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Scenario-based analysis of the carbon mitigation potential of 6G-enabled 3D videoconferencing in 2030

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\textbf{ABSTRACT}

Videoconferencing and teleworking have become indispensable for many public and private organizations since the appearance of COVID-19. However, the extent to which the pandemic may have a lasting effect on people’s daily life and work remains to be seen. Poor visual and acoustic quality of online meetings could reactivate old communication patterns in the long term. New technologies such as 6G and 3D holography, offering enhanced video quality and online experience, could further drive virtualization in communication. This article investigates the CO\textsubscript{2} mitigation potential resulting from the partial replacement of business travel by 6G-enabled 3D videoconferencing in Germany in 2030. The carbon footprint calculation combined with scenario analysis has shown significant results when direct and indirect energy effects are considered. In the different scenarios investigated, a virtual conference would cause between 0.2% and 0.9% of the emissions of a mean-distance conference trip taken by a German business traveler. Considering the mitigation potential of all German conference travel in 2030, emissions could be decreased by 2.1 MtCO\textsubscript{2}eq (8.9%) and 20.5 MtCO\textsubscript{2}eq (88.4%), respectively, compared to 2019 under conservative and optimistic assumptions. In terms of current national total emissions, increasing virtualization of conferences could contribute between 0.3% and 2.8% to the German mitigation efforts.

1. Introduction

Global environmental changes such as global warming and the loss of natural ecosystems put our established way of living and development efforts increasingly into question. The ever deeper intrusion of humans into natural ecosystems can have severe consequences for us as it encourages the emergence of dangerous infectious diseases (\textit{Millennium Ecosystem Assessment, 2005; UN Environment, 2019}), which are rapidly gaining global significance due to our travel habits (Wilson, 1995), as COVID-19 has just taught us. Even though the long-term effects of the current pandemic are as yet unknown, it is already recognized as a pivotal event that forces us to fundamentally change our communication and collaboration routines in business and private environments by accelerating...
Videoconferencing and teleworking have become indispensable in a lockdown situation for many public and private organizations. Various web applications have gained competitive advantages in recent months despite security concerns and less experienced users, because they are quickly installed and offer platform-independent and cost-effective communication (Hacker et al., 2020). In contrast, common videoconferencing technology, primarily conceived for installations in meeting rooms, requires additional infrastructure and trained users and usually comes with less interactive features.

Videoconferencing has created new formats of collaboration and knowledge transfer. It provides an inclusive environment where people who cannot travel for personal or other reasons (e.g. parents, disabled people, people with small budgets or limited time) can meet. Moreover, it can contribute to traffic relief and resource savings. However, if compared with the triumph of other digital products (email, e-commerce) and taking the often poor visual and acoustic quality of online meetings into account, it cannot be excluded that additional trips will be considered in the future due to an unchanged appreciation for face-to-face meetings (Behrendt et al., 2005; Larsen, 2015). Mokhtarian (2002) argues that, in hindsight, the adoption of new communication technologies has not reduced travel activities; in fact, they support people by allowing them to be more productive while traveling. She further sees empirical evidence that travel has been stimulated by telecommunication (complementarity effect) rather than substituted thanks to the facilitated access to information about interesting places to see and people to meet. Not to be neglected, economic indicators such as increasing incomes and decreasing prices have also had an influence on travel behavior.

New technologies improving the video quality and online experience could further drive the virtualization in communication. In reality, persons and objects are perceived in 3D with height, width, and depth information. Due to the 2D displays used nowadays, the depth information is lost in videoconferences. This leads to a flat virtual meeting experience with poorly perceptible information. For instance, indirect communication between participants is severely restricted by the lack of body language. Here, 3D holographic communication can provide a significant boost in attractiveness and usage. As shown in Fig. 1, 3D display technology emulates reality by projecting the three room dimensions and makes the user experience more natural. With the additional depth information, objects no longer appear to the observer just on the display, but also in front of and behind it. A new technological approach makes it possible that no classic 3D glasses are required for the visualization of spatial depth. Dedicated 3D camera systems and powerful processors are already under development and could be integrated into future devices (computer displays, windshields, smartphones, and smartglasses) without greatly affecting the form factor of the device. However, this technology requires a high data transmission rate in the network if used for videoconferencing. For further information about 3D holographic displays, the reader is referred to Haeussler et al. (2009) and Haeussler et al. (2017).

Germany’s economy is export-oriented and knowledge-based, which led the country to become the second most popular place to host international business conferences and trade shows (ICCA, 2020). In addition, 195 million business trips from Germany to national and international destinations were recorded for 2019 (VDR, 2020). However, the abatement potential through de-materialization of such business travel is seen as being comparatively low in Germany, with just 5% in 2030 (14 MtCO₂ equivalent (eq) for E-work, 1 MtCO₂eq for E-learning), compared to other sectors such as smart grids, smart buildings, and smart manufacture (GeSI, 2018). In contrast, at the level of a specific case, Ong et al. (2014) showed that a five-hour videoconference with four participants only has between 0.11% and 7.4% of the energy and carbon footprint of in-person meetings if direct consumption and embodied energy of ICT devices is taken into account. Burtscher et al. (2020) estimated the avoided emissions of the annual European Astronomical Society (EAS) meeting by comparing the direct emissions of the virtual meeting in 2020 (1,777 participants) with the previous year’s real meeting in Lyon (1,240 participants). They found that the emissions from the virtual meeting accounted for only 0.03% of last year’s travel emissions.

A recent German study investigated the CO₂ emissions of HD video streaming by directly measuring the data traffic and energy consumption of data centers and different network types (Kohn et al., 2020). Wired transmission via fiber optic cables and copper cables turned out to be the most efficient way of consuming HD video content as it produces 2–4 gCO₂eq emissions per hour. The new 5G standard is expected to reach 5 gCO₂eq emissions per hour and should be further disseminated in public space together with WiFi.

![Fig. 1. Schematic depiction of 3D videoconferencing realized by a spatial light modulation display emanating modulated light waves to generate a 3D object in space.](image-url)
hot spots, the authors conclude. Today, 5G technology provides a bit rate of up to 3 Gb/s, which is even expected to increase to up to 20 Gb/s by the mid-2020s. It is already predictable that these bit rates may not be sufficient for future applications. This is particularly the case for data-intensive transmissions in the case of local cloud computing, which enables compact and low-cost local devices. The successor, 6G, is expected to be on the market around 2030. 6G should enable transmission rates of up to 200 Gb/s, reduce latency to less than 1 ms, and achieve a higher energy efficiency level (Fettweis, 2019). Insofar, 6G improves the possibilities and constitutes a technological prerequisite for real-time 3D videoconferencing. The need for 6G intensifies when considering an increasing number of users in large and dense co-working spaces.

This research article sheds light on how 6G enables innovative applications that could contribute substantially to a low-carbon economy. Specifically, we ask how far CO₂ emissions can be reduced in the future using advanced videoconferencing in conjunction with high-performance 6G internet, which we consider necessary to prevent a so-called Zoom fatigue. For the special case of a mixed use of high-quality 2D videoconferencing and 3D holographic videoconferencing partially replacing business travel activities in Germany in 2030, the future CO₂ mitigation potential on a country level is estimated for the first time. Furthermore, we want to know under which technical conditions the highest savings can be achieved. We therefore distinguish between different virtualization degrees, transport modes, travel distances, and technological concepts for transmitting and processing 3D content. In doing so, we want to show that, with the further development of ICT towards 6G, even 3D holography does not have to remain a science fiction pipe dream. However, our analysis focuses more on technological aspects and not so much on socioeconomic implications of virtual meetings.

The article is structured into six sections. Following the introduction, a description of the technological development of ICT in general and wireless communication in particular is given in Section 2. Section 3 shows the methodological approach and selected input data for the study. All results are presented in Section 4 and discussed concerning limitations and future research demand in Section 5. The article concludes with general lessons learned and future challenges in Section 6.

2. 6G Technology enabling future Online Communication

As a reaction to the unsustainable development of the economy, the European Commission announced a new strategic initiative in December 2019, the European Green Deal, which includes a set of deeply transformative policies to reach climate-neutrality and stop environmental degradation on the European continent by 2050 (European Commission, 2019). The new, holistic view recognizes the interdependencies between environmental issues in different sectors (nexus approach), but also between the three dimensions of sustainability (ecological, economic, and social). It is emphasized by the Commission that a higher level of digitalization is needed in many industrial sectors to support the successful transition of the entire economy. Innovative digital technologies that could leverage policy actions include artificial intelligence (AI), new cellular broadband networks such as 5G, cloud and edge computing, and the Internet of Things (IoT). However, the Commission also acknowledges that the energy and material efficiency of the ICT sector itself has to be enhanced, including networks, data centers, and end-user devices (European Commission, 2019).

The ICT sector already contributes about 10% to the global electricity consumption and is predicted to reach an electricity demand of 8,265 TWh, representing 20.9% of the future global electricity supply, in a moderate forecast model for the year 2030 (Andrae and Edler, 2015). According to GeSI (2015), ICT’s carbon footprint has so far been around 2% of the global greenhouse gas emissions and is expected to slightly decline by 2030. Strategies to reduce ICT’s own energy demand and carbon footprint consist of the streamlining of computing processes, renewable energy supply, cooling and energy harvesting from waste heat of data centers, as well as shifting to high-performing hyper-scale data centers (Jones, 2018). On the internet user side, small but collective actions (e.g. switching off the video function in online meetings, selecting low video quality for streaming of videos, reducing online time in general, deleting unnecessary data on cloud storage) can multiply internet-related CO₂ emissions savings (Obringer et al., 2021).

Following the taxonomy described in Berkhout and Hertin (2004) and Horner et al. (2016), a differentiation between three energy effects caused by online-meetings should be considered: (1) direct energy consumption, which occurs throughout the life cycle of information and communication technology (ICT) used for online meetings; (2) indirect energy effects through an increased efficiency in other sectors or the substitution of energy-intensive practices such as traveling (de-materialization and virtualization); and (3) further indirect energy effects associated with structural or behavioral changes in society and the economy (long-term socio-economic effects). Horner et al. (2016) found in their literature review that uncertainty remains in the scientific community regarding the net energy effects of ICT, mainly due to the high dependency of study results on the assumptions made and missing information about the influence of user behavior. However, indirect effects can turn out to be positive if efficiency gains are not offset by undesired consumer reactions (rebound effect), i.e. more and long-distance traveling due to falling resource prices or time savings (Berkhout and Hertin, 2004). According to GeSI (2015), the 2030 target is to reduce the global carbon dioxide (CO₂) emissions with ICT by 20%. ICT-enabled abatement of CO₂ in other sectors in 2030 could be nearly 10 times higher than the direct effects according to regularly updated projections by GeSI (2015).

2.1. Drivers for Internet Traffic

Today, more than 50% of the world’s population is connected to the internet using more than 18.4 billion networked devices (Cisco, 2020). The ICT sector is growing continuously as the technological evolution of individual components of the ICT ecosystem (networks, data centers, and devices) reinforce each other. The development is not only characterized by miniaturization and better computing performance, but also by an increase in absolute global data processing and exchange via the internet, which has reached a magnitude of 10¹² bytes (zettabyte) per year (IEA, 2017). There are some key developments that drive internet traffic and thus the
energy consumption of ICT:

- Improvement in the picture and video quality of smart TVs and smartphones is a significant multiplier for internet traffic. UHD/4K videos, for instance, require two times higher bit rates than HD videos (Cisco, 2020). At the same time, more high-resolution streaming content has been made available by video-sharing platforms and new media companies, but also by traditional TV operators. Meanwhile, video streaming reached a share of 60.6% in global downstream internet traffic (Sandvine, 2019).

- Mobile communication gains competitive advantage over cable communication as more powerful technology standards for broadband cellular networks (4G/LTE, 5G) capture the market and the number of public WiFi hotspots increases. 4G and 5G could cover 56.6% of the mobile market in 2023. In addition, ultra-narrowband wireless networks providing high coverage with low power demand are predicted to reach a share of 14.4% by 2023 (Cisco, 2020). However, the proliferation of mobile networks leads to higher energy consumption. This is caused by the free-space path loss for transmission via air, which is higher compared to transmission losses in cable networks. Compared to fiber optic networks, the power consumption of mobile networks can be 45 times higher when considering 3G or seven times higher in the case of 4G. Since the introduction of mobile communication, next-generation standards have gradually improved the energy efficiency of data transmission. But any efficiency gains achieved through the technical advancement of mobile network standards are jeopardized as data-intensive applications such as high definition (HD) video streaming become more popular.

- Machine-to-Machine (M2M) devices such as smart meters, video surveillance, and RFID tags already dominate the scene with a relative share of 33% of all networked devices and form the backbone of the IoT. By 2023, they could reach a share of 50% followed by smartphones (23%). Home and work applications could contribute two-thirds of all M2M connections by 2023 (Cisco, 2020).

- The share of the population with access to the internet has been rising steadily since the 1990s due to technological progress, but also as a result of socioeconomic growth in emerging and developing countries. Meanwhile, about 87% of the population in developed countries use the internet on a regular basis, compared to 44% in developing and almost 20% in least developed countries (Statista, 2021).

- More recently, the COVID-19 pandemic has restricted mobility and direct human contacts worldwide in an unprecedented way. As a consequence of the lockdown in many countries in March 2020, the internet traffic volume increased by 15–20% due to data-intensive applications supporting remote working, home schooling, and online entertainment (Feldmann et al., 2020). Even when the restrictions are eventually lifted, changed communication habits could create learning effects and thus persist in the future. New business models could be stimulated that focus more on the service than on the product perspective, e.g. mobility as a service.

6G, although not yet defined and developed, should enable us to cope with these challenges in the long term and the multitude of new applications encompassing 3D imaging, sensing and detection, wireless cognition, autonomous devices, accurate positioning (Rappaport et al., 2019), and all those yet to come connecting people and machines in an Internet of Everything (IoE) (Saad et al., 2020).

2.2. Evolution of mobile Communication Services and an Outlook for 6G

The peak bit rate acts as a central key parameter for each mobile communication generation. It is fundamental to enable the possibility of mobile services such as video or audio content streaming. For an estimation of the upcoming 6G technology, we take a look at the development over the past 30 years and extrapolate it as shown in Fig. 2. Accordingly, bit rates around 200 Gb/s can be expected for 2030, which corresponds to a tenfold increase of 5G in its maximum development stage.

![Fig. 2. Illustration of the evolution of peak bit rates for mobile communication standards from 1990 to 2020 based on (Lo, 2018; 3GPP, 2021) and their extrapolation to 2030.](image-url)
In Latva-aho et al. (2019) and Samsung (2020), peak bit rates of up to 1000 Gb/s are mentioned. To realize such rates, data transmission in the Terahertz (THz) band has to be achieved with the help of III/V technology such as indium phosphide, gallium arsenide, or silicon-germanium. Tb/s bit rates and THz carrier frequencies might be ambitious even for a development period of about 10 years as considered in this study. Furthermore, there are many unsolved problems, for example:

- Data transmission in the sub-THz band (100 GHz-1 THz) is mainly affected by the free-space path loss and limited output power of the power amplifiers. Large antenna arrays might be a possible solution but suffer from narrow beam angles (Samsung, 2020).
- There is still no technical solution for an efficient analog-to-digital or digital-to-analog conversion for bandwidths of 100 GHz and more (Orhan et al., 2015).
- The long-term availability and sustainability of raw materials for III/V technology in mass production is questionable. Gallium, indium, aluminum/bauxite and phosphorus/phosphate rock are included in the 2020 list of critical raw materials to the EU European Commission (2020), which is based on an assessment of the individual material's economic importance and supply risk. In addition, the related analysis of the end-of-life recycling input rates (EOL-RIR) in the EU-28 shows that the demand for gallium (0%), indium (0%), bauxite (0%), phosphorus (0%) and phosphate rock (17%) is higher than what can be met by secondary raw materials. Elements such as phosphorus and arsenic cannot be economically recovered in metallurgical processes at present due to incomplete and inflexible infrastructures (Reuter et al., 2019).

When developing the 1G to 5G standards, the major improvement goal was a higher bit rate. We believe that for 6G the challenge will be to also consider sustainability aspects. This includes the minimization of the energy consumption during the whole product lifetime including fabrication, operation, and recycling, as well as the adoption of eco-design principles and the Resource Nexus, taking into consideration impacts on different environmental resources, such as water, soil, energy, other geo-resources, and biodiversity (Bleischwitz et al., 2018).

As promising approaches, we see the use of adaptive parallelized transmitter and receiver units, which adapt according to the demand and thus consume only as much energy as necessary. Access to peak bit rates of up to 200 Gb/s should depend on the purpose and context in terms of what is really needed for the particular application. Most of the time, the systems would typically work at much lower bit rates to save energy. In this context, downward compatibility with older standards such as 5G or LTE, as well as the symbiotic operation with a new ultra-low power narrow band IoT standard is important. In moments of no data transmission, the transmitter and receiver can be immediately set to a sleep mode to minimize energy consumption. Self-learning algorithms that form the backbone of the control unit can evaluate input parameters and react in real-time according to the required performance.

2.3. Technological Concepts for 3D Videoconferencing in 2030

To realize 3D videoconferencing, novel technologies for hologram generation are needed. This includes 3D cameras and depth information measurement devices, 3D holographic displays, fast computing hardware for real-time processing, efficient computing algorithms, high-speed transceivers, optional eye tracking systems and much more. Even though the technical implementation is still in its infancy, we will attempt to draft scenarios for future videoconferencing here.

Fig. 3 schematically shows three technological concepts for 2D/3D videoconferencing. In Fig. 3(a) and 3(b), a 3D hologram is recorded and displayed by a 3D camera and a holographic display, respectively. For comparison, a high-quality 2D videoconferencing is assumed in concept 3(c). All devices are wirelessly connected via 6G to a local cloud, which acts as a terminal to the internet. The 6G data transfer is controlled by an artificial intelligence within the local cloud. According to the demands of needed bit rate, parameters such as bandwidth, center frequency, modulation schemes, and transmission power are adjusted to achieve the maximum efficient transmission. The battery icon symbolizes the power consumption of the device, local data transfer, local cloud, and internet data transfer. A further aspect is the location for the image data computation. In Fig. 3(a) it is implemented in the local cloud, and in Fig. 3
3. Methodology

3.1. Scoping for Scenario Development

This study examines the future substitution potential of German business trips with 2D/3D videoconferencing and the related energy consumption and greenhouse gas emissions using scenario analysis. The substitution potential represents the potential that can be additionally tapped, neglecting the pre-pandemic share of virtual meetings in German business travel. The time horizon for the forecast is 2030, as we expect both 6G and 3D holography technology to be sufficiently mature by then. The scope of the analysis was set to cover predominantly the use phase and energy upstream chains as these were considered most relevant, the use phase in particular because here the user is more capable of making free decisions. Embodied energy respectively carbon from the production of vehicles and ICT devices as well as their disposal was also included. Belkhir and Elmeligi (2018) found that the contribution of the production of internet infrastructure such as data centers and communication networks to the annual life cycle footprint ranges from 1.7% to 8% only and could therefore be neglected. Due to the minor share and missing life cycle inventories, internet infrastructure was also disregarded in this analysis. The development of the carbon footprint model including assumptions follows ISO (2006a) and ISO (2006b). The functional unit is defined as a 10-h business conference attended by a single person from Germany in the year 2030. With regard to the location of a real conference, we distinguish between conferences implemented in Germany, Europe, or globally. For a virtual conference, which is regarded here as being implemented in Germany, we assume a two-day meeting with a length of $2 \times 5$ hours since for conferences or training courses without a "material component", a shorter daily time format seems more suitable (Clausen and Schramm, 2019).

Scenario analysis is a method to investigate future developments and thus support strategic planning by not relying solely on the extrapolation of historical trends, but by taking into account professional knowledge about new opportunities and risks (Brauers and Weber, 1988). However, the results only represent a possible future based on the given assumptions and choices. In terms of typology, our scenario analysis can be regarded as predictive (What will happen if virtual conferences significantly substitute real conferences?) as well as explorative (What can happen if the share of virtual conferences increases a little, moderately, or strongly in 2030?) (Börjeson et al., 2006). With the pre-pandemic situation (2017–2019) taken as reference (baseline), we developed three future scenarios for a possible replacement of real conference trips in 2030 by 2D/3D virtual meetings (see Fig. 4):

- **Business-as-usual scenario 2030, BAU$_{2030}$**
- **Scenario A$_{2030}$: 80% real, 20% virtual (low substitution)**
- **Scenario B$_{2030}$: 60% real, 40% virtual (moderate substitution)**
- **Scenario C$_{2030}$: 10% real, 90% virtual (high substitution)**

We expect virtualization to be primarily achieved through the use of 2D videoconferencing, but increasingly supplemented by 3D holography, reaching a share of 10% by 2030 on a conservative view. As display-integrated 3D holography is likely to be more widely deployable, more affordable, more resource-efficient and overall more manageable in terms of security requirements compared to external solutions such as virtual reality goggles, we assume that it will most likely become the standard for business videoconferencing in 2030. In the following, the methodological approach behind the calculation of the energy consumption of innovative 3D videoconferencing and avoided business travel is explained in more detail.

![Fig. 4](image-url). Absolute number of German conference trips between 2016 and 2030 and increasing substitution potential through advanced 2D/3D videoconferencing in three scenarios (A$_{2030}$: 20% virtual meetings, B$_{2030}$: 40% virtual meetings, C$_{2030}$: 90% virtual meetings).
3.2. Calculation of Power Consumption for Videoconferencing in 2030

In order to obtain basic information about the practical implementation of our 3D holography scenarios and the necessary bit rates, expert interviews with the 3D holography technology company SeeReal were conducted. Principally, it is necessary to distinguish between the transmission of 3D content, which is the basis of 3D hologram calculation, and the transmission of the 3D hologram itself.

For exemplary scenarios we estimate a high-quality 4K (3840 x 2160 pixel) resolution with 24-bit true color depth and a 1:1000 H.265 video compression rate. A 3D content transmission requires an additional spatial depth information with a 10-bit resolution and at least one additional video image. In our example, the spatial depth information is compressed by a factor of 100. Furthermore, 3D content especially for moving objects in augmented and mixed reality needs 90 frames per second due to higher requirements for a natural motion perception (Intel, 2021), whereas only 60 frames per second are sufficient for the 2D concept. Using this data, the bit rate for transmitting 3D content is 190 Mb/s. A high-quality 2D transmission requires 19 Mb/s. As shown in Table 1, those bit rates \( R_{\text{int}} \) have to be provided for the data transmission via the internet.

As mentioned above, the transmission of 3D content alone is not sufficient to display a 3D hologram, which is calculated locally with separate algorithms. In the concept according to Fig. 3(a), the computing of the 3D hologram takes place in the local cloud. The latter has the advantage that the terminal device can be realized in a more cost and resource-efficient, compact, and light-weight manner. Moreover, networked local cloud computing also enables functions and applications that are beyond the available onboard hardware performance of the device.

3D holography is based on light diffraction where visibility depends on the diffraction angle and pixel size. Therefore, four to six times more pixels than the displayed resolution must be transmitted locally to the 3D holographic device for sufficient hologram generation. In addition, hologram data can hardly be compressed, which further increases the necessary bit rate. In the present concept, this results in an exemplary 3D hologram data stream of 195 Gb/s, which is transmitted by high-speed 6G data transmission to the 3D holographic device. In contrast, in the concepts depicted in Fig. 3(b) and (c), the computation of the 3D hologram and the 2D video image is performed on the terminal device. In these cases, the 3D content and the 2D video image data stream is forwarded by the local cloud to the terminal devices.

A major factor in estimating the overall power consumption is the necessary energy for data transfer via the internet. According to Aslan et al. (2018), 0.06 kWh/GB were calculated for the transmission network (IP core network and access networks) in 2015 with an approximate decrease of 50% every two years. In order to take into account a possible slowing of this trend caused by the inherent scaling limitations of current semiconductor technologies, we conservatively assume that this ratio will only halve every three years from 2015 to 2030 (15 years). The energy per GB in 2030 \( E_{\text{int,2030}} \) is calculated with

\[
E_{\text{int,2030}} = 0.06 \times \frac{\text{kWh}}{\text{GB}} \times \frac{2^{15/3}}{2^{15}}
\]

\[
E_{\text{int,2030}} \approx 1.875 \times \frac{\text{Wh}}{\text{GB}}
\]

The power \( P_{\text{int,2030}} \) corresponding to a necessary internet bit rate \( R_{\text{int}} \) is directly obtained from \( E_{\text{int,2030}} \) with

\[
P_{\text{int,2030}} = R_{\text{int}} \times E_{\text{int,2030}}
\]

### Table 1
Calculation of the overall power consumption for three technological concepts to realize 2D/3D videoconferencing.

| Bit rates of data transmission: | Technological concept
|------------------------------|---------------------|
| Bit rate, Internet \( R_{\text{int}} \) (Gb/s) | (a) 0.19 | (b) 0.19 | (c) 0.02 |
| Bit rate, Local Network \( R_{\text{LN}} \) (Gb/s) | 195 | 0.19 | 0.02 |

**Power consumption of data transmission:**

| Power consumption, Internet \( P_{\text{int}} \) (W) | (a) 160.3 | (b) 160.3 | (c) 16.9 |
| Power consumption, Local Network \( P_{\text{LN}} \) (W) | 3.9 | \( 3.8 \times 10^{-3} \) | \( 4.0 \times 10^{-4} \) |

**Power consumption of local devices:**

| 3D holographic device, local cloud computing (W) | 10 | -- | -- |
| 3D holographic device, on board computing (W) | -- | 15 | -- |
| 2D high-quality device, on board computing (W) | -- | -- | 10 |
| Local cloud + 6G AI (W) | -- | 27.5 | 27.5 |
| Local cloud + 6G AI + holographic data computing (W) | 32.5 | -- | -- |
| Power consumption, Sum (W) | 206.7 | 202.8 | 54.4 |

1. See Fig. 3
2. Estimation from Aslan et al. (2018), 1.875 Wh/GB \( \rightarrow P_{\text{int,2030}} = R_{\text{int}} \times 843.75 \times \frac{W}{\text{Gb s}^{-1}} \).
3. Estimation considering e.g. Fritsche et al. (2017) and Mammelä (2015): 20 pJ/bit \( \rightarrow P_{\text{LN,a}} = R_{\text{LN,a}} \times 20 \times \frac{nW}{\text{Gb s}^{-1}} \).
For power consumption of the 6G wireless local network we use estimations from Mämmelä (2015) as well as our own work. In Fritsche et al. (2017), bit rates up to 50 Gbs⁻¹ with 3.1 pJ/bit were measured. Due to a higher power consumption by additional digital-to-analog converters and high-performance power amplifiers to reach reasonable transmitting distances for the high speed 6G concept in Fig. 3(a), 20 pJ/bit will be utilized as an estimation.

The device-related power consumption refers to data in Stobbe et al. (2015). To consider additional power consumption for the 3D camera and a high-resolution 3D display, the power consumption is based on a notebook PC of the year 2025. For the computation of the 3D holographic image data, 5 W are estimated. Since the calculation of 2D video data requires considerably less computing power, the power consumption of the terminal device is left at 10 W. The power consumption of the local cloud is liberally obtained for a desktop PC in 2025.

An individual examination of the power consumption in Table 1 shows that, for the 3D concepts (a) and (b), more than three-quarters of the total power is spent on internet data transmission, which highlights the importance of the power consumption of the terminal device is left at 10 W. The power consumption of the local cloud is liberally obtained for a desktop PC in 2025.

An individual examination of the power consumption in Table 1 shows that, for the 3D concepts (a) and (b), more than three-quarters of the total power is spent on internet data transmission, which highlights the importance of the power consumption of the terminal device.

### Table 2
General assumptions and input parameter for the scenario analysis.

| Input parameter                        | Specification | Reference               |
|----------------------------------------|---------------|-------------------------|
| Time horizon                           | 2030          |                         |
| Region                                  | Germany       |                         |
| Life cycle                              | Use phase + energy upstream chains |               |
| Cut-off criteria                       | Upstream chains for production of ICT and vehicles, end-of-life |               |
| Scenarios 2030                          | BAU₂₀₃₀, A₂₀₃₀ (low substitution, 20%), B₂₀₃₀ (moderate substitution, 40%), (high substitution, 90%) |               |
| Video quality                          | 4 K/2D, 4 K/3D |                         |
| Average duration of online meetings    | 2 × 5 h (2D: 90%, 3D: 10%) |               |
| Definition of single trip              | 1 trip = 1 person |               |
| Number of real business trips          | Base₂₀₁₅: 195.4 million, BAU₂₀₃₀: 246.7 million, A₂₀₃₀: 197.4 million, B₂₀₃₀: 148.0 million, C₂₀₃₀: 24.7 million | VDR (2020), own calculation |
| Number of virtual business trips       | A₂₀₃₀: 49.3 million, B₂₀₃₀: 98.7 million, C₂₀₃₀: 222 million | Own calculation |
| Purpose of business trips              | 40% of business trips to: Seminars and trainings (21%), Trade fairs and exhibitions (11%), Conferences (8%) | Sonntag et al. (2019) |
| Destination: Split, Average travel distances | DE: 79%, 355.9 km EU: 17%, 975.0 km INT: 4%, 7500.5 km | BMVI (2017) |
| Travel profile, modal split           | DE*: car (64%), train (Base₂₀₁₅: 23%, 2030: 32%), bus (1%), plane (Base₂₀₁₅: 9%, 2030: 0%), others (2%), EU*: car (25%), train (9%), bus (5%), plane (58%), others (2%), INT: car (2%), train (0%), bus (0%), plane (97%), others (1%) | BMVI (2017) |
| Emission factors for transport 2018   | Car: 147, train: 32, bus: 29, plane: 230 | UBA (2020) |
| Emission factors for transport 2030   | Car: 115, train: 13, bus: 29, plane: 230 | BMU (2020), ifeu (2017) and Bundesregierung (2019) |
| Emission factors for embodied carbon in transport | Car: 19.3, train: 20.5, bus: 6.9, plane: 26.8 | UBA (2013) |
| Emission factor MIX₂₀₁₈ for electricity 2018 (gCO₂eq/kWh) | 468 | UBA (2019) |
| Emission factor MIX₂₀₃₀ for electricity 2030 (gCO₂eq/kWh) | 189 | Interpolation based on ifeu (2017) and Bundesregierung (2019) |
| Emission factors EEE₂₀₃₀ for embodied carbon in ICT devices (gCO₂eq/h) | PC with display: 47.6, laptop: 34, mean: 40.8 | Gröger (2020) |
| Power consumption of ICT              | See Table 1   | See Table 1             |

Base₂₀₁₅: Baseline scenario 2019; BAU₂₀₃₀: Business-as-usual 2030; A₂₀₃₀: Scenario A 2030; B₂₀₃₀: Scenario B 2030; DE: Germany; EU: Europe; INT: International; ICT: Information and communication technology; CO₂eq: Carbon dioxide equivalent; pkm: Passenger-distance in kilometer *does not add up to 100% due to rounding errors
3.3. Estimation of ICT-enabled CO₂ Savings in Business Travel

Assumptions for avoided business travel as well as the modal split were derived from actual business travel statistics and mobility studies (see Table 2). From a total of 195.4 million business trips in 2019, only 40% are in focus of this analysis, namely those conducted with the purpose of attending seminars and trainings (21%), trade fairs and exhibitions (11%), and conferences (8%) (Sonntag et al., 2019; VDR, 2020). Other business trips with the aim of visiting individual customers, project partners or own branches, as well as bonus trips are more strongly rooted in personal encounters and are therefore more difficult to replace. For the business-as-usual scenario, the number of business trips in 2030 (246.7 million) was determined by extrapolation, assuming the same average growth rate as observed for the past decade (+26%).

In 2017, the majority of business trips were to destinations in Germany (79%), followed by Europe (17%) and other international destinations (4%) (BMVI, 2017). Due to a lack of robust information about the situation in the future, we continued with the same values. We also kept the modal split, i.e. the share of car, rail, bus, and air travel, constant as the relative numbers have only slightly changed by 2–3% since 2002 (BMVI, 2017). Based on the current political discussions about further mitigation potentials in the mobility sector (EURACTIV/AFP, 2021), we assume that domestic trips by plane will be no longer competitive compared to trains in 2030 and completely substituted. Other transport modes, such as motorcycles, bicycles, and local public transport, account for a share of only 1–2% and were therefore not considered relevant for total carbon emissions. In the absence of precise figures for the target sample (business trips to conferences, etc.), average assumptions were made and partly general mobility characteristics were applied to business travel.

For the calculation of carbon emissions, average travel distances were used for the three destinations (German, European, international). The emission factors originate from UBA (2020) and indicate the direct average carbon emissions of individual modes of transport expressed as grams of carbon dioxide equivalents per person kilometer (gCO₂eq/km). In order to respect technological developments in the mobility and energy sector, such as a higher share of electric vehicles and renewable energies, we extrapolated the latest emission factors to the year 2030. For passenger cars, we used the official fleet threshold (BMU, 2020), and for long-distance trains, we updated forecasts for the 2030 electricity mix in Germany according to the same approach as described in Section 3.2.

4. Results

4.1. Consideration of CO₂ Emissions Related to a Single Trip

This section presents the results achieved with the scenarios and assumptions defined in the previous section (see Table 1 and Table 2). First of all, a direct comparison of a single real trip with a virtual conference is carried out for the individual case. The emissions caused by the different modes of transport are set in relation to the direct emissions caused by the operation of ICT devices and infrastructure for a 10-h videoconference. For the real trip to be compared, the average distance to the conference venue located somewhere in Germany, Europe or beyond Europe was used as described in Section 4.2. Moreover, carbon emissions of an average trip weighted according to the percentage distribution (MEAN) were calculated. Concrete assumptions are given in Table 2.

The operational and embodied emissions of the ICT devices yield the overall emissions for a virtual conference EMvirt. The operational emissions were based on the power consumption Psum,2D and Psum,3D for a 2D and 3D video transmission according to Table 1 multiplied by the conference duration tconf and the emission factor for electricity of a reference year MIXYEAR. The power consumption for 3D videoconferencing Psum,3D is represented by the average value of the technological concepts (a) and (b). Moreover, the calculation includes the 3D share in the videoconference r3D. The embodied emissions were estimated by multiplying the emission factors EEICT for embodied carbon in ICT devices given in Table 2 with the conference duration tconf. For the sake of simplicity, we assume that the devices used for the five-hour virtual conference are not used for any other purpose on that same day. The summation of both shares results in Eq. (5):

\[ EM_{virt} = t_{conf} \times MIX_{YEAR} \times (r_{3D} \times P_{SUM,3D}(E_{int}) + (1 - r_{3D}) \times P_{SUM,2D}(E_{int})) + t_{conf} \times EE_{ICT}. \] (5)

With a projected emission factor for electricity of 189 gCO₂eq/kWh in 2030, a total conference duration of 10 h, a 3D share of 10%, and an emission factor for embodied carbon in ICT devices of 40.8 gCO₂eq/h emissions of 539.2 gCO₂eq were calculated for a single virtual conference.

For a single real trip, the emissions EMreal can be found in Table 3. Here it is already obvious that an international trip (INT) causes

| Table 3 |
|---------------------------------|
| Destination | EMreal (kgCO₂eq) | EMvirt/EMreal |
| DE | 69 | 0.78% |
| EU | 365 | 0.14% |
| INT | 3,777 | 0.01% |
| MEAN | 268 | 0.20% |
the highest CO$_2$ emissions with 3,777 kgCO$_2$-eq. This is approximately 14.1 times higher than the MEAN with 268 kgCO$_2$-eq per trip.

The ratio $EM_{virt}/EM_{real}$ indicates the factor by which the emissions of a virtual conference are lower than those generated by real travel. In general, this factor is very low for all destinations. Already for a domestic trip (DE), a reduction of travel emissions to only 0.78% is possible if substituted by a virtual conference. The potential for mitigating emissions from international travel is many times higher since a virtual conference would only cause 0.01% of the emissions of a real trip.

To test the sensitivity of the results, three parameters were modified individually: the energy required for internet transmission $E_{\text{Int}}$, the emission factor $\text{MIX}_{\text{YEAR}}$, and the 3D share $r_{\text{3D}}$. If $\text{MIX}_{\text{YEAR}}$ remains at the level of 2018 ($\text{MIX}_{\text{2018}} = 468$ gCO$_2$-eq/kWh), this would yield a factor of 0.27% as shown in Table 4. It is obvious that emissions from virtual conferences change proportionally to the emission factor of the assumed energy mix. In a best-case scenario, we assume that $E_{\text{Int}} = E_{\text{Int,min}}$ already halves every two years. This decreases the ratio to 0.18%. If $E_{\text{Int}} = E_{\text{Int,max}}$ remains at the level of 2015 as a worst-case assumption, the ratio is still 0.88%. For pure 2D and 3D video transmission, the results are 0.19% and 0.30%, respectively.

The assumptions for $E_{\text{Int}}$ and $\text{MIX}_{\text{YEAR}}$ are used to determine the carbon footprint per gigabyte transferred via the internet. For the emission factor $\text{MIX}_{\text{2030}}$, this results in values of $0.062$ gCO$_2$-eq/GB ($E_{\text{Int,min}}$) and $11.34$ gCO$_2$-eq/GB ($E_{\text{Int,max}}$), respectively. This enormous range illustrates the possible increase in efficiency of data transmission by 2030, assuming the trend forecasted in Aslan et al. (2018). In Section 3.2, $E_{\text{Int,2030}}$ was calculated as 1.875 Wh/GB. Under the given assumptions, the carbon footprint of internet use amounts to 0.354 gCO$_2$-eq/GB.

Away from the elusive ratios in Table 3, we now consider the theoretical duration of a virtual conference until it produces the same CO$_2$ emissions as those of a real conference. In Fig. 5, the relationship between the duration $t_{\text{eq}}$ and the corresponding CO$_2$ emissions of a real trip is illustrated including break-even points for different destinations (horizontal lines). Of the six scenario cases resulting from the variation of three parameters, the energy required for internet transmission $E_{\text{Int}}$ shows the highest sensitivity due to the exponential behavior of this parameter. The cases $E_{\text{Int,min}}$ and $E_{\text{Int,max}}$ form the upper and lower limits of the range of possible results (see Table 4 and Fig. 5). Nevertheless, even a virtual conference held under the worst-case scenario $E_{\text{Int,max}}$ would have to run continuously for about 287 h to achieve the same CO$_2$ emissions as an averaged-distance conference trip within Germany. In the best-case scenario $E_{\text{Int,min}}$, 1,400 h would already be necessary. The difference is much more pronounced for international conference travel. Here, the necessary continuous videoconference time would be between 15,900 and 78,100 h.

### 4.2. Absolute ICT-enabled CO$_2$ savings for German Conference Trips in 2030

In addition to the CO$_2$ emissions for the individual case, we now consider the carbon dioxide mitigation potential at the national level. To this end, the absolute savings potential resulting from the avoidance of conference travel by using ICT technology is calculated. The main focus is on the evaluation of the four developed future scenarios BAU$_{2030}$, A$_{2030}$, B$_{2030}$, and C$_{2030}$. The emission contributions from the different modes of transport (modal split) as well as the differences between the scenarios are broken down in tabular form (see Table 5).

In Fig. 4, the number of conference trips until 2030 is indicated for the BAU scenario. According to the moderate and best-case scenario, these real trips are replaced by 20% (A$_{2030}$), 40% (B$_{2030}$) or 90% (C$_{2030}$) virtual trips. The difference between BAU$_{2030}$ and scenarios A$_{2030}$, B$_{2030}$ or C$_{2030}$ yields the avoided emissions in 2030. Pursuant to Table 3, the total emissions caused by virtual conferences account for a maximum of 0.78% compared to real conferences. These comparatively low emissions have a very little influence on the calculation of the absolute ICT-enabled CO$_2$ savings, which is generally not visible in the results displayed in Table 5.

For the calculation of total CO$_2$ emissions caused by real trips, German (DE), European (EU), and other international (INT) destinations are considered individually. By multiplying the average travel distances according to BMVI (2017) with the number of business trips in the given scenarios, the total travel kilometers in respect to the destination are determined. Subsequently, total kilometers are distributed to the corresponding modes of transport using the modal split. CO$_2$ emissions are ultimately calculated by multiplying the transport-specific emission factors with total distances. The results for the subdivision into travel destination, scenario, and mode of transport as well as the total sums for each scenario are listed in Table 5. In addition to the future scenarios, a baseline scenario for the year 2019 (Base$_{2019}$) is given. The number of real conference trips in A$_{2030}$ will remain at about the same as in 2019 (see Fig. 4). As shown in Table 5, the reduction in emissions of 2.06 MtCO$_2$-eq (8.9%) between Base$_{2019}$ and A$_{2030}$ is primarily due to a lower emission factor of cars and the substitution of air travel by trains in 2030. Only from a higher proportion of virtual conferences do the emissions decrease perceptibly by 7.34 MtCO$_2$-eq in B$_{2030}$ and 20.51 MtCO$_2$-eq in C$_{2030}$ compared to Base$_{2019}$. This corresponds to a reduction of 31.6% and 88.4%, respectively. International trips, which account for only 4% of all conference trips, cause more than

| Variable | Defined Value | $EM_{\text{virt}}/EM_{\text{real}}$ |
|----------|---------------|-------------------------------|
| $\text{MIX}_{\text{2018}}$ | 468 gCO$_2$-eq/kWh | 0.27% |
| $\text{MIX}_{\text{2030}}$ | 189 gCO$_2$-eq/kWh | 0.20% |
| $E_{\text{Int,min}}$ | $0.33 \times 10^{-3}$ kWh/GB | 0.18% |
| $E_{\text{Int,max}}$ | 0.06 kWh/GB | 0.88% |
| 2D only | $r_{\text{3D}} = 0$ | 0.19% |
| 3D only | $r_{\text{3D}} = 1$ | 0.30% |
scenario. The net carbon mitigation for scenario A amounts to 10.55 MtCO₂eq in 2030, approximately 0.3% (low substitution), 1.0% (moderate substitution), and 2.8% (high substitution) could be saved if the best be achieved. This view conflates the social science perspective with the technology perspective and, thereby, allows us to better evaluate the function first instead of the product to avoid following the unsustainable pathway. This means, for instance, not to ask which video quality is technologically better or which means of transport is economically preferable, but how the desired function can best be achieved. This view aligns with the concept of a knowledge society, which is particularly concerned with de-materialization and emission reduction strategies. The analysis of the German transport sector, for example, shows that the energy consumption of the internet and corresponding CO₂ emissions caused by substituted German conference trips to domestic, European, or other international destinations in 2030 are 5.27 MtCO₂eq compared to BAU₂₀₂₀. The scenario B₂₀₃₀: comfort only, and C₂₀₃₀: scenario C 2030; *includes other transport modes such as bus, motorcycle, etc., as well as the total emissions caused by the virtual conferences.

Table 5
Total and avoided CO₂ emissions caused by substituted German conference trips to domestic, European, or other international destinations in different scenarios.

| Emissions | Scenario     | DE Destination and Mode of Transport (MtCO₂eq) | EU Destination and Mode of Transport (MtCO₂eq) | INT Destination and Mode of Transport (MtCO₂eq) | SUM* |
|-----------|--------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|------|
|           |              | Car  | Train | Plane | Car  | Train | Plane | Car  | Train | Plane | Car  | Train | Plane | SUM* |
| Total     | Base₂₀₁₉     | 4.67 | 0.61  | 1.02  | 1.08 | 0.12  | 3.86  | 0.16 | 0     | 11.68 | 23.2 |
|           | BAU₂₀₂₀      | 4.77 | 0.59  | 0     | 1.1  | 0.1   | 4.87  | 0.16 | 0     | 14.75 | 26.41|
|           | A₂₀₃₀        | 3.82 | 0.47  | 0     | 0.88 | 0.08  | 3.9   | 0.13 | 0     | 11.8  | 21.14|
|           | B₂₀₃₀        | 2.86 | 0.36  | 0     | 0.66 | 0.06  | 2.92  | 0.1  | 0     | 8.85  | 15.86|
|           | C₂₀₃₀        | 0.48 | 0.06  | 0     | 0.11 | 0.01  | 0.49  | 0.02 | 0     | 1.48  | 2.69 |
| Avoided   | A₂₀₃₀/Base₂₀₁₉| −0.85| −0.14 | −1.02 | −0.2 | −0.04 | 0.04  | −0.03 | 0     | 0.12  | −2.06|
|           | B₂₀₃₀/Base₂₀₁₉| −1.81| −0.25 | −1.02 | −0.42| −0.06 | −0.94 | −0.06 | 0     | −2.83 | −7.34|
|           | C₂₀₃₀/Base₂₀₁₉| −4.19| −0.55 | −1.02 | −0.97| −0.11 | −3.37 | −0.14 | 0     | −10.2 | −20.51|
|           | A₂₀₃₀/BAU₂₀₂₀  | −0.95| −0.12 | 0     | −0.22| −0.02 | −0.97 | −0.03 | 0     | −2.95 | −5.27|
|           | B₂₀₃₀/BAU₂₀₂₀  | −1.91| −0.23 | 0     | −0.44| −0.04 | −1.95 | −0.06 | 0     | −5.9  | −10.55|
|           | C₂₀₃₀/BAU₂₀₂₀  | −4.29| −0.53 | 0     | −0.99| −0.09 | −4.38 | −0.14 | 0     | −13.27| −23.72|

Fig. 5. Relationship between the duration of a virtual conference tₜᵣᵢᵦ and corresponding CO₂ emissions of a real German conference trip to different destinations taking into account the variability of break-even points resulting from the definition of the emission factor of the energy mix MIXₓᵧᵧᵧ, the energy consumption of the internet Eᵦᵦᵦ, and the 3D share (2D only (tᵦᵦᵦ = 0), 3D only (tᵦᵦᵦ = 1)).

5. Discussion

Germany is a country poor in raw materials and therefore relies on the development of innovative energy- and resource-efficient technologies to remain competitive. In addition, Germany has set itself ambitious goals to counteract climate change and, as a knowledge society, is particularly concerned with de-materialization and emission reduction strategies. The analysis of the German carbon mitigation potential for high-quality 2D/3D videoconferencing in 2030 has shown significant results if taking the direct and indirect energy effects of ICT into account. Compared to the annual German CO₂ emissions in 2020, which were 739 MtCO₂eq (UBA, 2021), approximately 0.3% (low substitution), 1.0% (moderate substitution), and 2.8% (high substitution) could be saved if the innovative videoconference technology would already be available and deployed, as outlined in our scenarios. This gives the innovative technologies under consideration, which are currently being developed in Germany, high political relevance as well as economic potential. It remains uncertain, however, as to whether there will be any rebound effects induced that could eventually lead to a net increase in travel and thus in carbon dioxide emissions. For example, a greater global connectivity among people and the capacity freed up by higher work efficiency could be used to drive business development, eventually leading to new business travel. Furthermore, behavioral changes in dealing with new digital technologies are not only to be expected, but also necessary. Users will have to learn to evaluate the function first instead of the product to avoid following the unsustainable pathway. This means, for instance, not to ask which video quality is technologically better or which means of transport is economically preferable, but how the desired function can best be achieved. This view conflates the social science perspective with the technology perspective and, thereby, allows us to better...
inher the overall environmental impact of innovative technologies.

Another uncertainty of our analysis arises from the definition of the scope and assumptions about future technological energy efficiencies. We followed the official policy objectives to characterize the electricity mix and vehicle emissions in 2030. Technological advancements such as the energy intensity of data traffic were extrapolated based on past developments. Hence, any short-term or non-linear events, such as radical changes in the transition of our economy, can not be captured. Energy consumption and emission figures for the production and disposal of internet infrastructure were excluded. Due to the generally complex interlinked value chains of state-of-the-art technologies, previous studies such as Ong et al. (2014) investigated the full life cycle only for a limited number of infrastructure components. In the case of technologies not yet on the market, such as 6G and 3D holography, life cycle inventories are understandably missing completely and forecasts based on present technologies, which also generally have a time lag before they enter official inventories, are linked with high uncertainties. From this, we infer that a closer look at the embodied energy and carbon of future 3D/6G-specific infrastructures is an important research gap.

Globalization is a strong driving force for the global economy and growth in travel (Clausen et al., 2019). COVID-19 in turn has revealed the downsides of globally intertwined supply chains and unlimited mobility. It remains to be seen to what extent the pandemic could have a lasting effect on people’s daily life and work and how much the environment could be relieved by a sustained decline in business travel and commuting. Unlike the financial crisis, this time people were obliged to radically limit their social life and to adopt alternative strategies of collaboration. Employees and employers, especially in the tertiary sector, have learned that working from home can mean more flexibility in the organization of daily work without losing productivity, provided that a suitable working environment exists. Against this backdrop, it is conceivable that many virtual meetings will be retained for the future.

Surveys from the pre-COVID-19 era have shown that around half of the German companies with high business travel activity are replacing travel with virtual meetings, also with the intention of improving their own corporate environmental performance (DRV, 2019). Moreover, at the level of organizations, a growing number of self-commitments and travel regulations are being changed to prevent short trips by plane especially (Clausen and Schramm, 2019). This positive trend could be supported by technology allowing more realistic, high-quality, and interactive videoconferencing. Especially for meetings with international participation, so-called regional hub concepts could be interesting options as suggested by Bürtscher et al. (2020). Lessors of conference rooms or trade fairs as well as broadcast stations could provide space and professional 3D conference equipment to pool participants from a certain region, thereby making long-distance trips obsolete. Moreover, a dedicated room for videoconferencing could greatly increase the productivity of a meeting by eliminating the disruptive noise typically found in a home office or open office situation. In this way, 6G/3D technology could encourage the development of innovative business models.

Other fields of application for 3D in conjunction with 6G also exist in medicine, engineering, construction and research, where 3D video transmission can take joint planning, development, modeling, operation, and monitoring to a new level by easily involving different experts from around the world when they are needed. Maintaining high security standards when handling sensitive data will become even more important for general acceptance as virtualization increases. Nevertheless, it will still be necessary to travel in person for certain selected purposes, especially in cases where tight personal networks need to be established and the social spirit of communication is indispensable.

As with any new technology, the sustainability of 6G or 3D is not limited to improvements in energy efficiency; in fact, the consumption of finite and possibly scarce material resources is of equal importance for the overall environmental assessment. In supporting a circular economy, eco-design principles must be adhered to from the very beginning of the development process before new technologies are scaled up and disseminated. The extent to which 6G and 3D will demand virgin raw materials and enable circularity is, therefore, in need of further investigation.

6. Conclusions

The scenario-based calculation of the carbon mitigation potential of German business travel in 2030 emerging from an increased use of 6G-enabled 3D videoconferencing has shown significant results when direct and indirect energy effects of ICT are considered. We found that even such a data-intensive conference can save most of the carbon emissions of a real conference. In the different scenarios investigated, a virtual conference would cause between 0.2% and 0.9% of the emissions of a mean-distance conference trip taken by a German business traveler. The energy required for internet transmission $E_{\text{net}}$ has shown the highest sensitivity in the presented calculations. Considering the mitigation potential of all German conference travel in 2030, emissions could decrease by 2.1 MtCO$_2$eq (8.9%) and 20.5 MtCO$_2$eq (88.4%), respectively, compared to 2019 under conservative and optimistic assumptions. In terms of current national total emissions, increasing virtualization of conferences could contribute between 0.3% and 2.8% to the German mitigation efforts.

There is also considerable potential for saving greenhouse gas emissions in other areas through 6G-enabled virtualization of products and services, if any misuse in the form of overconsumption can be avoided by an intelligent and conscious handling of the new possibilities. Environmentally-benign online behavior should therefore be encouraged through information campaigns, nudging, or incentives.

The relevance of digitalization for Europe’s transition towards a carbon-neutral and circular economy is strongly emphasized in the Green Deal of the European Commission. Even if the makers rather had 5G in mind, we believe that the successor 6G will more strongly stimulate the creative potential for developing energy- and resource-efficient use cases along entire value chains and facilitate cross-innovations. Early and concerted research activities as well as accelerated commercial exploitation of 6G and associated technologies could put Europe in a vanguard position, which it failed to achieve with 5G. However, successful market diffusion also hinges on competitive costs and social acceptance. A high level of transparency regarding the advantages and possible disadvantages of the
technology is therefore essential in order to avoid the communication problems encountered with 5G.

Coping with the consequences of the pandemic and climate change simultaneously will require tremendous resources in the coming years, which is why appropriate framework conditions have to be put in place for 6G as early as possible to ensure Europe’s digital competitiveness in the future.

CRediT authorship contribution statement

Andres Seidel: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization. Nadine May: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization. Edeltraud Guenther: Conceptualization, Writing - review & editing, Project administration, Funding acquisition. Frank Ellinger: Conceptualization, Writing - review & editing, Project administration, Funding acquisition.

Declaration of competing interest

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

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