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The potential of virtual reality meetings in international research projects for greenhouse gas emission mitigation

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Abstract

Purpose – European Union (EU) research projects generally involve international teams based in different countries. This means that researchers need to travel internationally to participate for in-person meetings, which are crucial for facilitating collaboration among research teams and provide a platform for teams to share their progress. Unfortunately, much of the international traveling in EU projects is done by air and therefore it has a significant carbon footprint. One potential solution that has gained attention in recent years is virtual reality (VR) and the metaverse. The aim of this work is to investigate to what degree VR meetings provide a viable alternative to physical meetings in the context of EU research projects and can thus contribute to climate change mitigation.

Design/methodology/approach – A three-stepped approach was chosen. First, the requirements for VR meetings were determined by collecting all relevant aspects of physical meetings through a questionnaire. Second, a set of VR meeting experiments were designed and executed. Third, carbon footprints for both physical traveling and VR meetings (lifecycle) were calculated.

Findings – We conclude that VR can be a powerful tool which can supplement international projects and mitigate carbon emissions associated with traveling for in-person meetings by an estimated 7–19 times.

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Originality/value – This paper explores the suitability of the current generation of VR technology and quantitatively evaluates its effectiveness for greenhouse gas emissions mitigation in the context of a European research project.

Keywords Virtual reality (VR), Metaverse, Virtual meetings, International research projects, Carbon emission mitigation

Paper type Case study

1. Introduction

The Covid-19 pandemic led to an increase in remote work (Eurostat, 2022), proving its effectiveness for a wide range of industries. As the pandemic restrictions lifted, many people chose to continue working remotely, aiming, *inter alia*, to achieve a better work–life balance, reduce their commuting costs and carbon emissions, and save time. Therefore, virtual meetings and video conferencing, which became widely accepted during the pandemic, are now expected to remain the workplace norm. Nevertheless, some activities, such as connecting with colleagues, brainstorming, or onboarding new employees, lose some of their effectiveness when done remotely. This creates the need for new, effective approaches towards remote work.

Effective communication and teamwork are essential for the success of research projects and collaborations with a diverse pool of stakeholders. While it is easy to return to the office for some activities, this is not the case for EU research projects that often involve international teams based in different countries. This is because researchers need to travel internationally to participate in in-person meetings, which are considered crucial for facilitating collaboration among research teams and provide a platform for teams to share their progress.

Unfortunately, much of the international traveling in EU projects is done by air and therefore it has a significant carbon footprint. For example, a return flight between Amsterdam and Rome is approximately 2,600 km, which corresponds to about 750 kg CO_2-eq. (carbon dioxide equivalents) emitted (Atmosfair - Flight Emissions Calculator, 2023). In order to meet the Paris Agreement objectives, all aspects of our society, including the research community, need to reduce their carbon footprints. While the aviation industry is preparing to become more sustainable, this process is expected to take many decades (TU Delft and NLR, 2021), and may not succeed without a reduction in air traffic (Bergero *et al.*, 2023; Sacchi *et al.*, 2023). Therefore, researchers need to investigate alternatives to the carbon-intensive aspects of their work (Eichhorn *et al.*, 2022).

One potential solution that has gained attention in recent years is the metaverse. The concept of the metaverse is not something new (Stephenson, 1992), and it is often described as the next generation of the internet, a network of 3D virtual worlds utilizing virtual reality (VR) and augmented reality (AR) technologies (Park and Kim, 2022). Users, existing as avatars in the metaverse, can interact with each other and various digital media in immersive environments through VR headsets or AR glasses.

This multidimensional and immersive aspect of the metaverse provides a new set of tools and forms of communication and collaboration making it especially promising in the workplace. Many organizations have already started utilizing VR technology for employee training, to hold company events and to facilitate collaboration between different design teams. VR has also been used in a multitude of business settings including education (Yang and Goh, 2022), the medical field (Singh *et al.*, 2020), manufacturing, entertainment, etc. (Xiong *et al.*, 2021).

It has been recognized that although physical mobility cannot be completely replaced for all applications, it "can be substituted by virtual mobility in various other circumstances" in an academic context (ALLEA, 2022). These authors recommend "promoting virtual communication through recommendations and providing software, training and technical support". Nevertheless, the need for moving towards less carbon-intensive international meetings is recognized and its implementation advocated in a range of scientific communities (e.g. Köhler *et al.*, 2022; Lefresne *et al.*, 2023; Stevens and Moss, 2023; Wenger and Turi, 2023; Wassénius *et al.*, 2023; Papies *et al.*, 2024).

The aim of this case study is to investigate to what degree VR meetings provide a viable alternative to physical meetings in the context of EU research projects and can thus contribute to climate change mitigation. As such, the paper aims to inform current and future international collaborative research projects.

The research was part of the EU Water-Futures project (Water-Futures, 2024) and included a series of VR experiments and questionnaires with a small group of researchers working within Water-Futures and/or at KWR Water Research Institute. Additionally, the study provides preliminary insights into VR's environmental impact and compares it to carbon emissions from air travel. This paper first discusses existing literature on digital replacements for physical meetings. Then, we continue to discuss our research methods that include stakeholder engagement via questionnaires among researchers in the Water-Futures project and VR experiments held within our organization, KWR Water Research Institute. We present results of these approaches and an analysis of the carbon footprint of VR meetings in the fifth section and discuss its potential role in mitigating carbon emissions from international travel. Finally, the most important takeaway from this case study is that VR can be a powerful tool which can supplement international projects and mitigate carbon emissions associated with traveling for in-person meetings by an estimated 7–19 times.

2. Literature

The field of virtual (reality) meetings and VR hardware has seen rapid development over the past decade, but has been a topic of research and development for much longer than that. We refer the interested reader to generic literature reviews such as that by Halarnkar *et al.* (2012), and topical overviews such as that of Philippe *et al.* (2020) on VR in teaching and training, and focus here on the aspects of collaboration and carbon footprint. When presenting VR meetings as an alternative to physical meetings that require extensive traveling, one should consider the advantages and disadvantages of one with respect to the other. Several of these are discussed below. It has been argued in the literature that face-to-face meetings are more effective in a number of cases, whereas technologically-mediated meetings may be more effective in others (Bathelt and Turi, 2011; McVeigh-Schultz and Isbister, 2022). However, McVeigh-Schultz and Isbister (2022) argue, following Hollan and Stornetta (1992), that new technologies may, and should, actually provide additional interactions rather than merely imitate existing ones from face-to-face meetings.

The COVID crisis has provided us with a unique "natural experiment" in which we were forced to collaborate at a distance. This has inspired a lot of research over the past 4 years. Many of the papers cited in this concise literature overview stem from this period, and focus on conferencing, as this activity has received most attention in the literature. We discuss recent literature contributions on the carbon mitigation potential, advantages and disadvantages of virtual meetings (in particular conferences), hybrid meetings and recent developments in adoption, and finally, a more philosophical perspective of using technology to combat technology-spawned problems.

2.1 Carbon mitigation potential

Virtual conferencing has been recognized as a carbon-friendly alternative to physical conferences for over two decades (e.g. Reay, 2003). The need for climate change mitigation and the role and responsibility of academia in this have only become apparent to a wider audience within the academic community in recent years. This is illustrated by the papers advocating a reduction of the carbon footprint of conferences cited in the introduction.

There is no doubt that virtual meetings have a much lower carbon footprint than in-person meetings, in particular when long-distance travel by airplanes is required. An *et al.* (2023) showed that online educational workshops can reduce the carbon footprint by up to 88% compared to their physical equivalents in a comprehensive evaluation that includes raw materials, electricity and water. For scientific conferences, Cavallin Toscani *et al.* (2023) find that virtual conferences reduce the environmental impact by two to three orders of magnitude compared to in-person conferences. Similarly, Periyasamy *et al.* (2022) find that for a national public health conference held in India, emission mitigations of a factor 55 or more were possible, taking into account attendance as a function of the meeting format (digital or physical) and existing travel mode preferences. And Tao *et al.* (2021) report a 94% carbon footprint reduction by shifting from in-person to virtual conferencing.

2.2 Additional advantages and disadvantages of virtual meetings

Pidel and Ackermann (2020) discuss insights from the literature on applying VR to long-distance collaboration, identifying a number of advantages. These include the ease of communicating a concept (less reliance on the imagination) and the possibility of viewing things from a different person's perspective. These also identify development needs, such as a good representation of facial expressions, and challenges, including motion sickness and eye fatigue, technical literacy requirements, and rapidly developing technology that can increase overhead and lock people in or out. With respect to the first item, the importance of body language has been recognized and multiple studies stress the added value of including non-verbal communication modes in virtual environments (Etienne *et al.*, 2023; Rogers *et al.*, 2022). Kimmel *et al.* (2023) investigated the influence of facial expressions in two collaborative VR tasks and showed that Social Presence in VR can be improved by making eye and mouth movements part of the VR experience.

Also, clear additional advantages have been reported for virtual conferences in particular. These include reducing the financial burden and the social costs, and increase participation "from institutions and countries with limited resources, women, disabled scientists and early career researchers and practitioners" (Skiles *et al.*, 2022). These authors also report a major disadvantage of virtual conferencing: people experience that the social networking is lacking.

Chessa and Solari (2021) compared the experiences of university lectures provide through a web conference system to those using a VR social platform. They found that people appreciate the novelty and find VR more stimulating than the more traditional web conference system, but less efficient and dependable. Presumably, this is partly due to technology maturity. Participants reported gave higher scores for experiences of presence and involvement. We must also note that the VR social platform was offered on laptop screens and not through VR headsets – this was suggested for follow-up research.

There seem to be career advantages to air travel for researchers. Analysis of a large survey (6,000 respondents) indicates that there is a correlation between the amount of air travel that a researcher does and her/his publication rate and h-index (Berné *et al.*, 2022). These authors suggest that key is obtaining (early-career) and maintaining (established researchers) scientific visibility through flying. Though they make careful inferences, the authors recognize this chicken-and-egg question for what it is: it is difficult to determine whether visibility results in travel (reputation effect) or travel in visibility (exposure effect).

2.3 Hybrid meetings and recent developments in adoption
Between physical and virtual meetings, a third option has emerged, hybrid meetings, which add an online component to physical conferences (Puccinelli *et al.*, 2022). Also a hub-model of merged regional annual conferences, linked by virtual conferencing technology to allow participants of any regional conference to participate in any session, has been proposed as a way to significantly reduce long-haul air travel and associated carbon emissions (Klöwer *et al.*, 2020).

However, finally, it seems that virtual conferencing is in decline again, now that mankind has moved beyond the COVID pandemic. Falk and Hagsten (2023) report that only 20% of 547 investigated conferences (held between August 2022 and July 2023) offered hybrid solutions, and only 13% virtual alternatives. They note that there seems to be a discontinued adoption of online conferencing technology. Still, post-COVID virtual conferencing mostly means using a screen rather than a VR device. It is conceivable that improved VR conferencing technology and progressing adoption of VR devices, combined with growing awareness of the adverse environmental impact of physical conferences, may break this trend.

2.4 Technology as a panacea?
Crowther (2023) asserts that there are limitations to and risks with new technological solutions as a means to address problems caused by prior technologies. We acknowledge that this is the case here as well (i.e. VR technology as a solution to combustion-based technology causing climate change). From the same perspective, the focus of the aviation industry on so-called sustainable aviation fuels (Watson *et al.*, 2024), that many may consider a viable road towards sustainable conferencing, is a technological solution to the technology-spawned problem of anthropogenic climate change. It is clear that this approach engenders many limits and risks, such as large green energy and/or bio feedstock requirements, potential "food vs. fuel" competition, threat to biodiversity, and incompleteness as a solution for non-CO_2 climate effects (Tudge *et al.*, 2021; Becken *et al.*, 2023). In this context, we consider replacing traveling by VR as a measure that is within the direct sphere of influence of an individual or group of researchers.

3. Methods
3.1 Stakeholder questionnaire
We started by developing a stakeholder questionnaire targeting researchers that work within EU research projects. This questionnaire was designed, in an iterative process that included an expert in research on engagement and collaboration, and following established practices (e.g. Krosnick and Presser, 2010), to collect information regarding the amount of travel associated with EU projects, the types of meetings held, required materials, and participants' prior experience with VR technology. The information gathered was then used to establish a baseline for the traveling carbon footprint of research projects, and to inform the design and structure of the VR meeting experiments. The questionnaire was sent to all researchers working in the EU project. In view of the small population size of researchers within the project ($n = 28$ at the time of sending out the questionnaire), we recognize that the results of the questionnaire cannot be considered statistically significant at response rates that can be reasonably expected. When applying Cochran's (1977, Section 4.4) sample size estimate for categorical data, a minimum sample size of 20 out of 28 is found for a confidence level of 90% and a 10% margin of error. Therefore, from the outset, we consider the questionnaire results as indicative of a direction rather than fully quantitative. The full questionnaire is provided in the Supplementary material. In addition to the stakeholder

questionnaire, also a technical questionnaire was sent to the IT staff of the participating groups in order to better understand the technical possibilities and limitations. This technical questionnaire is not further discussed in the present paper.

3.2 Experimental preparation and setup

The experimental setup was informed by the results of the stakeholder questionnaire, aiming to replicate as many as possible of the activities typical of physical meetings within a VR setting. To facilitate all necessary activities in VR, the first step of the experiment setup process was to carefully select the software and hardware.

In terms of hardware, a variety of devices were chosen to evaluate potential variances in user experience, taking also into consideration market availability, cost-effectiveness, and user feedback and reviews. Distinguishing technical characteristics that were taken into consideration are the devices' optics, display resolution, refresh rate, field-of-view, and weight.

The selection of the VR meeting platform was similarly strategic, prioritizing broad compatibility with various VR headsets and the capability to support the diverse collaborative activities identified in the stakeholder questionnaire.

Pre- and post- experiment questionnaires were designed for the participants following established practices (e.g. Krosnick and Presser, 2010). The full questionnaires are provided in the Supplementary materials. Also, for this phase of the research, the sample size is a concern. Again, applying Cochran's (1977, Section 4.4) sample size estimate for categorical data, and considering that we want the results to be representative for a large group of researchers in a range of collaborative EU projects, a sample size of 68 would be desirable for a confidence level of 90% and a 10% margin of error.

3.3 Experimental procedure

Following the selection of hardware and software, the experimental procedure was structured into four distinct phases:

(1) *Preliminary questionnaire:* Participants were first asked to complete an initial questionnaire that gathered information on their previous VR experiences, perceptions, and any concerns they had regarding the technology.

(2) *Introduction to VR hardware and software:* A 30-min introductory session was then conducted to familiarize participants with the VR hardware and software, emphasizing navigation within the virtual workspace. During this session, participants learned how to properly wear and adjust the VR devices for optimal use. Then they were guided through the VR environment, where they were introduced to essential navigation controls, including moving between rooms and interacting with other participants through actions like waving and greeting. The session also covered the use of specialized VR tools essential for effective communication and collaboration. Tools demonstrated included virtual whiteboards, sticky notes, 3D pens, and sharing personal files such as documents and presentations on large-screen displays within the virtual space.

(3) *VR experiment:* At the core of this study was the VR experiment itself, where each experiment session required two participants, from different physical locations to, enter a shared virtual meeting space on the selected VR platform. A session coordinator, connected via a desktop application, facilitated the experiment, guiding participants through each step, addressing queries, and ensuring safety and comfort through constant visual supervision and the support of a VR assistant for any

technical issues. Within this virtual environment, participants engaged in a series of tasks designed to reflect the collaborative activities outlined in the preliminary questionnaire, utilizing all virtual tools introduced during the introductory session. The experiment was structured as follows:

- Task 1: Presentations in VR

Each participant was required to deliver a presentation using slides that outlined their current research interests and activities. This task was designed to simulate the experience of giving and receiving presentations in a VR setting, a common component of research project meetings.

- Task 2: Collaborative research project development

Participants then proceeded to a virtual meeting room where they utilized the VR tools introduced during the introductory session, such as whiteboards and sticky notes, to brainstorm and develop a collaborative research project idea. This session was designed not only to leverage their combined expertise to formulate a viable research proposal but also to simulate connecting, brainstorming, and collaborating within VR environments. Additionally, participants were encouraged to use a 3D pen to create visual representations of their project ideas.

(4) *Interviews and post-VR questionnaire:* The final phase involved conducting interviews and administering a post-VR questionnaire to evaluate the effectiveness of the VR meetings and gather participants' feedback on their experiences and perceptions.

3.4 Environmental impact analysis

The concluding part of our methodology compared the environmental impact of in-person meetings and VR meetings. This involved estimating travel-related CO_2-eq emissions for in-person meetings and lifecycle emissions for VR equipment. Given the lack of specific data on VR devices, we extrapolated from available lifecycle assessments of similar electronics. This approach allowed us to assess the relative sustainability of using VR technology for project meetings against traditional travel.

4. Case study

Our framework, aimed at investigating the extent to which VR meetings can serve as a sustainable alternative to physical meetings, was applied to the Water-Futures EU research project. The Water-Futures project is a six-year project funded by the European Research Council (ERC) Synergy Grant. It brings together four research groups from the Netherlands, Cyprus, Germany, and Greece to collaborate and build on synergies that will advance the sustainable development of the water distribution networks of the future.

The project's focus on creating synergies and fostering collaboration to solve complex problems about the future is perfectly aligned with our VR meetings research. The stakeholder questionnaire was distributed to researchers participating in the Water-Futures project and all VR experiments took place at the KWR Water Research Institute, one of the four participating research entities of the project.

5. Results

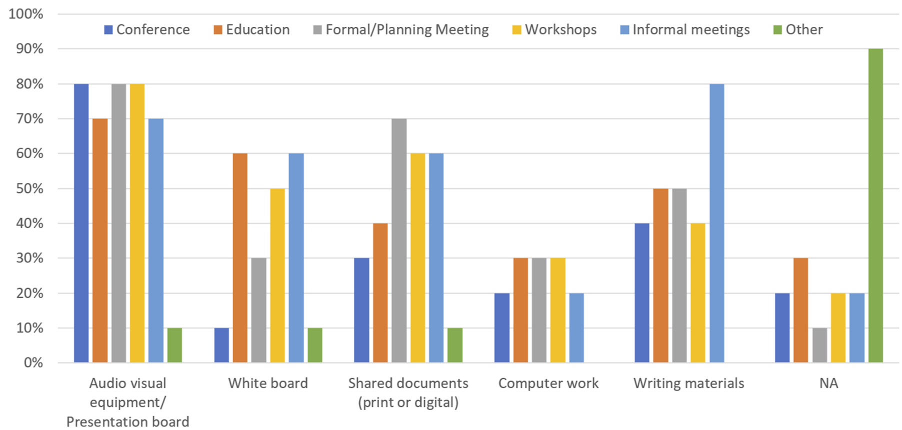
5.1 Stakeholder questionnaire results

The stakeholder questionnaire received 10 responses from Water-Futures participants: 80% were scientific researchers, 10% PhD researchers, and 10% principal investigators. This is below the desired minimum sample size for statistical significance, as discussed above. Therefore, the results need to be interpreted as merely indicative.

The results showed that researchers in EU projects travel significantly across Europe. With 50% of participants traveling 2–5 times a year and 20% traveling over 15 times a year.

One important aspect of the questionnaire was identifying the most common in-person meeting types and activities. This information was crucial for designing VR experiments that accurately replicate the actual interactions researchers have while traveling for work. When it comes to the types of meetings researchers participate in, we found that the most attended ones (>70% of participants) were conferences, formal planning meetings, and workshops. Participants travel to attend these meetings on average of 1–5 times per year. Additionally, participants provided descriptions of the various activities that are commonly carried out in each meeting type. Figure 1 shows the most common activities and the percentage of participants who engage in them. Across all types of meetings, meeting with other colleagues and giving/listening to project presentations were the most common activities done in physical meetings.

Therefore, VR must be able to replicate these experiences, both physically and socially. Within VR it is technically possible to recreate the physical equipment needed (Table 1) such as a presentation board, shared documents, and white boards with pens and sticky notes. VR should also be able to recreate social interactions better than online meetings due to the immersive aspects of VR.



Source(s): Created by authors

Figure 1. Types of activities at physically held meetings

	Materials needed
Conference	Audio visual (AV) equipment
Formal/planning meeting	AV equipment
	Shared documents (print or digital)
	Writing materials
Workshops	AV equipment
	Shared documents (print or digital)
	Whiteboard

Note(s): >50% of participants
Source(s): Created by authors

Table 1. Types of materials needed per activity

When it comes to prior VR experience, the majority of the respondents have little experience in VR, but they show a willingness to try. 80% of participants have never used VR before. 80% of participants were willing to try and use VR as an extra form of communication within Water-Futures or similar EU Projects. However, 20% of participants were unwilling to try VR as virtual meetings have already heavily reduced the amount of travel and because of fear of motion sickness from VR equipment.

Overall, participants felt that the usage of VR had many uses in the workplace and can see its potential to reduce emissions in the future. Additionally, participants envisioned other uses of VR in an experimental context as well. Therefore, it was decided to pursue experimentation of VR.

5.2 Experimental results

Based on the responses we received from the stakeholder questionnaire, the next step was to select the appropriate hardware and software for our experiments. The selected hardware for the experiments included the Meta Quest 2, which in our pre-experiment evaluation was deemed superior in terms of retail price, refresh rate, and weight, and HTC Vive Focus 3, deemed superior in terms of optics, resolution, and field of view, devices, while the chosen VR meeting platform was Glue (2023).

Ten KWR employees, not involved in the Water-Futures project, but all with experience in collaborative projects and travel for project/conference purposes, volunteered to be involved with the testing of VR in a business setting. The demographics of the participants was 8 men and 2 women from in their 20s–50s (50% in their 20s, 10% in their 30s, 30% in their 40s, and 10% in their 50s). Again, we recognize that the number of participants in the experiment is relatively small. Their number was limited by willingness, availability, and scheduling limitations. Therefore, we again consider the results to be indicative rather than fully quantitative.

Before and after the experiment, participants were asked how they felt about using VR in the workplace and ranked it on average as 3.4 out of 5.0. Post experiment this feeling rose to 3.7 out of 5.0. Largely, participants felt that the immersive experience of VR created a more social atmosphere and a reduction in distractions.

Overall participants felt interacting in Glue was easy. Participants were able to navigate the space easily and felt very connected with the other participants. Positive points noted include the feelings of increased focus and ability to creatively brainstorm. The presentations and brainstorming section of the experiment was rated similar to that of physical meetings. Negative aspects include delays or lagging of system and limited avatar options. Additionally, participants note that the meeting was still not comparable to a physical meeting as when you normally take breaks from work you can socialize with other participants. In VR, participants do not have the networking during breaks that normally occurs at events because the participants will need to physically take off the glasses and have a break from the virtual world.

When interacting with Glue participants found it difficult to interact with the white board and sticky note tools within the space. Grabbing the pen tool and writing also stressed the participants. This frustration lessened the longer they were in VR. There appears to be a learning curve here as well.

5.2.1 Negative effects. Some participants reported negative physical ailments during and after use of VR equipment including motion sickness, headache and eye strain. Three users of the Meta and HTC device noted complaints with using VR, in two cases lasting up to 8 h after exiting of VR.

5.3 Carbon footprint of traveling to physical meetings and VR

Water-Futures' in-person meetings are held three times annually at one of the partner institutions. Table 2 shows the CO_2-eq emissions generated by a researcher from their country of residence to attend an in-person meeting at one of the partner institutions. These were obtained from Atmosfair (2023) and include both direct CO_2 effects and non-CO_2 effects (contrails, ozone formation, etc.). The data show that for three round trips per year, researchers could emit anywhere between 1,061 (for a person from Bielefeld attending in-person meetings in Bielefeld, Athens, and Amsterdam) to 2,726 kg CO_2-eq (for a person from Cyprus attending in-person meetings in Bielefeld, Athens, and Amsterdam) from air traveling, and over the six-year project duration, this equates to 6.36–16.35 tons CO_2-eq per person. This compares to the overall 1.5 degrees compatible remaining carbon budget of 25 tons per world citizen (MCC, 2024).

When it comes to the environmental footprint of electronic devices, manufacturers often perform life-cycle assessments (LCAs). An LCA often contains a product carbon footprint report, which is an evaluation of the impact of a product (measured in CO_2-eq emissions) throughout its entire lifecycle.

Unfortunately, when it comes to VR devices, manufacturers have not yet released any information or data regarding their carbon footprint. However, VR devices have components that are similar to other electronic devices like smartphones, laptops, and gaming consoles. Hence to gain a better understanding of the environmental impact of VR devices, we searched for publicly available LCAs of similar electronic devices from major manufacturers. The data we found show that the environmental impact of such devices ranges from 20 to 165 kg of CO_2-eq emissions annually (Table 3).

Assuming similar weights and components, VR devices likely have a comparable environmental impact to the electronic devices analyzed above. However, we must note that VR devices can be expected to make more heavy use of off-site servers for their operations, comparable or even more so than gaming consoles. We observe that for the gaming console in our overview, the use aspect represents 79% of its life-cycle footprint, compared to 4–65% for the listed laptops. To estimate the carbon footprint of our VR devices, we combine the production, transport, and end-of-life processing of Surface Laptop Go2 (due to weight similarity) with the use footprint of an Xbox Series X (due to usage intensity). In this way, we provisionally estimate the lifecycle emissions at 78%*825 kg CO_2-eq/5 years = 128.7 kg CO_2-eq/year for use and (100%–22%)*115 kg = 89.7 kg for production and transport, or 862 kg for the duration of the project. Therefore we conclude that substituting some in-person meetings with VR meetings is likely to be a more sustainable option than flying by a factor of 7–19 for the Water-Futures project. For any project in which people are traveling by air for more than approximately 600 km per year (862 kg CO_2-eq/6 years/0.234 kg CO_2-eq per km for air travel < 700 km (CO2 emissiefactoren, 2023)), VR is the more sustainable option. We must note that the numbers listed in Table 3 have not necessarily all been produced using the same methodology and may therefore not be comparable. Therefore, our conclusions based on these numbers should be treated only as provisional estimates. It is also important to point out that the environmental impact of VR devices can still vary greatly depending on the manufacturer and how the materials are sourced and used. Although we assume that the carbon footprint of VR devices is comparable to other electronic devices, we should

Table 2. CO_2-eq emissions (kg) for round-trip travel between partner institutes in Water-Futures

	Athens	Bielefeld	Nicosia	Amsterdam
Athens	–	869	378	984
Bielefeld	869	–	1,161	192
Nicosia	378	1,161	–	1,187
Amsterdam	984	192	1,187	–

Source(s): Created by authors

Table 3.
Environmental impact assessment of electrical devices

Product	Category	Manufacturer	Emissions (kg CO_2-eq)	Production (%)	Transport (%)	Use (%)	End-of-life processing (%)	Lifecycle (years)	Annual emissions (kg CO_2-eq)	Weight (kg)
iPhone 14 (128 GB)	Smartphone	Apple	61	79	2	18	1	3 to 4	15	0.17
Surface Laptop Go 2	Laptop	Microsoft	115	71	7	22	0	3	38	1.13
Travel Mate P6	Laptop	Acer	141	33	2	65	0	5	28	1.10
ASUS P1512	Laptop	Asus	226	51	10	38	1	4	57	1.80
16-inch MacBook Pro	Laptop	Apple	349	66	6	27	1	3 to 4	87	2.10
HP ZBook Fury 16 G9 Mobile Workstation PC	Laptop	HP	404	77	5	18	0	4	101	3.60
Surface Book 3 15-inch display	Laptop	Microsoft	421	84	13	4	0	3	140	1.91
Xbox Series X	Gaming Console	Microsoft	825	19	3	78	0	5	165	4.45
Oculus Quest 2	Standalone VR headset	Meta	–	–	–	–	–	–	–	0.75*
HTC focus 3	Standalone VR headset	HTC	–	–	–	–	–	–	–	1.07*

Note(s): *Controllers included
Source(s): Created by authors

acknowledge that the VR industry has a fast-paced nature and devices can become outdated quickly due to the industry's developing phase. This means that VR might have a higher environmental impact than other electronic devices such as laptops or smartphones which can be refurbished and reused. On the other hand, our analysis ignores the carbon footprint of additional components of the physical trip (hotel, transport, etc.). Therefore, even with a significantly lower life span, the carbon footprint or VR meetings appears to be smaller by a large margin.

6. Discussion

Our research contributes to the picture emerging from the existing literature that VR can be a promising tool for research collaboration and a more sustainable alternative to meetings that require air travel. Our findings based on questionnaires sent to researchers participating in EU projects and an experimental study, were insightful. The questionnaires showed that despite a majority of Water-Futures researchers are unfamiliar with VR, they hold a positive attitude towards the technology and are willing to integrate it into their work. We do note that the small sample size challenges the robustness of these results.

Our experiments with 10 researchers showed that for most participants, VR allowed them to feel connected, present, more creative and they were able to collaborate effectively. While VR comes with a learning curve, by the end of the 2-h session, the researchers became more comfortable and creative with using the available VR tools.

However, there are still significant issues with VR that need to be improved, such avatar option availability, motion sickness, headaches, and eye strain. Research shows that nausea may be reduced by increasing the resolution of the VR set, but that real-world motion sensitivity remains a primary predictor for these discomforts in VR (Hein *et al.*, 2023). This underlines the need for further research into motion sickness-triggering factors and their mitigation in VR technology. Biswas *et al.* (2024) provide guidelines both for developers of VR technology, including making visuals *less* realistic and develop for short duration use, and for users, including building up exposure and taking brakes. As both VR technology and our understanding of its adverse effects continue to advance, we anticipate that these issues will be improved. After the experiments ended, we found that the percentage of researchers that have a positive attitude towards VR slightly increased. This is encouraging, as it suggests that even with the challenges described, VR still holds potential as a collaboration tool.

In terms of sustainability, our research shows that VR devices can serve as a sustainable alternative to air travel in any scenario, but more so if the headsets are used for as long as possible. However, manufacturers need to become more transparent about the carbon footprint of VR devices.

7. Conclusions and outlook

In conclusion, this study presents promising findings for the use of VR in research collaboration, both in terms of collaboration outcomes and sustainability, potentially reducing carbon emissions associated with traveling by a provisionally estimated factor of 7–19 for the Water-Futures project. VR is estimated to be the more sustainable option for any project where people travel by air for more than 600 km per year. Indeed, productive engagement with others was shown to be feasible and fun in a VR environment, but some limitations and drawbacks exist. Also, there may be additional challenges that could stem from, e.g. different cultural settings or different types of research projects. These aspects were beyond the scope of the present work, but could be part of future research if signals of these potential issues are encountered in practice.

However, the imperative of reducing our greenhouse gas emissions may inspire sufficient flexibility with prospective users to experiment with this in spite of these limitations and shortcomings in currently available devices and software. The technology is developing rapidly – these issues can be expected to be reduced or resolved within one or two generations of devices. In our view, the technology is ready to start organizing meetings and experiment on a larger scale, to decide on operational implementation. There is also a lot of mostly unexplored potential in the use of more VR tools within collaborative VR environments, such as typing, screen integration and data and 3D model visualization (for comprehensive discussions on these topics, see Abramczuk *et al.*, 2023; Korkut and Surer, 2023). The former would facilitate several collaborative natural and machine language-based tasks such as writing, editing and programming. The latter would allow more effective instruction, and collaborative analysis and interpretation of data.

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Supplementary material

The supplementary material for this article can be found online.

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