in the pessimistic scenario, 1.0%-points in the expected scenario, and 4.4%-points in the optimistic scenario. For the theoretical potential, our estimation approach yields an increase of roughly 25%-points. We assume that 2/3 of this increase will be covered with electricity from photovoltaic generators and 1/3 with electricity from wind generators and that it reduces the use of imported electricity from nuclear, fossil and non-verifiable energy sources.

Using these assumptions, the Swiss electricity mix according to Alig et al. (2017), with an expected build-out of renewable energies according to the Swiss Energy Strategy in 2030 (SFOE, 2018) and emission factors from ecoinvent (ecoinvent Centre, 2018; Wernet et al., 2016) we roughly estimate that each kWh of electricity consumed in Switzerland by 2030 will cause 73.3 g CO_2e in the BAU scenario, 72.6 g CO_2e in the pessimistic scenario, 70.4 g CO_2e in the expected scenario and 60.3 g CO_2e in the optimistic scenario (for details regarding the electricity mix see 2.2 on page 26). For the theoretical potential, we estimate an emission factor of 41.2 g CO_2e/kWh. Multiplying these emission factors with the estimated electricity consumption in 2030 by scenario yields the estimated absolute GHG emissions from electricity consumption in Switzerland.

We also considered rebound effects. In a study on changing needs for space heating and cooling due to global warming in Switzerland over the period 2010-2060, Gonseth et al. (2017) find a reduction of energy needs for room heating by 15.9%, but a rebound effect of 35%. We assume that a rebound effect of this size also exists for electricity savings through energy-feedback technologies. For reduction of line losses, we assume a lower rebound effect (17.5%), because cost savings through reduced line losses will not necessarily be shared with consumers.

We could not find data on rebound effects due to an increased use of electricity from renewable energy sources in Switzerland. As a proxy, we used the result of a study on the increase in domestic electricity consumption due to use of photovoltaic generators in Australia (Deng & Newton, 2017). The study estimates that each kWh electricity from photovoltaic generators increases electricity consumption between 0.167 and 0.209 kWh (we use the average of both values; 18.8% rebound). To roughly estimate the GHG emissions caused by non-5G equipment required for smart grids, we considered ICT equipment installed in households (smart meters, smart plugs and bridges) and extrapolated it to country-wide values using the expected number of households in Switzerland in 2030 and the adoption rates by scenario (result in section 3.6.3). We could not account for the amount of ICT equipment that will be installed in the grid due to insufficient data availability. Table 28 provides an overview of the main assumptions. Figure 12 shows the estimated GHG abatement potential by scenario.

GHG abatement lever	**Baseline GHG emissions**	**Impact**				**Adoption**					**Rebound effect**
		Pes.	Exp.	Opt.	Theor.	BAU	Pes.	Exp.	Opt.	Theor.	
Reduction of electricity consumption through energy feedback systems	4’651 kt CO_2e	-2.3%	-2.3%	-2.3%	-2.3%	20%	30%	40%	50%	100%	35%
Reduction of line losses		-2.5%	-5%	-10%	-10%	0%	10%	20%	30%	100%	17.5%
Increased of share of electricity from renewable energy sources in electricity consumption		1.9%	3.8%	8.9%	25.4%	0%	10%	25%	50%	100%	18.8%

Table 28: Main assumptions for estimating GHG abatement potential of smart grid in Switzerland in 2030.

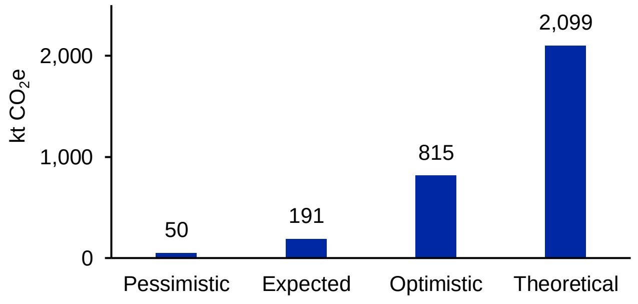

Figure 12: Estimated GHG abatement potential through smart grid applications by scenario.

Conclusion and recommendations

Due to the large number of actors involved in the transition towards a smart grid (e.g. electricity service providers, ICT companies, electricity consumers, policy makers, consumer protection agencies) with their partly diverging interests, a coordinated transformation and collaboration among all involved actors is essential for success.

In order to utilize the potential of smart grids for climate protection, it will be necessary to build out distributed (renewable) energy generation and establish a system which utilizes their full potential and systematically reduces the use of electricity from GHG-intensive energy carriers (in particular, imported electricity from fossil energy carriers).

The regulatory framework for generating, trading and selling electricity needs to be adapted. For example, future electricity markets need to allow for dynamic, real-time pricing and trade of flexible resources, and need to be more closely integrated with electricity grids. As data exchange increases significantly in smart grids, new data protection standards are required which guarantee privacy and security while allowing for essential smart grid applications (e.g. trade of flexible electricity resources). As transforming the existing electricity grid into a smart grid is a capital-intensive project, energy and communication technology standards are required to ensure compatibility of technologies and to reduce investment risks. Incentives for companies and households to adopt technologies required for smart grids (e.g. energy feedback systems) and to trade their flexible electricity resources should be established. This might be challenging as it requires businesses and households to allow external control of their electricity consumption to some extent.

3.5.3 Automated driving (AD)

Terminology

One of the major trends in the automotive sector is the development of driving automation systems supported by digital ICT. Many terms exist to describe the same or similar technologies (e.g. “self-driving cars”, “autonomous driving”). We use the terminology suggested by SAE International (2016), a large standard developing association in the transport sector.

A driving automation system is the “hardware and software that are collectively capable of performing part or all of the [dynamic driving task] on a sustained basis” (SAE International, 2016, p. 3), such as radar or LiDAR components to capture information on the surroundings of vehicles or onboard computers to analyze the captured data and derive steering instructions. The dynamic driving task describes “all of the real-time operational and tactical functions required to operate a vehicle in on-road traffic” such as lateral and longitudinal vehicle control (steering, accelerating, breaking), object and event detection, recognition, classification as well as response preparation and execution (SAE International, 2016, p. 5).

Driving automation systems can be classified by degree of automation into 6 levels from “no driving automation” (level 0) to “full driving automation” (level 5) (SAE International, 2016). From levels 1 to 3, the system overtakes more and more dynamic driving tasks form the driver, but the driver still has to be attentive in case of unforeseen events; whereas on levels 4 and 5, the vehicle can drive (mostly) without driver intervention. The “recommended usage for describing a vehicle with driving automation capability is ‘level [1 or 2] driving automation system-equipped vehicle’ or ‘level [3, 4, or 5] ADS-equipped vehicle’” (SAE International, 2016, p. 27). For simplicity, we will use the term ”automated vehicle” (AV) in the following.

AD is expected to have substantial impacts on GHG emissions associated with transport due to increases in fuel efficiency of AVs (e.g. due to smoother acceleration and breaking or the possibility to drive in the slipstream of the preceding vehicle) and due to changes in vehicle-miles traveled (e.g. due to increased attractiveness of car transport and access for children or senior citizens who could not steer a conventionally-driven car) (Taiebat et al., 2018).

(Automated) driving in Switzerland

In 2019, roughly 4.6 million cars as well as 0.4 million trucks and vans were registered in Switzerland (FSO, 2020b). In 2018, the transport sector in Switzerland caused 14.8 Mt CO_2 (without international aviation), or 40% of the CO_2 emissions caused in Switzerland (FSO, 2020c). 97.5% of these emissions are caused by road transport (specifically passenger cars and to a smaller extent trucks, vans and busses) and only 0.2% were caused by rail transport (FSO, 2020c).   .

There is no research on the adoption of AD in Switzerland so far. A study on Germany (Krail et al., 2019) assumes that in 2020, 25-26% of registered cars re equipped with level 1, 1% with level 2 and 0% with higher-level AD systems. The study assumes that by 2030, first cars with level 3 or 4 AD systems will drive on German roads. Still the penetration of level 3-5 AD systems will increase only slowly and is expected to lie between 34% and 41% by 2050. The penetration of AD systems in truck and van transport as well as in public transport is expected to be higher because of the possible cost savings, e.g. due to omission of the driver, increased fuel efficiency or cheaper insurances (Krail et al., 2019).

Today, first pilot projects on AD are conducted in Switzerland. Before a larger adoption of level 3-5 AD systems in Switzerland can be expected, further testing and advancement of the required technology and the legal and regulatory framework for AD is required (Perret et al., 2018).

5G and automated driving

Communication technologies required for automated driving

Freyberg et al. (2019) distinguish three communication technologies which are required for AD:

- Environment information capturing technologies directly monitor a vehicle’s surroundings with sensors (e.g. cameras, radars) in order to identify objects (e.g. pedestrians) and react to them.
- Short-range vehicle-to-x (V2X) communication enables bidirectional information exchange among vehicles, roadside infrastructure (e.g. traffic lights) and other participants in road transport (e.g. pedestrians). Establishing short-range V2X communication can improve safety of AD (specifically at higher automation levels), e.g. by informing surrounding vehicles about the intention of a vehicle to change lanes or a sudden and fast deceleration.
- Long-range V2X communication enables the aggregation of information captured from a larger number of moving vehicles in order to conduct meaningful analysis such as real-time traffic maps. Important information such as road hazard warnings or driving recommendations can be sent back to the vehicles.

Environment capturing technologies can be supported by cellular mobile networks (e.g. if a cellular network among vehicles in the proximity is created), but capturing information about the environment in proximity (e.g. pedestrians which suddenly cross the street) cannot rely on cellular mobile networks, as these are cannot be 100% reliable (e.g. in case of areas with no reception) (Freyberg et al., 2019). However, short- and long-range V2X communication can be enabled by cellular mobile networks.

Frequently mentioned key requirements for enabling V2X communication for AD are to connect a large number of vehicles plus roadside infrastructure, the possibility to transmit data while the sender and/or receiver are moving at higher speeds, sufficient capacity to transfer data between many objects in a given area, high coverage (along road infrastructure), high reliability, and for some applications also low latency (e.g. lane change notifications by surrounding vehicles) (Rude Baguette, 2019; Barney, 2019; Köllner, 2020; Molinaro & Campolo, n.d.). Currently, there is a discussion among policy makers, automotive and telecommunications companies, industrial associations as well as researchers about whether cellular V2X (C-V2X, based on the 4G and 5G standard) or Wi-Fi protocols shall be used for

V2X communication in AD (Rude Baguette, 2019; Köllner, 2020; Russon, 2018). Wifi-based V2X communication is currently mainly advanced in the USA. China decided to build on C-V2X and Europe did not decide for either one of the technologies yet (Köllner, 2020). In the following, we compare the properties of Wifi-based V2X communication versus C-V2X, and 4G with 5G C-V2X.

Wifi vs. C-V2X

A comparison of Wifi with 4G C-V2X showed that the difference in latency between Wifi and C-V2X is not large, but that C-V2X is easier to install and configure (Hainen et al., 2019). C-V2X performs better with respect to range and reliability (5GAA, 2019). Thus, an advantage of C-V2X is that it can be used to transmit data between vehicles and road infrastructure in proximity and also to transfer data between vehicles and a central unit which aggregates the data from many vehicles, analyzes it and sends live traffic information and driving recommendations back to the vehicles. The wider range coupled with high data rates will also be an advantage of 5G C-V2X, if vehicles will transmit data captured via sensors (e.g. cameras, radars) to a central unit which uses this data to improve AD technology (e.g. through machine learning).

4G vs. 5G C-V2X

Today's C-V2X standard is based on 4G and 5G mobile networks (Luber & Donner, 2020). Some applications have shown that 4G C-V2X can support AD (e.g. Ford, 2018). 5G mobile networks perform better in meeting important requirements for C-V2X such as higher reliability, higher capacity, the possibility to connect more devices and reliably transmitting data at higher speeds. Latency of data transfer in 5G networks is lower than in 4G mobile networks which has positive effects on safety. Obviously, when data on maneuvers (e.g. braking, lane changes) of vehicles in proximity arrive earlier, the vehicle can react earlier. For these reasons, it is expected that in future C-V2X will be improved further based on the capabilities provided by 5G (Freyberg et al., 2019; Köllner, 2020).

Which standard will prevail in the long run will certainly depend on more than the technical features of the communication protocols (e.g. lobbying by stakeholders). Many experts assume that in the long-run AD will significantly benefit from 5G mobile networks due to its suitable characteristics (Rude Baguette, 2019; Barney, 2019; Freyberg et al., 2019; Hinchey, 2019; Köllner, 2020; Molinaro & Campolo, n.d.): the possibility to transmit data reliably, among many moving vehicles and roadside infrastructure at ultra-low latency.

GHG abatement potential and rebound

AD systems have the potential to avoid GHG emissions by increasing fuel economy of road vehicles, e.g. through smoother acceleration and breaking compared to humans, platooning of vehicles (vehicle convoys and adaptive cruise control to coordinate driving speed and minimize distance between vehicles to reduce wind resistance) or due to weight reductions while still fulfilling safety standards (which is possible because AVs are safer than conventionally-driven vehicles) (Alam et al., 2010; Anderson et al., 2016). A review of studies assessing fuel savings through AD yields fuel savings ranging between 2% and 25% and sometimes 40% (Taiebat et al., 2018).

Driving automation can be a facilitator of vehicle electrification (e.g. route selection and driving mode adaptation according to battery life) and thereby enable further GHG emission reductions (Taiebat et al., 2018). If AD optimizes the utilization of existing road transport infrastructure (e.g. the capacity of roads increase because the distance between cars decreases) it can also reduce the need for building additional transport infrastructure, whose construction and operation is associated with a large amount of GHG emissions.

However, there is a high risk that AD induces additional road trips or increases vehicle-miles traveled (VMT) for several reasons:

- Additional trips by children and elderly who would not use a conventionally-driven vehicle (Harper et al., 2016).
- AVs can avoid the inconvenience of finding a parking spot by driving around or back home during waiting time (Anderson et al., 2016).
- Increased throughput on existing roads (Anderson et al., 2016) (higher capacity e.g. due to reduced distance between vehicles or less accidents, which attracts more traffic).
- AVs are more convenient and can induce additional and longer trips (Anderson et al., 2016).
- Decrease in travel time cost, because other activities can be performed in parallel (erosion of the competitive advantage of public over individual transport regarding time utilization) (Anderson et al., 2016).

A review of studies in the field yields changes in VMT through AD in the broad range between -30% and +341% (Taiebat et al., 2018). Most studies, however, expect an increase in VMT rather than a decrease.

If AD leads to transport time and cost savings for individuals, saved time and income can also be spent on other activities with GHG emissions. For example, a study estimates that AD, electrification, right-sizing of vehicles, shared mobility and increased availability of public transport could reduce costs of vehicle, infrastructure and transportation system operations by more than 40% (Fulton et al., 2017). Improving energy efficiency and thus reducing cost in road freight transport can also trigger additional demand for road freight transport (Llorca & Jamasb, 2017).

Due to the high risk of rebound effects in the form of increasing VMT through AD, it is important to identify measures which can lead to a VMT reduction or at least limit the increase in VMT to an acceptable level. These can include the use of sharing models to reduce private car ownership and increase the average utilization of vehicles (esp. through ride sharing) or automated public transport (e.g. busses which dynamically adapt their route to demand) which shift demand from motorized individual transport to public transport (Hilty, 2019; Taiebat et al., 2018). A simulation study in Zurich found that if AVs are owned privately, VMT increases by 40%, whereas when AD systems are only used for automated taxis, VMT would increase by 25% (considering motorized individual transport, taxis and public transport) (Hörl et al., 2019). This increase is explained by the fact that AD can significantly decrease the cost of taxi services because driver cost today account for the major share of taxi service cost (Hörl et al., 2019).

A study on impacts of AD on transport in Switzerland suggests that a combination of public and private transport ("Öffentlicher Individualverkehr") would have the highest potential to substitute motorized individual transport (Perret et al., 2018). This mode of transport is more attractive for consumers because it is more flexible in terms of departure times and routes and faster than traditional public transport.

Other use case impacts

AD can have substantial environmental impacts beyond GHG emissions. Depending on impacts on traffic congestion, number of road transport vehicles, VMT, driving speed and demand for road transport infrastructure, noise and particulate matter emitted by vehicles as well as land use for transport infrastructure will change in a complex way. In the long term, AD can lead to more dispersed and lower-density settlement because people will be willing to live in larger distances from city centers or employer offices (Anderson et al., 2016). In contrast, AD can also lead to increased living density in city centers if less vehicles are on the roads and the need for parking space decreases (Anderson et al., 2016).

AD will also have social impacts. First, AVs are expected to cause less accidents and increase safety in road transport (Anderson et al., 2016). Second, it can increase individual mobility of people who cannot use conventionally-driven vehicles (elderly, children, disabled) (Anderson et al., 2016).

In the mobility and road freight service sectors, driving jobs may become obsolete leading to job losses (Anderson et al., 2016). Transport service providers will enter a new round of intensified competition. Automotive companies might have to share revenues with other companies which develop AD technology (e.g. telecommunication companies).

Estimation of GHG abatement potential

We estimate GHG abatement potential through AD separately for motorized individual transport, public transport by autobuses and road freight transport by truck and van. Based on the expected mileage in 2030 according to a study commissioned by the Federal Office for Spatial Development (Mathys et al., 2016) and emission factors of transport modes in 2030 according to Paul Scherrer Institut (2020) we estimate that motorized individual transport in Switzerland will cause 14’625 kt CO_2e, autobuses will cause 549 kt CO_2e, and freight transport by trucks and vans will cause 2’268 kt CO_2e in Switzerland in 2030. For the pessimistic, expected and optimistic scenarios, as well as for the theoretical potential, we reduced this baseline according to the amount of avoided commuter traffic and business travel estimated in the use case flexible work to avoid double counting of reduction potentials.

We did not find detailed predictions of the adoption of AD in Switzerland and therefore used results of a comprehensive study on AD in Germany (Krail et al., 2019). Based on this study and accounting for the uncertainties, we assume that automated eco-driving with vehicle-to-vehicle communication and platooning can lead to fuel savings of 6% in the pessimistic scenario, 11.4% in the expected scenario and 16.9% in the optimistic scenario. In this case, the optimistic assumption is the same as the theoretical potential.

Based on the same study, we assume that automated mobility services will lead to a reduction of VMT in motorized individual transport of 0% in the pessimistic scenario, 7.3% in the expected scenario and 14.6% in the optimistic scenario. For automated public transport services, we assume a reduction of autobus VMT by 0% in the pessimistic, 1.4% in the expected and 2.9% in the optimistic scenario. For automated freight transport services, we assume a reduction in truck and van VMT by 0% in the pessimistic, 2.3% in the expected and 4.5% in the optimistic scenario. Again, we use the optimistic assumptions also for the theoretical potential.

Based on the same study in Germany, we assume that the adoption of automated eco-driving with vehicle-to-vehicle communication and platooning in motorized individual transport in 2030 will reach 0% in the pessimistic, 0.5% in the expected and 1% in the optimistic scenario. For autobuses, we assume adoptions of 0%, 8% and 16%, and for freight transport by truck and van 0%, 3.5% and 7% accordingly. For the theoretical potential, we assume an adoption of 100% for all transport modes.

To estimate the rebound effect (increase in VMT) in motorized individual transport and public transport by autobuses, we use the average of rebound effects documented in a review of studies on AD (159%) (Taiebat et al., 2018). In road freight transport, we assume a rebound effect of 17.6% according to Llorca and Jamasb (2016). We further assume that additional VMT in motorized individual transport will be driven with electric cars, but in public and freight transport with conventional combustion engines.

To estimate the GHG emissions caused by non-5G equipment required for AD, we considered AD ICT equipment according to Gawron et al. (2018) (e.g. computer modules, cameras, radars) and extrapolated this estimate to country-wide values using the expected number of road vehicles in Switzerland in 2030 and the adoption rates by scenario (result in section 3.6.3). We could not account for the amount of ICT equipment that will be installed in road infrastructure due to insufficient data availability. Table 29 provides an overview of the main assumptions. Figure 13 shows the estimated GHG abatement potential for the use case AD by scenario.

Transport mode	**Baseline GHG emissions**	**Fuel savings**			**Reduction in VMT**			**Adoption**					**Rebound effect**
		Pes.	Exp.	Opt./Theor.	Pes.	Exp.	Opt./Theor.	BAU	Pes.	Exp.	Opt.	Theor.	
Motorized individual transport	14’625 kt CO_2e	6%	11.4%	16.9%	0%	7.3%	14.6%	0%	0%	0.5%	1%	100%	159%
Autobuses	549 kt CO_2e	6%	11.4%	16.9%	0%	1.4%	2.9%	0%	0%	8%	16%	100%	159%
Truck and van transport	2’268 kt CO_2e	6%	11.4%	16.9%	0%	2.3%	4.5%	0%	0%	3.5%	7%	100%	17.6%

Table 29: Main assumptions for estimating GHG abatement potential through automated driving in Switzerland in 2030.

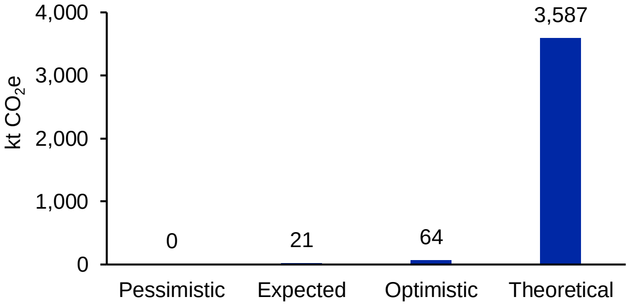

Figure 13: Estimated GHG abatement potential through automated driving by scenario.

Conclusion and recommendations

In order to utilize the potential of AD for GHG emission reductions it is essential to systematically identify potentials of this technology for increasing fuel economy and reducing VMT. The main challenge will be to avoid rebound effects which will lead to an overall VMT increase. Therefore, policy makers in Switzerland need to develop an integrated transport strategy which considers AD and shared transport services which substitute private vehicle trips, increase vehicle utilization and, thus, decrease VMT (Perret et al., 2018). This might even require reconstructing transport infrastructure which allows for automated public transport (e.g. more stop possibilities on streets) (Perret et al., 2018). Transport service providers should develop business models which are targeted to VMT reduction.

For an increase in adoption of AD, policy makers, car manufacturers and ICT companies need to collaborate to further advance AD and required communication technology, test the technology and decide upon AD policies and standards which are also compatible in an international context.

3.5.4 Precision farming

Terminology

Various definitions of “precision farming” and related terms (e.g. “smart farming”, “precision agriculture”) exist, most of which refer to applications of ICT to increase farm productivity and save resources (Agrarheute, n.d.; Balafoutis et al., 2017; Pivoto et al., 2018; Tullo et al., 2019). The core of the related concepts is the ability to monitor the condition of plants or animals (e.g. using moisture sensors in soils or temperature sensors for animals), analyze gathered data and adjust agricultural inputs (such as fertilizer or feed) according to the needs of plants or animals with higher precision than before (Balafoutis et al., 2017; Tullo et al., 2019).

Precision farming can be applied to plant production or animal production (precision livestock farming). Soto et al. (2019) provide an overview of precision farming applications in plant production such as variable-rate nitrogen and pesticide application, variable-rate irrigation and seeding or machine guidance. For example, data on the nutrition content and moisture of soils can be captured with sensors and used to adjust irrigation and nitrogen fertilizer inputs according to the actual needs (Balafoutis et al., 2017). This can reduce GHG emissions from fertilizer production and reduce nitrous oxide (N_2O) – one of the most impactful GHGs – emissions from agricultural soils (Soto et al., 2019). Machine guidance systems can guide tractors in the same lanes over fields and thereby optimize application of inputs (e.g. seeds, fertilizers) while reducing crop damage and soil compaction (Poncet et al., 2016).

Precision livestock farming aims "to automatically monitor, model and manage animal production and converting bio response into relevant information that can be easily applied to different management aspects focusing both on the animal and on the environment" (Tullo et al., 2017, 2019, p. 2752). Tullo et al. (2019) provide an overview of precision livestock farming applications such as precision feeding, lameness detection, real time milk analysis, and fertility management. For example, data on temperature and movement of dairy cows can be used to analyze health condition of individual cows and adjust feeding (precision feeding). Thereby, the emission of methane (CH_4) – an important GHG – from enteric fermentation can be reduced. Such data can also be used to identify diseases of animals (e.g. lameness, mastitis) or optimize fertility management (e.g. identification of optimal time for insemination) and thereby reduce the number of animals required per unit of agricultural output (Tullo et al., 2019).

(Precision) Farming in Switzerland

In 2016, more than 150'000 people worked in roughly 52'000 agricultural worksites in Switzerland. The utilized agricultural area was 10'500 km^2 (FSO, 2019c) or roughly 25% of the surface area of Switzerland. The number of farms decreased and the average size of a farm increased significantly since 1995 (FSO, 2019c).

The livestock on Swiss farms in 2018 consisted of roughly 11.5 million chickens, 1.5 million cattle, 1.4 million pigs and significantly less sheep, goats and horses or other equine animals. While the number of pigs and cattle decreased slightly in the last 10 years, the number of chicken increased significantly (FSO, 2019c).

In 2018, 55% of inland agricultural GHG emissions in Switzerland were methane emissions (CH_4) from enteric fermentation (mainly form cattle), 25% were nitrous oxide emissions (N_2O) from agricultural soils and 19% were methane and nitrous oxide emissions from manure management (FOEN, 2020b). The shares are measured according to the global warming potential of the GHGs. Emissions from agricultural soils are mainly caused by application of synthetic fertilizers and manure. It has to be considered that the global warming potential of methane is 25 times and that of nitrous oxide is 298 times higher than that of carbon dioxide (CO_2), based on a time horizon of 100 years (IPCC, 2007).

Only few data on adoption of precision farming technologies in Switzerland exist. Interviews of various experts in the agricultural sector in Switzerland showed that adoption of precision farming technologies in plant production (e.g. variable-rate nitrogen application) in Switzerland is very low, while application of precision livestock farming technologies is slightly higher. A study on the adoption of precision farming technologies in Austria showed that 6% of farms apply precision farming technologies to 13% of arable land (Hirt, 2018). Several living laboratories to test precision farming technologies have been set up in Switzerland, such as the Swiss Future Farm (Swiss Future Farm, 2020) or AgroVet-Strickhof (AgroVet-Strickhof, 2020).

5G and precision farming

Collecting data on conditions of animals or plants by manually observing plants and animals is highly labor-intensive. Through distributed sensors (e.g. in soils or attached to animals), data collection can be automatized. While sensor data could be collected manually (e.g. by reading the displays of sensors), remotely gathering the data by means of wireless/mobile networks is significantly more efficient. These applications pose high requirements on networks in terms of number of connected devices, device energy efficiency (e.g. because sensors are not attached to a fixed electricity supply) and coverage of large (agricultural) areas. The mMTC usage scenario defined in the IMT-2020 standard addresses these requirements. It defines that 5G mobile networks are required to connect a large number of IoT devices (e.g. sensors) also in inconvenient locations and reduce power consumption of devices (and thus increase battery life) (ITU, 2017). Network technologies supporting mMTC usage scenarios, so called low power wide-area networks (LPWAN) already exist.

Low power wide-area networks (LPWAN)

Table 30 provides an overview of important characteristic of most common LPWAN technologies based on Afaneh (2020) and Swisscom (2019). To date, these technologies support 92% of IoT connections globally (IoT Analytics, 2020). LTE-M and Narrowband-IoT use the licensed (cellular) radio frequency spectrum, whereas LoRa and Sigfox use the unlicensed (non-cellular) spectrum. In Switzerland a LoRa-based network is already in operation covering 96.7% of the Swiss population (Swisscom, 2020). As 5G networks also use the cellular spectrum, they are often considered an advancement of LTE-M and NB-IoT networks. Accordingly, the NB-IoT and LTE-M standards shall be included in the 5G "ecosystem" (GSMA, 2018; Vos, 2018).

Characteristic	**Sigfox**	**LoRa**	**LTE-M**	**NB-IoT**
Radio frequency spectrum	Unlicensed	Unlicensed	Licensed (cellular)	Licensed (cellular)
Range	3-50 km	2-20 km	1-10 km	1-10 km
Data rate	100 b/s	10-50 kb/s	1 Mb/s	200 kb/s
Latency	not provided	1-10 s	10-200 ms	1.4-10 s
Power consumption	Low	Low	Medium	Low

Table 30: Characteristics of common LPWAN technologies based on Afaneh (2020). Latency based on Swisscom (2019).

While LPWAN technologies in the unlicensed spectrum have an advantage in range and energy consumption, LTE-M has an advantage in data rate and latency. Cost per connectivity module are lower for LoRa and Sigfox than for LTE-M or NB-IoT (Swisscom, 2019). The LoRa standard, however, is not open. That means LoRa chips can only be purchased from one company, a fact which creates dependency and lock-in effects (Zeh, 2019). An advantage of cellular LPWAN technologies is that they are standardized by international standardization bodies (e.g. 3GPPP) and supported by a large "ecosystem" of organizations. Another advantage of cellular LPWAN technologies is that they support higher data rates and thus potentially more precision farming use cases can be realized. In the following, we discuss specific network requirements of precision farming applications.

Number of connected devices

The minimum requirement for 5G mobile networks is to support connections for at least 1 million devices for every square kilometer (ITU, 2017). According to Swisscom LPWAN technologies support more than 10'000 devices per radio cell (Swisscom, 2019). The density of connected devices that a "smart" farm will deploy can be expected to be clearly smaller. Only in cases when farms are located in agglomerations, it must be taken into account that they compete with connections established by households, companies and vehicles in the same area.

Device energy consumption

A central factor in large-scale deployment of sensors which are not connected to the electricity grid or generators (e.g. solar panels), is their battery life. Re-charging or replacing batteries for many sensors can be very labor-intensive and should be necessary only in large time intervals. To date, the energy required for sending and receiving data in 5G networks is intensively discussed. Many researchers argue that device energy consumption in 5G networks will be lower than in previous mobile network generations, e.g. because less time is required for synchronization and data transfer between a user device and a radio base station (Lähetkangas et al., 2014) or because devices have to transition less frequently from a sleep into an active mode (Reial et al., 2020). To date, energy features of 5G networks are still in development. If 5G networks meet the device energy-efficiency requirements defined in the mMTC usage scenario, they will clearly simplify the roll-out and integration of large amounts of sensors in farming, enable acceptable battery life and thus associated cost.

Coverage

According to the mMTC usage scenario, 5G connectivity services shall also be available in inconvenient locations. This is specifically crucial for farms located in remote areas. It depends on the rollout plans for 5G mobile networks to what extent farms in Switzerland will be able to benefit from the capabilities of 5G mobile networks. If the area where a farm is located is not covered with 5G mobile networks (or previous generations of mobile network technologies), the only option to implement precision farming is to use a combination of fixed line networks and non-cellular LPWAN networks (e.g. LoRa).

Data rates and latency

While most precision farming use cases do not require the exchange of large data volumes and low latency, some precision farming use cases do. For example, high-resolution images are required for identifying health condition of plants or weeds in fields, which can be captured using drones, self-driving tractors or robots. 5G mobile networks can allow farmers to navigate drones over fields, observe the conditions in high-resolution in real-time and steer the drone to areas where issues are suspected. Precision farming applications which involve automatic steering of machines over fields (e.g. tractors with lane keeping systems or small collaborative robots which remove weeds on fields and plant seeds) can set high requirements for data rates and latency.

To summarize, so far non-cellular LPWAN technologies perform better with respect to range and energy-efficiency, whereas cellular LPWAN technologies perform better with respect to data rates and latency and are less dependent on individual providers. If the mMTC (massive machine type communications) usage scenario specified by ITU (2017) improves the cellular LPWAN technologies with respect to range and energy consumption, it can support more use cases than existing LPWAN technologies based on one network technology by providing sufficient coverage in remote areas, the ability to collect data from many energy-efficient sensors, transmission of small and large data volumes.

GHG abatement potential and rebound

Plant production

A literature review of GHG emission reduction potentials through precision farming in plant production by Soto et al. (2019) yields six main applications:

- Variable-rate nitrogen application
- Variable rate irrigation
- Controlled traffic farming
- Machine guidance
- Variable-rate pesticide application
- Variable-rate planting/seeding
- Precision physical weeding

According to this study, variable-rate nitrogen application and variable rate irrigation have the highest potential to reduce GHG emissions, followed by controlled traffic farming, machine guidance and variable rate pesticide application. Reducing input of nitrogen-based fertilizers through variable-rate nitrogen application can reduce N_2O emissions from agricultural soils and GHG emissions caused during production of fertilizers (Soto et al., 2019). Variable-rate irrigation can reduce the amount of water needed, the energy required for pumping and transporting water, and can avoid extreme soil water availability, which boosts N_2O emissions (Soto et al., 2019). Controlled traffic farming and machine guidance can optimize routes of tractors over fields, which can reduce use of agricultural inputs (e.g. seeds, fuel) and avoid soil compaction (Soto et al., 2019). The authors estimated that variable-rate nitrogen application and machine guidance in the EU could have avoided 0.3-1.5% of total agricultural GHG emissions in the EU in 2015.

An experiment of variable-rate application of fertilizers in Switzerland compared conventional fertilization with variable-rate fertilization based on nitrogen monitoring using drones. Results show that use of fertilizers could be reduced by 10% while maintaining yield (Zehner et al., 2019). Bosshard et al. (2012) estimated an excess use of 9,000 tons of nitrogen in the agricultural sector in Switzerland, which could potentially be reduced through variable-rate nitrogen application (Stierli, 2017). However, a challenge for increasing the adoption of these technologies is that not all required sensor technology is available. For example, sensors which measure the nitrate-content of soils *in situ* are still under development. Currently, measurements still have to be conducted in laboratories (Burton, 2016).

Livestock farming

A review of precision livestock farming applications finds 11 applications which have the potential to reduce GHG emissions such as precision feeding, lameness and mastitis detection or fertility management (Tullo et al., 2019). “Feed is the most important and costly parameter in livestock farming and should be carefully calibrated to fulfill animals' energetic requirements during their lifetime, avoiding over-feeding and the subsequent wasting of nutrients in the environment” (Tullo et al., 2019, p. 2756). Precision feeding (e.g. by monitoring rumination and eating behavior of cattle) allows to tailor the diet to the needs of individual animals with positive impacts on welfare, productive life of animals and GHG emissions.

Systems to monitor animal healthcare can also be used to identify diseases such as lameness, impaired rumen functionality and mastitis. Detecting these diseases can increase the health of animals, their productivity (e.g. milk output) and reduce GHG emissions per unit of agricultural output (Tullo et al., 2019). Finally, identifying high-fertility windows of animals by monitoring the heat of animals allows to manage conception rates, increase the productivity (e.g. reduction of required resource inputs per unit of milk) and reduce the number of animals required to produce a given output (Tullo et al., 2019).

Another aspect, which came up in an expert interview, is that high performance herds (which are fed with concentrated feed) cause less GHG emissions per agricultural output. To maintain productivity of these animals at a high level, precise information on the condition of animals (e.g. health) is required, the data for which can be very labor intensive to collect and analyze. Gathering this data with sensors connected by mobile networks can reduce the cost of providing such information, help to detect issues earlier, and, thus, enable more farmers to manage such herds.

Rebound effects

Improvements in resource or emission efficiency in agriculture are subject to direct rebound effects. The main risk is that productivity increases are not leveraged to reduce net resource input and associated emissions but to increase output and lower prices, which could finally lead to an increase in resource use and emissions (backfire effect). A study finds substantial rebound effects (and even backfire effects) with respect to increases in land productivity and improvements in irrigation water use and the resulting higher level of production (Paul et al., 2019). An interview with an expert in the agricultural sector in Switzerland also showed that even though farmers might be able to reduce fertilizer use through precision farming technologies, they still could apply the maximum permitted amount of fertilizers to increase output (= 100% rebound effect).

It has to be noted that that highest potentials to reduce agricultural GHG emissions in Switzerland lie in consumption oriented measures (e.g. more plant-based nutrition) and changes of agricultural structures (e.g. animal stock, land use). Potentials of production-oriented methods (e.g. through precision farming applications) are generally lower (Bretscher et al., 2018).

Other use case impacts

Besides its GHG-reducing effects, variable-rate application technologies can reduce the amount of water, fertilizers and pesticides used and thereby reduce the amount of hazardous substances in soils and ground water (Tullo et al., 2019). This can help to maintain the productivity of soils for a longer time. In animal production, adjusting feed to animals needs and detecting diseases earlier can have a positive impact on the health and well-being of animals (Banhazi et al., 2012).

In general, automation in the agricultural sector can reduce the amount of monotone and burdening work (Bertschi, 2017), but also shrink the required workforce and lead to job losses (Balafoutis et al., 2017; Walter et al., 2017).

Precision farming can also yield economic benefits for farms such as cost savings due to automation and reduced need for agricultural inputs (Balafoutis et al., 2017; Bartzanas et al., n.d.). Reducing the amount of fertilizers and pesticides and the well-being of plants and animals can also be a strategy to attract customers which ask for more organic agriculture production (King, 2017).

A relevant economic risk of increasing adoption of precision farming technologies is that investing in such technologies is too expensive for small farms and thus can diminish their competitiveness with large, heavily industrialized farms (Walter et al., 2017). However, if small farms manage to adopt precision farming technologies early, it can also help to maintain their competitiveness in terms of cost (e.g. through automation) (Mishra & Tewes-Gradl, 2017).

Estimation of GHG abatement potential

We estimated the GHG emissions caused by production and use of synthetic fertilizers in Switzerland in 2030 (678 kt CO_2e) and from enteric fermentation of cattle (3’037 kt CO_2e) based on Switzerland’s fourth biennial report under the UNFCCC (FOEN, 2020a; WEM scenario).

Based on a project of the Swiss Future Farm (Zehner et al., 2019), we assumed that variable-rate nitrogen application can reduce 2.5% of GHG emissions of producing and applying synthetic fertilizers in the pessimistic scenario, 5% in the expected scenario and 10% in the optimistic scenario. For the theoretical potential, we also assumed a reduction of 10%.

Based on Bartzanas (n.d.) and expert interviews, we assumed that precision feeding of cattle can reduce 2.5% of GHG emissions from enteric fermentation in the pessimistic scenario, 5% in the expected scenario and 10% in the optimistic scenario and for the theoretical potential. Based on Tullo et al. (2019) we assumed that the combination of precision farming application for mastitis detection, lameness detection and fertility management can allow for an additional reduction of 2.5% of GHG emissions from enteric fermentation of cattle in the pessimistic scenario, 11% in the expected scenario, 20% in the optimistic scenario and for the theoretical potential. We did not consider other types of animals besides cattle, because cattle are by far the main contributor to agricultural GHG emissions from enteric fermentation in Switzerland.

Adoption of precision farming technologies in plant production in Switzerland is still low. Based on an expert interview in the field, we assumed that in the business as usual scenario and in the pessimistic scenario, adoption is 0%, 10% in the expected scenario and 20% in the optimistic scenario. Adoption of precision livestock farming technologies is higher. According to Hirt (2018), in 2016 6% of Austrian farms adopted precision farming technologies and the market grows at a rate of 12%. We assumed and adoption of precision livestock farming technologies in Switzerland in 2020 of 9% in a BAU scenario (12% annual growth rate between 2016 and 2020), 17% in the pessimistic scenario (6% annual growth rate between 2020 and 2030), 29% in the expected scenario (12% growth p.a.) and 49% in the optimistic scenario (18% growth p.a.). For the theoretical scenario, we assumed an adoption of 100%.

For precision farming applications to avoid GHG emissions from agricultural soils, we assumed a rebound effect of 100% because it is likely that farmers still apply the highest permitted quantity of fertilizers to increase yield. For reduction of emissions from enteric fermentation, however, lower rebound effects are likely because historic data on livestock from Switzerland shows that the number of cattle decreases while output of agricultural products from cattle (e.g. milk, meat) does not decrease (FSO, 2019c; Leuenberger, n.d.). We could not find studies on rebound effects in livestock production in Europe. A study in developing countries showed that "livestock numbers increase by 2% as a result of more abundant feed and additional demand for cheaper ruminant and non-ruminant meat" (Valin et al., 2013, p. 5). An expert interview confirmed that rebound effects in livestock production in Switzerland are low. Thus, we assumed a rebound effect of 2%.

To estimate the GHG emissions caused by non-5G equipment required for precision farming, we considered soil sensors, smart collars, variable-rate fertilization equipment, and office ICT equipment. We then extrapolated these estimates to country-wide values using the number of Swiss farms, amount of cattle and agricultural area expected in 2030 and the adoption rates by scenario (result in section 3.6.3).

Table 31 summarizes the main assumptions. Figure 14 shows the estimated GHG abatement potential by scenario. All of the reduction shown in the figure comes from precision livestock farming applications to reduce GHG emission from enteric fermentation, because rebound effects of variable-rate nitrogen application fully compensate realized savings.

GHG abatement lever	Baseline GHG emissions	GHG abatement potential				Adoption					Rebound effect
		Pes.	Exp.	Opt.	Theor.	BAU	Pes.	Exp.	Opt.	Theor.	
Reduction of fertilizer use through variable-rate nitrogen application	678 kt CO_2e	2.5%	5%	10%	10%	0%	0%	10%	20%	100%	100%
Reduction of emissions from enteric fermentation in cattle through precision feeding	3’037 kt CO_2e	2.5%	5%	10%	10%	9%	17%	29%	49%	100%	2%
Reduction of emissions from enteric fermentation in cattle through mastitis detection, lameness detection and fertility management		2.5%	11%	20%	20%	9%	17%	29%	49%	100%	

Table 31: Main assumptions for estimating GHG abatement potential through precision farming in Switzerland in 2030.

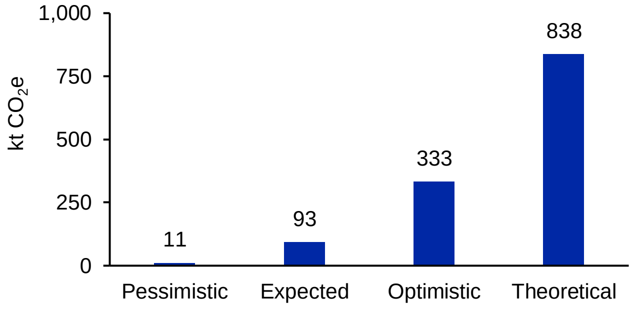

Figure 14: Estimated GHG abatement potential of precision farming applications by scenario.

Conclusion and recommendations

The main risk for not realizing GHG abatements through precision farming technologies is that increases in productivity are not leveraged to realize resource and emission reductions but to increase agricultural output. Thus, policy makers need to incentivize farmers to reduce the amount of agricultural inputs used, which will also reduce the associated environmental impacts. This can be achieved through market-based measures, e.g. by promoting agricultural products from environmentally-friendly production. For example, Paul et al. (2019) suggest a labeling system based on GHG emissions caused in production.

In order to increase the adoption of precision farming technologies, it is essential to convince and enable farmers to adopt such technologies. As many farmers are not familiar and uncertain about the actual benefits of such technologies, it is up to technology providers to demonstrate the benefits (e.g. in living labs), develop user-friendly and easy-to-implement solutions and provide consulting and training services to farms (Bartzanas et al., n.d.). This involves the further development of technologies required for automation of agricultural processes (e.g. nitrate sensors) (Burton, 2016) and the standardization of precision farming technologies to ensure compatibility of solutions from different providers (Pivoto et al., 2018).

As smaller farms are limited in their investment capital, sharing precision farming technologies across farms or providing service-based models (e.g. renting machines) can increase the access of small farms to such technologies. Financial instruments to support adoption of precision farming technology (e.g. investment supports) can also increase adoption (Walter et al., 2017).

In order to foster collaboration among farmers and providers of precision farming technology, agricultural industry associations and policy makers can create platforms for exchange (e.g. through trade fairs or specialist conferences). For example, a workshop on digitalization in the agricultural and food sector, organized upon request by the federal council, took place in Zollikofen in 2017 (FOAG, 2017).

All stakeholders should jointly work on a governance framework which allows for collection and exchange of agricultural data and a fair distribution of rights for using the data (Bertschi, 2017).

3.6 Aggregated results

In the following, we provide an overview of the results for the four selected use cases regarding the 5G network capabilities which support their adoption, the GHG abatement potential of each use case and the GHG footprint of the non-5G ICT equipment required to implement the use cases.

3.6.1 5G capabilities and use cases

Table 32 provides an overview of the main 5G network capabilities which provide benefits to the selected use cases.

Use case	**High data rates**	**High capacity**	**Ultra-low latency**	**Many devices**	**Low energy cons.**	**High reliability**	**High mobility**	**High availability**	**High security**
Flexible work	x		x			x	x		
Smart grid			x	x		x		x	x
Automated driving			x	x		x	x	x	x
Precision farming				x	x				

Table 32: Main benefits of 5G networks by 5G network capabilities and use cases. "x" means the realization of the use case benefits from the capability. Benefits beyond the ones analyzed in this study can exist.

The table shows that the most important benefit of 5G networks, when looking at all four use cases, are ultra-low latency, the possibility to connect many devices, high reliability, mobility, availability and security. In fact, for every use case, it is not a single capability but the combination of several capabilities within one wireless network standard which provides the main benefit. For example, ultra-low latency by itself would not provide sufficient support for the AD use case, but it does in combination with high reliability, availability and mobility. In the following we list combinations of the main capabilities which support the use cases:

- Flexible work: High data rates combined with low latency and high reliability can enable (new forms of) virtual collaboration and provides access to large data volumes from almost anywhere (also in transport) at any time.
- Smart grid: Requires highly reliable, available and secure connection of many devices (e.g. sensors in low-voltage part of electricity grid) at low latency to ensure the stability of grid as a safety-critical infrastructure.
- Automated driving: Requires highly reliable, available and secure data exchange between many moving vehicles at low latency (safety-critical).
- Precision farming: Requires the connection of many devices (e.g. sensors in fields) with low energy consumption because these are not connected to a fixed electricity supply network.

Existing mobile networks do not provide the capabilities to support all of these use cases. The reasons differ from use case to use case; they can be related, e.g., to capacity, latency or availability. Nevertheless, some use cases can potentially be realized with (a combination of) communication technologies other than 5G (e.g. WiFi-based AD, LoRaWAN for precision farming). This can also be seen in the ongoing debate whether AD shall be realized with 5G mobile network or with WiFi technologies (Chee, 2019). A central advantage of 5G technology over other network technologies is that it combines the advantages of various technologies (e.g. 2G-4G, LPWAN technologies, WiFi, fixed networks) and thus meets the diverse requirements of many use cases.

Assuming that each use case would be realized with (a combination of) different suitable network technologies (e.g. AD with WiFi, precision farming with LPWAN), the number of communication networks operated and managed in parallel would increase, leading to more administrative complexity, cost and environmental impacts. In order to avoid the build-out and operation of various communication networks in parallel, it is essential to establish a cross-sectoral dialogue with the aim to establish a communication infrastructure which meets the diverse requirements while minimizing the amount of network hardware and electricity requirements. This will have to include the timely phase-out of older network generations which might become obsolete once 5G networks are consistently available.

3.6.2 GHG emissions abatement potential

Figure 15 provides an overview of the GHG abatement potential in Switzerland in 2030 by use case and scenario.

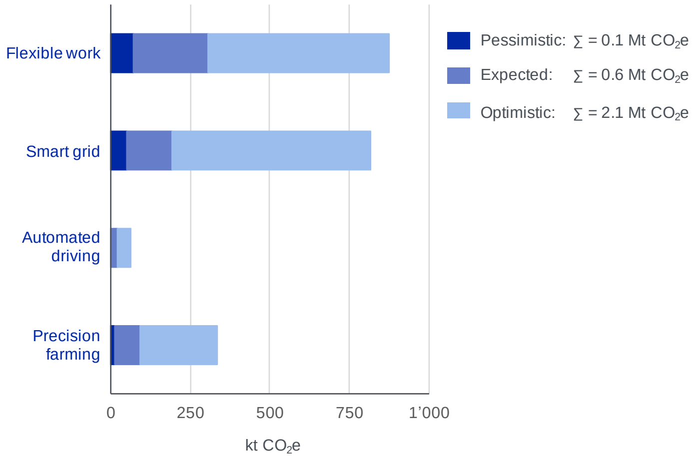

Figure 15: GHG abatement potential in Switzerland 2030 by use case and scenario.

In the optimistic scenario, the selected 5G-supported use cases can avoid roughly 2.1 Mt CO_2e/year in Switzerland in 2030, in the expected scenario 0.6 Mt CO_2e/year, and in the pessimistic scenario 0.1 Mt CO_2e/year. The largest potentials in 2030 lie in flexible work, smart grids and precision farming. The adoption of the four use cases is expected to be still relatively low by 2030 (specifically for AD); thus, the theoretical potentials of the use cases (maximum adoption, no rebound) to contribute to climate protection is even higher. Table 33 shows the main levers for realizing the GHG abatement potential and the main risks for increasing GHG emissions.

Use case	Main GHG abatement levers	Main risks for increasing GHG emissions
Flexible work	– Reduction of commuting distances and frequencies – Reduction of business trips – Reduction of office space	– Increased virtual collaboration induces additional business trips – Individuals spend saved time and money on GHG-intensive activities, goods or services (e.g. private travel) – (Heated) residential space increases due to working from home and (heated) office spaces at employer offices does not decrease
Smart grid	– Built out of renewable energy sources (e.g. wind, sun) – Dynamically adapting electricity demand according to availability of electricity from renewable energy sources	– Electricity consumers spend saved money on consumption of additional electricity or other GHG-intensive goods or services
Automated driving	– Increasing fuel efficiency through automated driving – Reducing number of vehicles and vehicles-miles traveled by increasing utilization of vehicles (e.g. through automated public transport)	– Increased attractiveness of car transport and access for underserved population increases vehicle-miles travelled and cannibalizes other, more GHG-efficient, transport modes
Precision farming	– Increasing productivity in livestock farming (e.g. through disease detection) – Reduction of agricultural inputs (e.g. fertilizers, water)	– Efficiency increase are used to increase yield and not to reduce use of agricultural inputs and GHG emissions

Table 33: Main levers for realizing GHG abatement potential and risks that should be mitigated at the same time.

3.6.3 GHG footprint of non-5G equipment required for use cases

Figure 16 provides an overview of the GHG footprint of non-5G ICT equipment required for the use cases. Production and operation of this equipment causes up to 0.16 Mt CO_2e/year in 2030 in the optimistic scenario, 0.08 Mt CO_2e/year in the expected and 0.03 Mt CO_2e/year in the pessimistic scenario. The footprint is largest for flexible work and smart grid, because the adoption of flexible work and the smart grid in 2030 is assumed to be higher than the adoption of AD and precision farming. Plus, there are more households and commuters in Switzerland than there are farms.

We have to consider, that the main emphasis of this study is to estimate the GHG impact of 5G mobile networks, and that we could not consider all non-5G ICT equipment required for realizing these use cases (e.g. fixed networks, data centers, ICT equipment installed in road infrastructure).

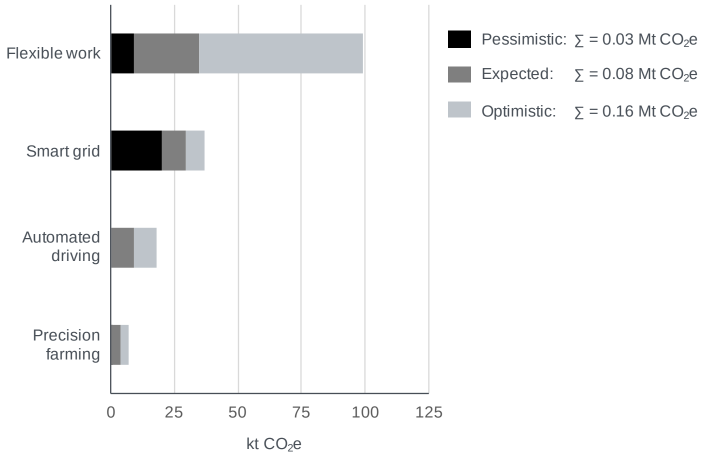

Figure 16: GHG footprint of non-5G equipment required for the use cases. This is the ICT equipment needed in addition to the 5G infrastructure for implementing the use cases.

3.7 Methodological reflections

Our results are subject to uncertainties and limitations specifically with respect to the estimation of a baseline scenario (business-as-usual GHG emissions in 2030), the estimation of the GHG abatement potential of the selected use cases, the estimation of rebound effects, and the estimation of the GHG footprint of non-5G ICT equipment required for use cases (e.g. not all equipment could be considered). We also limited the environmental indicators taken into account to GHG emissions, although it would be methodologically possible to include environmental impact categories beyond global warming potential. Most importantly, this study is focused on a small set of selected use cases which provided some initial evidence that a GHG abatement potential can be expected. Further use cases may exist which provide either substantial GHG abatement potentials or also high potentials to increase GHG emissions. This is an inherent limitation of this type of study because new use cases of either type can always be created by innovation, most probably even after the 5G infrastructure will be fully rolled out. Due to these limitations of our study, we recommend to focus the interpretation on comparative analysis (e.g. the comparison of GHG potentials across use cases and scenarios) instead of absolute figures.

4 Synopsis

By 2030, the production and operation of 5G network equipment installed in the Swisscom network is expected to cause emissions at a level of 0.018 Mt CO_2e per year of network operation. In comparison to the overall GHG footprint of the ICT sector in Switzerland of 2.1 to 2.8 Mt CO_2e, as projected for 2025 in an earlier study (Hilty & Bieser, 2017),[4] this is a share below 3%, even if we roughly include the 5G networks of other telecommunication network operators. This result is not very surprising, since ICT infrastructures (incl. networks) in general cause significantly less GHG emissions than the end user devices used to access the infrastructures if the foreign production of all devices is taken into account.

Therefore, as 5G mobile networks will cause only a small fraction of the GHG footprint of the ICT sector in Switzerland, measures to keep the GHG-footprint of ICT in Switzerland small should target not only 5G mobile networks, but the whole ICT sector.

The selected use cases which benefit from 5G networks can avoid GHG emissions between 0.1 and 2.1 Mt CO_2e in Switzerland in 2030. On the other hand, the non-5G equipment required for implementing the use cases will roughly cause additional emissions between 0.03 and 0.16 Mt CO_2e by 2030. Figure 17 gives an overview of the GHG footprint of 5G networks, the GHG abatement potential of 5G-supported use cases and the GHG footprint of the non-5G ICT equipment required for the use cases by scenario.

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[4] Considering telecommunication networks, data centers, operator activities and end user devices in Switzerland with GHG emissions calculated with LCA methodology from a consumer perspective (as in the present study).

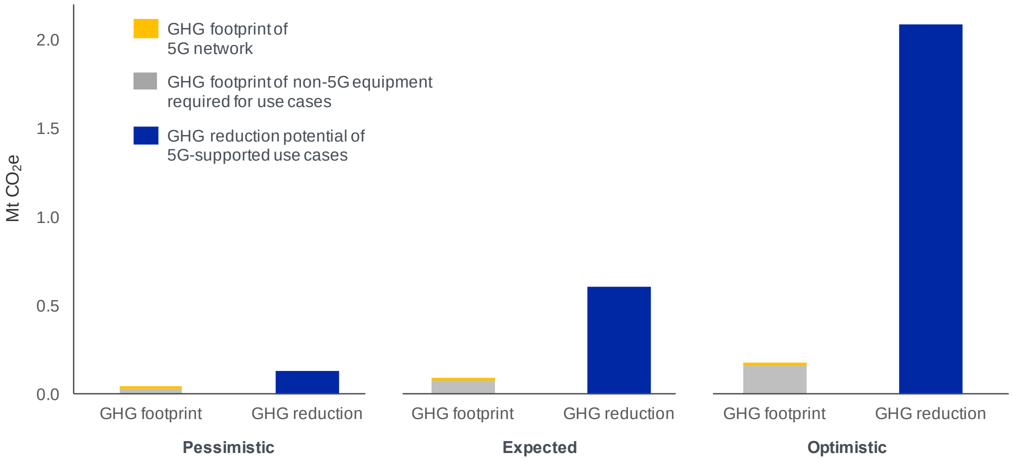

Figure 17: GHG footprint of the Swisscom 5G network, of non-5G equipment required for use cases, and GHG abatement potential of 5G-supported use cases in Switzerland in 2030. The GHG footprint of the non-5g equipment can increase with optimistic assumptions because they include higher adoption rates for the use cases, which requires more ICT equipment.

The comparison suggested by Figure 17 should be interpreted with some care. On the one side, it focusses on the Swisscom 5G network and some ICT-equipment which supports the use cases could not be considered (e.g. data centers, fixed networks). On the other side, various other use cases are supported by 5G networks (e.g. see Table 20 on page 32), which can have both increasing and decreasing effects on GHG emissions.

For looking beyond 2030, it should be taken into account that the expected adoption rates for the selected 5G-supported use cases we predicted for 2030 are relatively low. The theoretical potentials of the use cases to contribute to climate protection are significantly higher, which implies that with a wider time horizon, abatement potentials will increase.

Taking the resulting uncertainty into account, we can conclude that if 5G network capabilities are systematically utilized, there will be significant potential for GHG abatement in other sectors by 2030 (and beyond). The abatement potential is clearly larger than the GHG footprint of 5G networks in the same year. This holds true even if we consider the non-5G equipment required for enabling the use cases and (roughly) the 5G networks of other telecommunication network operators in Switzerland.

5 Conclusion

Increasing requirements placed on mobile networks in terms of number and types of connected devices, data volumes and supported applications shall be met by 5G networks. We assessed the GHG footprint of 5G networks and the GHG abatement potential of selected 5G-supported use cases in Switzerland in 2030.

By 2030, 5G networks operated by Swisscom are estimated to cause 0.018 Mt CO_2e GHG emissions per year. 5G networks in 2030 are expected to cause 85% less GHG emissions per unit of transmitted data than today's mobile networks.

5G is designed to enable enhanced mobile broadband, massive machine-type communications and ultra-reliable, low-latency communication. This will create significant benefits for use cases in transportation, manufacturing, farming, energy, buildings, entertainment & media, health and the public sector. We selected four 5G-supported use cases with a promising potential to reduce GHG emissions in Switzerland: flexible work, smart grid, automated driving, and precision farming. As a result of our assessment, we estimate that these use cases can avoid up to 2.1 Mt CO_2e/year in 2030 in an optimistic scenario, 0.6 Mt CO_2e/year in the expected scenario and 0.1 Mt CO_2e/year in a pessimistic scenario. The largest potentials in 2030 can be attributed to the use cases *flexible work* (by reducing business travel and commuting through enhanced virtual collaboration), *smart grid* (by increasing the share of renewable energies in the electricity supply system), and *precision farming* (by reducing use of agricultural inputs such as fertilizers and increasing productivity in livestock farming). The adoption of the selected use cases is expected to be still relatively low by 2030, which implies that the potential of the use cases to contribute to climate protection will increase in the further future.

4G mobile networks do not provide the capabilities to support all of these use cases. The reasons differ from use case to use case; they can be related, e.g., to capacity, latency or availability requirements. Although some use cases can potentially be realized with (a combination of) communication technologies other than 5G (e.g. WiFi-based automate driving, LoRaWAN for precision farming), there is an advantage in meeting the requirements of many use cases with one mobile network technology and infrastructure, as in the case of 5G networks.

There are two risks that counteract the GHG abatement potential of the 5G-supported use cases. First, rebound effects can compensate, if not overcompensate, for the expected GHG-reductions. This means that increased GHG-efficiency can in the worst case also cause an increase in demand for certain services, which leads to additional emissions. Second, there is additional (non-5G) ICT equipment required for enabling these use cases (e.g. laptops for flexible work, sensors for precision farming) whose production and operation causes additional GHG emissions. We estimate these additional emissions up to 0.16 Mt CO_2e/year in total by 2030.

Thus, if 5G network capabilities are systematically utilized to support use cases with high GHG abatement potentials, significant GHG abatements can be realized by 2030. The overall reduction potential of the use cases investigated in this study is clearly larger than the GHG footprint of 5G networks (even if we roughly include 5G networks of other telecommunication network operators in Switzerland) plus the GHG footprint of additional (i.e., not 5G-specific) ICT equipment required for enabling the use cases.

In order to put 5G at the service of climate protection, measures should be taken in two fields. First, the GHG footprint of the ICT sector should be kept small. Here, it is important to address all ICT infrastructure and equipment because 5G networks will be responsible for less than 3% of the footprint of the whole ICT sector, but making use of 5G will need additional ICT equipment that is not specific to 5G. Second, the GHG abatements enabled by use cases in the transportation, energy and farming sectors should be unleashed by creating conditions that are conducive to flexible work models, new mobility services, renewable energy sources, and forms of farming that target the reduction not only of CO_2, but also CH_4 and N_2O emissions. If no targeted action towards such framework conditions is taken, there is a risk that the reductions will remain smaller than the footprint of the ICT equipment needed to implement them and that rebound effects compensate, if not overcompensate for the possible GHG emission reductions.

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