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Next Generation Virtual Worlds:

Societal, Technological, Economic and Policy Challenges for the EU

I. Hupont Torres, V. Charisi, G. De Prato, K. Pogorzelska, S. Schade, A. Kotsev, M. Sobolewski, N. Duch Brown, E. Calza, C. Dunker, F. Di Girolamo, M. Bellia, J. Hledik, I. Nai Fovino, M. Vespe.

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Table of contents

Abstract

This report provides an overview of the opportunities that next generation virtual worlds may bring in different sectors such as education, manufacturing, health, and public services among others. This potential will need to be harnessed in light of the challenges the EU may need to address along societal, technological, and economic and policy dimensions. We apply a multidisciplinary and multisectoral perspective to our analysis, covering technical, social, industrial, political and economic facets. The report also offers a first techno-economic analysis of the digital ecosystem identifying current key players in different subdomains related to virtual worlds.

Foreword

In an era defined by rapid technological advancements and connectivity, the concept of virtual worlds has emerged as a captivating and transformative force. Virtual worlds are fascinating. Now the recent advancements in technology and the evolution of the internet have propelled them into a mainstream shared virtual space where people can interact in real-time, transcending physical boundaries and fostering innovation and collaboration.

Being at the forefront of scientific developments and new and vast societal trends is at the core of the Joint Research Centre's mission, especially when it comes to Digital Transformation. As the next generation of virtual worlds is expected to bring large opportunities and trigger new, complex challenges, this report is a contribution to anticipating what the impact of these technologies will be on society at large.

A tremendous and fast technology push is enlarging the limitless possibilities offered by these immersive digital environments, affecting sectors such as healthcare, manufacturing, education, and entertainment. As much as commerce can flourish through new marketplaces and immersive customer experiences, entertainment can thrive with new frontiers for storytelling, gaming, and social experiences, also the education sector can be revolutionised through interactive and immersive learning environments.

However, this transformative technology also presents challenges. Privacy and security concerns, ethical considerations, and societal inequities must be addressed in virtual worlds as much as in the real one. Here is where we, as policy makers, should intervene, to ensure we can shape virtual worlds in line with European values. The upcoming EU initiative on Web 4.0 and virtual worlds fully embeds this vision. It will aim at fostering open, interoperable and innovative virtual worlds that can be used safely and with confidence by people, businesses and public services.

Policymakers, industry leaders, and scholars need a comprehensive understanding of the interplay between technology, societal and economic trends, to contribute to a better-informed public discourse, and design policies that ensure the benefits of virtual worlds are harnessed by all. I am therefore pleased to introduce this science for policy report, which perfectly exemplifies our commitment to providing such a knowledge base, to helping shape the development, and to implementing and evaluating EU policies and initiatives that aim to reap the full potential of digital technologies.

Margrethe Vestager

Commissioner for Competition and Executive
Vice-President of the European Commission

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1. JRC.T3 - Joint Research Centre, Algorithmic Transparency Unit.
2. JRC.T1 - Joint Research Centre, Digital Economy Unit.
3. GROW.G3 - DG Internal Market, Industry, Entrepreneurship and SMEs, Digital Transformation of Industry Unit.
4. JRC.B1 - Joint Research Centre, Economy and Financial Resilience Unit.
5. JRC.T2 - Joint Research Centre, Cybersecurity and Digital Technologies Unit.

Executive summary

This report analyses different facets of next generation virtual worlds, where physical and virtual environments will blend into highly immersive and intuitive experiences. There are already early signs and examples of this future transition. The report offers a comprehensive overview of the historical context of virtual worlds, opportunities across different sectors, and the challenges likely to be posed in technical, societal, economic and governance realms. By considering the current landscape of players, both policymakers and scientists can gain valuable insights into the virtual worlds dynamics and make informed decisions to shape its next generation.

Policy context

The EU is now regulating technologies that are likely to be key drivers of next generation virtual worlds through the AI Act, Digital Service Act and Digital Market Act, but also the Data Act and the Data Governance Act amongst other policy initiatives. This report provides early insights and scientific underpinning in areas specific to next generation virtual worlds that would require further policy intervention to protect European values or boost the contribution of European industry.

Key conclusions

Opportunities arising from virtual worlds will require analysis considering associated risks, such as privacy, safety, and non-discrimination. Early assessment will be crucial, with equal emphasis on technological advancements and ethical considerations.

The advent of next generation virtual worlds holds significant potential for several sectors, notably education, health, public services and manufacturing. Exploring and harnessing this potential can yield substantial advancements and growth in these sectors.

Interoperability among different platforms and components is increasingly important to enhance experiences and maximise the value of next generation virtual worlds. Achieving interoperability through the adoption of common standards can facilitate the seamless integration of virtual worlds.

Policymakers must proactively engage with the rapidly evolving and transformative field of virtual worlds. This is crucial to stimulate the economy and foster the evolution of players in this domain while prioritising responsible and fair practices.

Main findings

Next generation virtual worlds will leverage recent and future developments in artificial intelligence, eXtended reality, the Internet of things but also connectivity and infrastructure advances. The opportunities these areas will offer for society and the economy are significant in several sectors.

At the same time this report acknowledges the presence of uncertainties and challenges surrounding next generation virtual worlds, and sets the stage for areas worth of future exploration and discussion from a scientific perspective, with links to the specific EU policy context.

Related and future JRC work

The JRC is planning to set up a Centre for Advanced Studies on next generation virtual worlds, where the impact on society and the policy challenges will be analysed from a multidisciplinary perspective. It will investigate the influence on individuals (digital twins, socialisation), high-stake sectors (health, education, labour), businesses (new services, business models), digital contents (NFTs), technology (human-metaverse interaction, blockchain) and/or social schemes (democracy, geo-politics, role of public sector).

Quick guide

The report begins with an introduction, delving into the historical context of next generation virtual worlds, and explores the reasons behind their significance, emphasising the timeliness and urgency of addressing them now.

Section 2 examines the opportunities that will likely arise from next generation virtual worlds across different sectors and highlights the potential for human-machine interaction, the transformative impact on education and training, advancements in health, medicine, and well-being, implications for manufacturing, and the relevance of next generation virtual worlds in the public sector. Additionally, the section briefly mentions other fields where virtual worlds can bring about significant changes.

With Section 3, the report then focuses on the challenges associated with next generation virtual worlds. It begins by discussing the technical challenges posed by emerging technologies and the generation of new types of data, infrastructure requirements and the need for standardization and interoperability. Privacy and security concerns are addressed as an additional challenge. Societal challenges are explored, encompassing ethical considerations and human rights implications, the impact on human health, cognition, and psychology, and the effects on education. Furthermore, the document acknowledges the significance of sustainability within the framework of virtual worlds.

Economic challenges related to next generation virtual worlds are discussed, including the influence on the economy, competition, taxation and the emergence of new business models. Governance and policy challenges are also examined, emphasising the importance of effective governance and comprehensive policies and legal frameworks to navigate virtual worlds successfully.

Finally, through the analysis of data on patents, research projects and scientific publications among others, Section 4 sheds light on the current landscape of the digital techno-economic sector of virtual worlds with a specific EU focus.

1. Introduction

In this report we refer to **'next generation virtual worlds'** as the current and future evolution of what we are observing in the field of **'eXtended reality (XR)'** user experiences. We acknowledge that, in accordance with the literature and the popular perception of the term, 'virtual reality' (VR) typically refers to 3D immersive, fully computer-generated environments to which users access, e.g., through VR headsets. However, the highly influential work by Paul Milgram (Milgram et al., 1995) points to the existence of a much richer continuum between fully-real and fully-virtual experiences. This continuum, depicted in Figure 1, represents the full spectrum of technological possibilities between the entirely physical world or real environment and the fully digital world or virtual environment. Different concepts such as 'augmented reality' (AR), 'mixed reality' (MR) or 'augmented virtuality' (AV) are used to refer to different grades within this spectrum, depending on the extent on which virtual and real elements coexist. However there is a lack of consensus on the exact boundaries among all these terms, which are sometimes used interchangeably (Kardong-Edgren et al., 2019). EXtended reality offers an umbrella term that covers all forms of virtual, augmented and mixed reality technologies (Xi et al., 2022), as well as all the different degrees of immersiveness and interaction offered to the user to engage with virtual contents (Figure 2).

This report considers next generation virtual worlds as experiences that incorporate varying degrees of virtual and real information, which users can access with different levels of immersiveness and interaction.

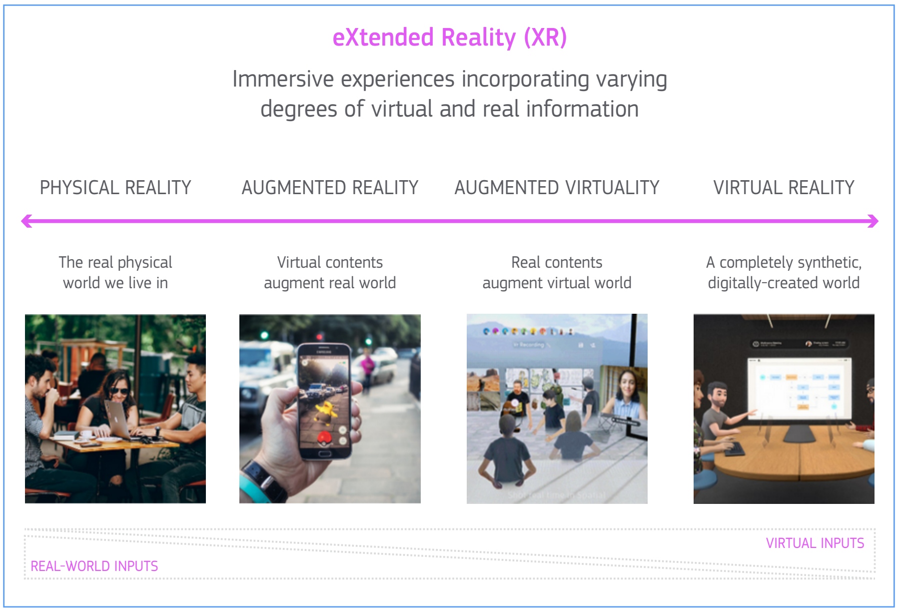


Figure 1

The reality-virtuality continuum, inspired from P. Milgram's original definition (Milgram et al., 1995). Centre-left picture corresponds to NIANTIC's Pokemon Go[6] augmented reality application; centre-right picture is a snapshot of the virtual meeting application by the company Spatial[7]; and rightmost picture is taken from META's Horizon Workrooms[8]. All the images are licensed under Creative Commons terms.

6. https://pokemongolive.com/.
7. https://www.spatial.io/.
8. https://forwork.meta.com/horizon-workrooms/.

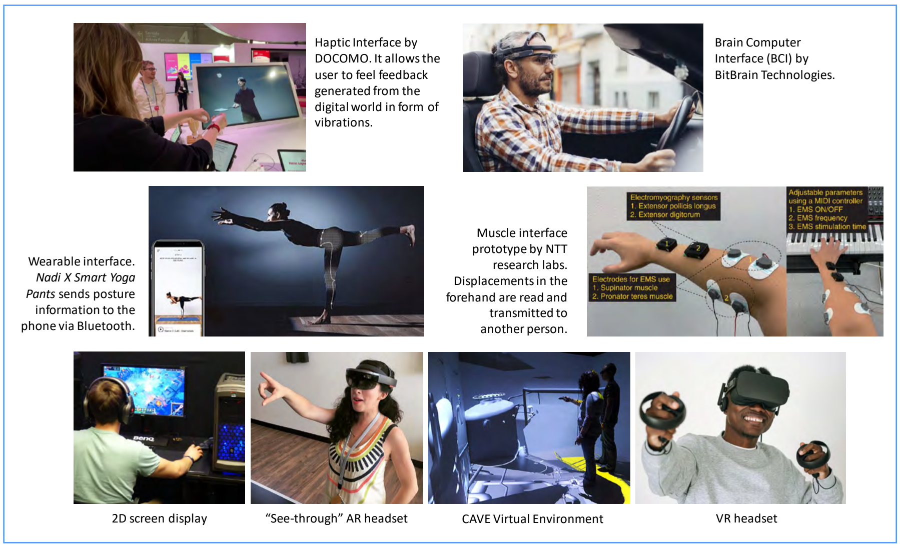


Figure 2

Devices typically used to interact with (top two rows) and visualise (bottom row) virtual worlds. Note that the same virtual world can be viewed with varying levels of immersiveness, ranging from 2D screen displays to VR headsets. All images are licensed under creative commons terms.

1.1 From Web 1.0 to Web 4.0: next generation virtual worlds in historical context

Web 1.0, Web 2.0, and Web 3.0 are commonly used to describe different stages of the evolution of the World Wide Web (Choudhury, 2014). To understand how next-generation virtual worlds will be shaped in the future, it is important to consider them within the historical context of the Internet.

The Web 1.0 (the 'Read-only Web') was the first generation of the web, which lasted from the early 1990s to 2004 (Berners-Lee, 1998). It was mostly static and focused on presenting information. It was primarily a one-way communication channel, where websites provided information and users consumed it. There was very little interaction or user-generated content. Its major limitations were that pages could only be understood by humans, i.e., they did not have machine readable content, and that the 'web master' was solely responsible for managing users and the contents of a website. The order of magnitude of Web 1.0 users was in millions.

The second generation of the web or Web 2.0 (the 'Social Web'), in place from 2004 to 2016, was characterized by a shift towards user-generated content and increased interactivity (Choudhury, 2014). This was mostly driven by the development of social media platforms, blogs, e-commerce and other collaborative tools (Hackl et al., 2022). Web 2.0 also brought the rise of the mobile web and ubiquitous design, which made it easier to access the web on a variety of devices. The Web 2.0 counted in billions of users.

Web 3.0 is the current and third generation of the web, focused on making it more intelligent, immersive and interconnected. It is considered to start in 2016 and counts in bilions of users. Some authors refer to it as the 'Semantic Web' (W3C, 2023) because it introduced the use of metadata, tagging, ontologies and other technologies to enable machines understand the content of web pages, improve data search and management, and create a more personalised and intelligent web experience for users. This resulted in smarter search engines, social networks and recommender systems knowing more about user preferences and delivering content with user-based context (Hackl et al., 2022).

Since the birth of Web 3.0, some ground-breaking technologies have started to be developed and integrated on it at an unprecedented fast pace. These include virtual reality (VR) and augmented reality (AR) systems mimicking physical interactions, artificial intelligence (AI) algorithms, cloud/edge computing, Internet of things (IoT) and 5G cellular networks. As a result, today's Web 3.0 websites provide increasingly connected, immersive and autonomous web experiences. Blockchain distributed storage technology is also being increasingly adopted to realise a decentralised autonomous network, allowing users to accomplish content publishing, economic transactions and other actions without going through a centralised platform.

Because of this rapid evolution, some experts consider the current Web 3.0 as the very beginning of a long-term **transition towards a new Web 4.0 paradigm, where physical and digital worlds will seamlessly blend** enabling more intuitive and immersive experiences (Choudhury, 2014). This technological transition will involve advanced artificial intelligence capabilities, as well as a seamless integration between the web and real objects and environments through technologies such as IoT and eXtended reality.

1.2 Next generation virtual worlds through the concept of metaverses

Within this rapidly evolving Web 3.0-to-4.0 context, next generation virtual worlds are likely to offer unprecedented user experiences that are difficult to predict. These might include more interconnected and smart virtual worlds, 3D fully immersive, highly social and personalised experiences for users through their avatars, as well as the integration of virtual currencies and marketplaces. This idea is closely linked to the **concept of metaverses**, a portmanteau between 'meta' and 'universes' that has been around for decades in science-fiction literature and the collective imagination, but that has just now started to be envisaged as a real and feasible type of virtual web experience. It is increasingly gaining attention from both the research community and industry (Ball, 2022). Therefore, it is likely to play an important role in shaping the future of virtual worlds (Basdevant et al., 2022) and its analysis deserves particular attention as follows.

The very first critical point to highlight about metaverses is the general **lack of consensus and considerable amount of ambiguity and buzzwords in their definition** (Kelly, 2023), as well as in a taxonomy of terms around it (Barrera et al., 2023; Park et al., 2022). Different stakeholders, ranging from academia to official institutions and key industry players, have proposed or adopted very different types of definitions which are sometimes very broad in scope (e.g., 3D *virtual worlds* (Crespo et al., 2013), *eXtended reality* (Xi et al., 2022), *the successor of the mobile internet* (Xu et al., 2022), *the 3D internet* (NVIDIA, 2023)) and, in other instances, much more elaborated (e.g. *the next generation of the Internet and Web, where immersive, interconnected, shared and persistent 3D virtual spaces coexist* (Kozinets, 2023), *a technology-mediated network of scalable and potentially interoperable extended reality environments merging the physical and virtual realities to provide experiences characterised by their level of immersiveness, environmental fidelity, and sociability* (Barrera et al., 2023)).

The bibliographic databases Web of Science[9] and Scopus[10] have indexed more than 500 papers in the period 2000-2022 explicitly mentioning the term *metaverse* or *metaverses*. About 300 of them have been published since 2019, with a clear increasing trend over time, from 53 publications in 2019 to 93 in 2022. By applying automated bibliometric analysis techniques (Aria et al., 2017) to the whole collection of published papers, we extract their most frequent keywords, keyword co-occurrence network and the main research communities. The results are shown in Figure 3 and shed some light and order on the main elements currently considered in metaverse-related studies.

9. Web of Science: https://www.webofscience.com/.
10. Scopus bibliographic database: https://www.scopus.com/.

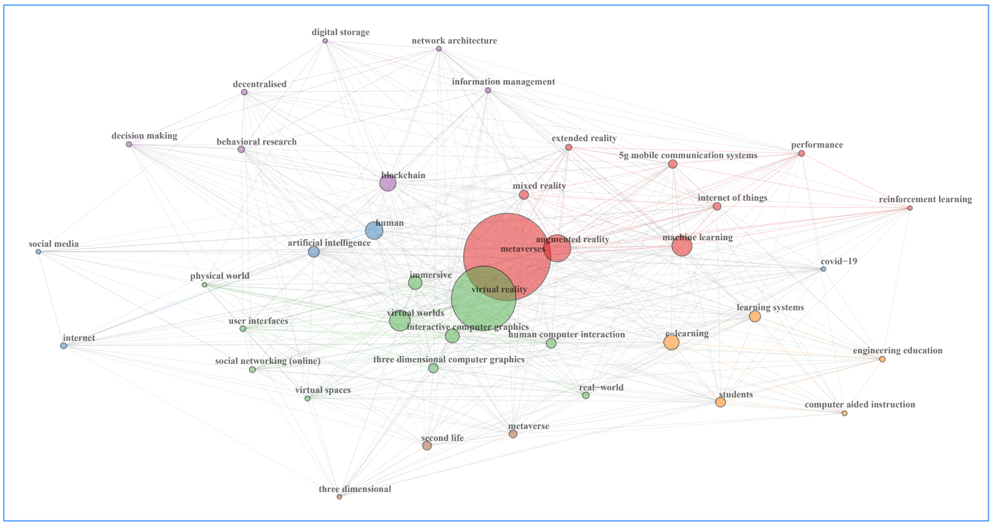


Figure 3

Keyword co-occurrence network resulting from the automated analysis of the more than 500 papers published on the metaverse in the period 2000-2022. The size of keyword is proportional to its relevance, and colours represent the different clusters of research communities.

The analysis reveals that metaverses are strongly linked to virtual reality, immersive 3D environments/worlds/spaces and related user interfaces. However, 'augmented reality', 'mixed reality', 'eXtended reality', 'physical world' and 'real world' also emerge, demonstrating that **the continuum between fully virtual and fully real worlds plays a vital role** in its definition. This interplay between real and virtual worlds is supported by recent definitions of metaverses, such as the one by the World Economic Forum stating that metaverses are *a future persistent and interconnected virtual environment where social and economic elements mirror reality* (World Economic Forum, 2023) and the one by the Organisation for Economic Co-operation and Development (OECD) defining them as *immersive environments based on augmented reality (AR), virtual reality (VR), mixed reality (MR) and other extended reality (XR) technologies that enhance the realism of virtual experiences, blurring the lines between the physical and digital worlds* (OECD, 2022).

The **societal and human-centric aspects** of metaverses also emerge from our analysis through keywords including 'social media', 'social networking (online)' and 'behavioural research'. In particular, a well-differentiated cluster of terms appears around education (yellow cluster in Figure 3), revealing the disruptive impact the technology could have in students and e-learning. Interestingly, the term 'COVID-19' is present close to societal aspects, meaning that the pandemic may have fostered the perception of a current limited offline social activity and an increasing need for enhanced online immersive social interactions, as suggested in many recent studies (Anderson et al., 2022; Basdevant, 2022; Dwivedi et al., 2022; Oh et al., 2023; Xu et al., 2022).

Finally, a myriad of technologies is present among most representative metaverses' keywords. These include 'Internet', 'artificial intelligence', 'machine learning', 'blockchain', 'Internet of things', '5G mobile communication systems', 'digital storage' and 'information management'. This finding is likely to translate the fact that they will be among the key technological building blocks of next generation virtual worlds. The concept of decentralisation is also strongly present. Just as happens with the internet, the community seems to envisage decentralised virtual worlds, operating on a distributed network of nodes rather than being controlled by a central authority (Basdevant, 2022).

1.3 Next generation virtual worlds: why and why now?

Next generation virtual worlds, including metaverses, are only now technically, economically and socially feasible thanks to key enablers that have rapidly evolved in very recent years. Their potential is now being accelerated by the increasing tendency of the following disruptive technological, economic and societal switches:

- **High technology readiness level of key enabling technologies.** These include artificial intelligence, blockchain, Internet of things (IoT) and 5G/6G, among others, that are only currently starting to be able to provide secure transactions, real-time and near zero-latency communications between physical and virtual worlds.
- **Novel and more immersive human-machine interfaces.** Beyond the traditional keyboard, joystick, mouse and microphone, more advanced and intuitive peripherical devices are now offering the means to navigate and socialise in virtual worlds in a fully immersive experience. These include VR/AR headsets with high-resolution displays, haptic feedback devices (Sun et al., 2022) allowing the perception of sensations such as touch, pressure or temperature, face/body motion trackers (Guan et al., 2022), gaze trackers, voice recognition devices and brain-computer interfaces (Bernal et al., 2022).
- **Availability of large and highly performant computing and data storage infrastructures.** Hardware advances in terms of graphics processors, super-computing, cloud and edge infrastructures are only now starting to be ready to face the computational needs, data traffic and structures (e.g. 3D data, 3D worlds, 3D objects, financial transactions, etc.) and allocation of the vast amounts of data that are likely to be generated by users in virtual worlds.
- **An unprecedentedly vast community of highly engaged adopters.** Social networks and so-called Very Large Online Platforms (VLOPs, those with more than 45 million users) comprise nowadays an unprecedentedly large community of users engaging, socialising, creating content and transacting on a daily basis. Generation Z and millennials, who are likely to be the main users of virtual worlds, are spending more than 2h38 min per day on social media (World Economic Forum, 2019).
- **The pandemic** has accelerated the demand for new and improved online social tools (Anderson et al., 2022), e.g. to fight feelings of loneliness (Oh et al, 2023).
- **The society is starting to value digital assets** such as digital art, music, tweets or memes (Kapoor et al., 2022) in a similar way as real (tangible) assets, both from a social and economic perspective.
- **Interest from the public sector and governments.** Some governments have started to explore virtual worlds as a mean to engage with citizens and perform touristic and administrative city-related activities (Oh et al., 2023; Yfantis et al., 2022). Following these developments, the European Commission has decided to focus the work of the newly established Expert Group Innovation Friendly Regulations Advisory Group (IFRAG) (IFRAG, 2023) on the implication of virtual worlds on the public sector, the delivery of public services across country borders, and use cases at local level (the Citiverse).

- **Strong investments from the private sector.** There is a strong interest from the private sector that is fuelling the development of virtual worlds. This can be seen in the activities of leading technology companies, including hardware suppliers such as NVIDIA Corporation (NVIDIA, 2023), social platforms such as Facebook (that has even been re-branded as Meta[11]) and other big techs such as Microsoft (Microsoft, 2022). Moreover, different types of firms including Nike, Disney, McDonalds and Gucci are investing millions of dollars in developing virtual technologies for marketing purposes and engaging with costumers (Barrera et al., 2023). Although precise data on the global volume of metaverses-related Research & Development (R&D) investments is not published, survey-based reports show that it has sharply increased in the last three years. According to (McKinsey, 2022), private spending is almost doubling each year (80% CAGR) reaching USD 120 billion in 2022, and metaverse-related private equity and venture capital funding amounts to USD 8-10 billion per year. These levels are comparable to early investments in artificial intelligence. Internal investments from the top 30 companies in this emerging field are much higher. Meta alone plans to spend around USD 19.2 billion on metaverses in 2023 (Mobile World Live, 2022) and Microsoft announced the acquisition of Activision Blizzard (Microsoft, 2022) for USD 68.7 billion to leverage some of the world's most popular games as building blocks in its future virtual world business.

1.4 Uncertainty, open opportunities and challenges

There is an enormous **social expectation and great uncertainty** about what Web 4.0 and next generation virtual worlds paradigms will bring. Recent research, news and articles on these topics offer mere conjecture about how technology, society and economy will evolve in this new context, but only after its real deployment in the next few years will the true scope and evolution become clear. In any case, next generation virtual worlds will undoubtedly both positively and negatively impact many industry sectors from gaming and entertainment to high stakes sectors such as education, health, economics and politics. They will also bring new opportunities and challenges in the technological, societal, economic, legal and political dimensions.

In this report, we analyse, discuss and balance opportunities and challenges that next generation virtual worlds are likely to offer. We apply a multidisciplinary and multisectoral perspective to our analysis, covering technological, social, industrial, policy and economic facets.

11. META official webpage. https://about.meta.com/what-is-the-metaverse/.

2. Opportunities across different sectors

2.1 Human-machine interaction in virtual worlds

Before entering into the sectoral analysis of the opportunities that virtual worlds may bring, it is important to understand how these developments will affect human-machine and human-human interactions and behaviour and what type of opportunities they may bring. Next generation virtual worlds will integrate various types of technologies including virtual, augmented and eXtended reality (VR, AR and XR) with digital twin and blockchain technology, which will formulate new types of infrastructure for the development of immersive environments interconnected with the real world. In this context, fields such as Human-Machine Interaction (HMI), cognitive psychology and brain sciences are trying to understand how humans interact with and within the immersive environments and how those interactions impact human behaviour in both virtual and real worlds. Existing research indicates that virtual worlds have the ability to radically change the way we connect, perceive, and experience the world around us. Traditionally, research in HMI includes two aspects; the interaction of the user with the interface and the impact of this process on the user's behaviour. With virtual worlds, this cyclical process becomes more complex. The human experience associates not only with the virtual, real-time, multisensory interactions in realistic immersive simulations of the environment but also with the hybrid social environments that might embed conversational, AI-powered, human-like avatars that enable natural conversations in multiple modalities while navigating within various cyber-physical environments (Koohang et al., 2023).

From an HMI perspective, current research focuses on the input the system receives from humans, the type of decisions the system generates (based on human input), the ways in which these decisions are communicated towards humans and the impact they have on the human behaviour. With next generation virtual worlds, however, several emerging areas must be considered in order to better understandi the cognitive, psychological and behavioural processes of the user:

Figure 4

Teleoperation of the physical humanoid robot EVE with the use of immersive reality technology at the exhibition of the International Conference on Automation and Robotics (ICRA2023).

- **Inputs the system perceives from humans:** given the emerging characteristics of next generation virtual worlds, one of the most important technical problems to be addressed is how the system perceives the user's input. The key limitation of existing input devices (e.g., keyboards and touch screens) is that they cannot free the users' hands and accurately reflect body movements. Recently, researchers have begun to study freehand manipulation that allows more intuitive and concrete interaction in immersive and hybrid environments. These emerging techniques often rely on computer vision and brain-computer interfaces. However, the issue of the interpretation of those inputs in terms of 'understanding' human behaviour remains open.

- **Interactivity of the system:** interactive technologies form the user experience in the virtual world, enabling users to create and exchange content, digital assets in virtual worlds, and move between different virtual locations (Koohang et al., 2023). It is expected that the complexity of the emerging inter-connected systems will bring about new possibilities for human-machine interaction.

- **Immersiveness of the system:** the degree of immersivenessof the system related to features such as the embodiment (users' tendency to perceive the virtual body they control as their own biological body and their actions in VR as their own actions in real life), the interactivity, the navigability, sense-ability (users' ability to sense, e.g. touch, smell, hear and taste in the virtual environment) and create-ability (ability to create aspects that do not exist in the physical world and recreate existing aspects of the physical world to diminish negative and enhance positive aspects of it in VR) (Davis et al., 2009).

- **Affordances that support collaboration:** specific design decisions could enhance cross-regional collaboration experiences, such as creating a virtual world where real-life people in different geographic areas can collaborate and discuss, or even conduct experiments together to simulate real-world changes.

- **Device-dependent and device agnostic behaviours:** while the devices that provide access to the virtual worlds seem to have a catalytic role on human experiences and interactions, the human brain can easily adapt to current interfaces. Most people can be fully immersed in a simulated 3D environment even without the use of special equipment only with the use of screen-based graphic design. This human ability, however, is still to be fully understood.

An increasing number of behavioural studies show that capturing the richness of the real world for virtual face-to-face communication in shared environments can be proved particularly impactful for human psychology, cognition and brain and eventually for human behaviour. As such, virtual worlds have some unique elements that might change human behaviour in ways that are not fully understood yet, such as the following:

- **Sense of human presence in multiple interconnected virtual worlds:** presence is a complex psychological feeling of 'being there' in VR, which involves the sensation and perception of physical presence, as well as the possibility to interact and react as if the user was in the real world (Heater, 1992). According to the Embodied Social Presence theory (Mennecke et al., 2011) avatars can be successfully used as mediators of social interactions in virtual worlds. In the context of embodiment, the occurrence of specific acts of communication and interaction creates a sense of presence that is derivative of human cognition and similar toreal interactions in the real world. The core concept of this theory is that in a virtual world, users, represented by avatars, first feel the existence of their own avatars, then through interaction of their avatars with others, they feel a common existence and generate a sense of social presence in the virtual world (Mennecke et al., 2011 and Zhang et al., 2022).

- **Representation of the self with avatar(s):** virtual worlds are environments where new social fabrics emerge, in which humans can manifest their personalities in virtual spaces and make individual choices about what to present with the selected avatar and how much these features would represent their real identity (Figure 5). The construction of identities with a specific digital signature, preview and integrity can be anonymous or can offer connections with the real person in the physical world. Potentially each person can present their choices or represent themselves with multiple avatars which means that each person can represent themself with multiple identities and personalities. In this context, it would be interesting to study what kind of experiences people will look for, how socialisation in the virtual worlds will transform our socialisation in the physical world, how work will transform and how people will care about their virtual identity or identities.

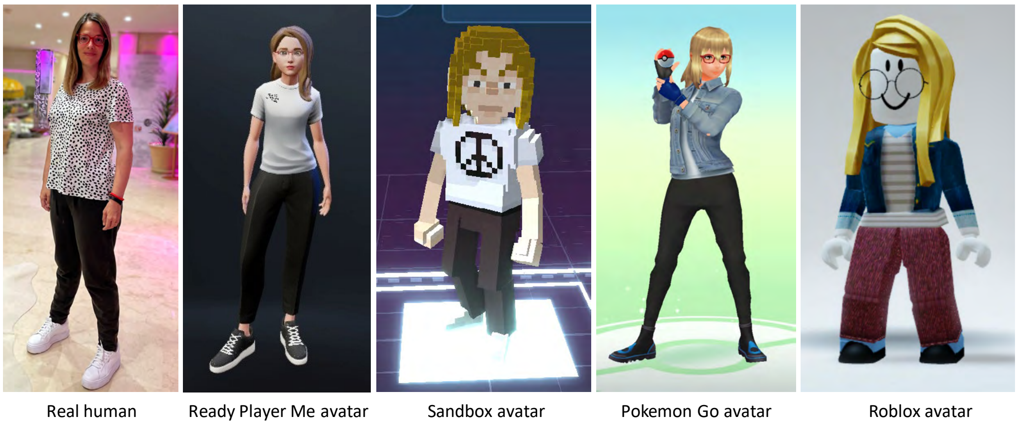


Figure 5

Example of different representations of the self through avatars. Leftmost picture corresponds to the real person. Then, from left to right: Ready Player Me cross-platform avatar[12], Sandbox avatar[13], Pokemon Go[14] avatar and Roblox[15] avatar.

12. https://readyplayer.me/.
13. https://www.sandbox.game/en/me/avatar/.
14. https://pokemongolive.com/.
15. https://www.roblox.com/.

The above-mentioned developments on the interaction of humans with and within virtual worlds, which blur the line between virtual and physical world, create the potential for a transformation in various fields of application as discussed in the next sections.

2.2 Education and training

Within the context of the European Commission priority 'A Europe fit for the Digital Age', the Digital Education Action Plan (2021-2027)[16] is a policy initiative that sets out a common vision of high-quality, inclusive and accessible digital education in Europe and aims to support the adaptation of the education and training systems of Member States to the digital age. In this context, technical developments and emerging technologies are explored in relation to their role in education.

Taking as a starting point that students' learning is highly correlated with the associated tools for the scaffolding of their learning process, we hypothesise that next generation virtual worlds are expected to have a significant impact on education and training. Existing research that breaks down the characteristics of immersive and connected virtual environments indicates the potential opportunities in different age groups and subject matters. For example, Tlili et al. (2022) found that the majority of studies that explore the use of immersive technologies in education mainly focus on higher education and mostly elaborate on subject matters related to natural sciences, mathematics and engineering (53%) followed by studies on the role of immersive technologies on the arts and humanities (11%). Key et al. (2021) examine how augmented reality, lifelogging, mirror world and virtual reality can be used to enhance students' educational experiences with immersive interactive experiences, visualisations, personalization and different kinds of communication within educational settings. However, it is expected that the next generation of virtual worlds will integrate the variety of experiences that currently are connected to specific tools and modalities. The integration of cyber-physical experiences through the use of different techniques is expected to bring elements of gamification in education and to re-orient the educational goals towards skill-based learning.

A recent review study published by the European Commission (2023) summarises a set of the opportunities of eXtended reality (XR) as applied in the field of education. Based on the relevant literature, the report concludes that education can become more effective and inclusive using XR technologies. More specifically, it refers to the following opportunities:

16. https://education.ec.europa.eu/focus-topics/digital-education/action-plan.

- Companies and organisations can employ XR for procedural training in a cost-efficient way.
- XR allows training for the development of soft skills.
- Awareness-raising can be more effective using XR.
- XR allows for the expansion of creative opportunities in art and design.
- XR aids the development of computational thinking skills.
- Collaboration among students becomes more effective using XR.
- XR simulates a range of physical training.
- XR makes language learning more effective, engaging and accessible.

As mentioned by Hwang and colleagues (2022), highly social and immersive next generation virtual worlds have the potential to provide new directions for education that are different from those based purely on VR or AR. In a similar line, UNICEF has identified learning, playful development and socialisation as well as accessibility and inclusion among the opportunities that virtual worlds and the metaverse bring for children[17].

Below, we summarise key opportunities that might emerge with next generation virtual worlds in relation to education and training:

- **New forms of social learning:** humans learn through social interactions. Upcoming virtual worlds are expected to open new avenues for social communication especially in the context of interconnected learning environments which can be used to expand the current experiences of social learning. Teacher-to-student or peer-to-peer learning can take place in virtual spaces without the limitations of physical space. This context might affect the current educational curricula and increase the focus on the development of students' global citizenship skills.
- **New forms of learning through experimentation and play in cyber-physical environments:** humans learn through exploration, experimentation and play. Especially designed learning environments can offer the possibilities for project-based experimentation, creation and sharing as a new educational tool for the support of new pedagogies that will promote students' motivation and creative skills. These environments can be designed to be safe and developmentally-appropriate and to give the opportunities for personalised learning based on a student's curiosity, while at the same time allowing students to take risks in controlled environments.
- **New learning experiences and high immersion through virtualisation of connected spaces:** totally novel experiences can be offered to students that will further trigger their motivation for learning. In the example of second language learning, the aim is more than a course or a learning activity; instead, it aims to enable students to have a living environment using English for working, learning, social events and entertainment, just as if they were native English speakers. As such, two learning experiences, namely classic VR (e.g. a serious VR game with limited interaction) vs. social virtual worlds are very different in nature (Hwang et al. 2022).

17. https://www.unicef.org/globalinsight/media/3056/file/UNICEF-Innocenti-Rapid-Analysis-Metaverse-XR-and-children-2023.pdf.

While next generation virtual worlds seem to open new directions for education and training, further evidence is needed to understand the impact of this environment and related interactions on students' behaviour and learning (European Commission, 2023). In addition, further investigations are needed regarding the negative effects and the ethical considerations of those technologies in the area of education (European Commission, 2023; Charisi et al., 2022). As in every field, next generation virtual worlds should be designed in a way that respects human rights with a special caution regarding the risks related to minors. Lastly, one of the potential emerging questions is how the experiences and knowledge students may develop in virtual worlds can transfer into the physical environment and how emerging challenges will be mitigated for the best interest of every student.

2.3 Health, medicine and well-being

Virtual worlds and related eXtended reality (XR) experiences offer many opportunities, both for healthcare professionals and patients (European Commission, 2023). In the following we will discuss the most relevant ones.

Surgeons are among the healthcare professionals that are likely to benefit the most from such experiences, which have the potential to help **improve their performance during surgeries** and reduce human errors (Barteit et al., 2021; Chan et al., 2021). First, XR could enhance pre-operative planning, as the ability to view in 3D may help surgeons or radiologists to assess a patient's condition more accurately before undertaking a surgical procedure (Wellens et al., 2019). Second, they might be used in real-time as well. For instance, head-mounted AR displays allow overlaying virtual contents onto the actual anatomy of the patient while they are on the surgical table, eliminating the need for external monitors, reducing context switching and associated cognitive load and errors (Elmi-Terander et al., 2018). Furthermore, hands-free image displaying/capturing is especially beneficial during surgery to maintain sterility and avoid infections (Shluzas et al., 2016), and can also be applied in extreme conditions, such as in emergency surgeries, where less experienced surgeons can be guided remotely by more expert colleagues (Andersen et al., 2017).

Virtual environments might also benefit **medical analysis and diagnosis**. Improved high-resolution 3D microscopic images of patients' anatomy can enable a better understanding of data and diagnostics, leading to more accurate treatments (Goo et al., 2020; Riley-Missouri, 2019). Patients can be diagnosed while observing them in virtual environments. For example, VR devices can help to tackle the difficulties of testing human visual conditions, by providing a mechanism to reliably assess the core visual functions with standardised stimuli (Foerster et al., 2016; Panachakel et al., 2020). The diagnosis of mental health, neurological and cognitive disorders are particularly promising. Interactive virtual environments offer a safe platform to recreate real-life situations in which the behaviour and reactions of patients can be observed and treated (García-Betances et al., 2015). Both VR and XR have already been used to diagnose and/or treat addictions, phobias, social anxiety, post-traumatic stress, psychosis, schizophrenia, attention-deficit or hyperactivity disorders, autism, eating disorders, and obsessive-compulsive disorders, Alzheimer's and Parkinson's disease (Cogné et al., 2017; Segawa et al., 2020).

As in other fields (see Section 2.2 'Education and training') virtual worlds open the door to **enhanced training of medical skills** (Logeswaran et al., 2021). For example, XR gives surgical trainees the opportunity to gain realistic experience in a 3D operating room, as well as creating opportunities to study 3D models of human organs (Ayoub et al., 2019; Kordali, 2021). It allows to practise real-life clinical procedures without risking patients' safety. Furthermore, XR in healthcare education has proven to enhance privacy and reduce embarrassment while learning, as students can practise on virtual patients (Saab et al., 2021). Learning through XR is not only beneficial for healthcare professionals, but also for patients and caregivers. XR demonstrations of medical procedures offer patients greater awareness, confidence and health literacy, which leads to better doctor-patient relationships and better-informed decisions (e.g. when giving consent for a surgical procedure) (Kordali, 2021; Perin et al., 2021). Caregivers often experience psychological distress due to the illness of a family member. XR can be used to simulate the feeling of living with a certain medical condition (e.g. dementia, visual impairment) and improve empathy in caregivers (Jones et al., 2020).

Regarding **therapies**, immersive experiences have demonstrated the ability to alleviate acute and chronic pain such as that associated with burns, phantom limb and cancer (Cieślik et al., 2020). VR applications distract and entertain, blocking out noises from the physical world which may result in patients perceiving less pain (Jeffs et al., 2014). **Exposure therapy** is a well-known use of VR in the treatment of mental health disorders with great benefits for anxiety, eating disorders, substance use disorder and post-traumatic stress disorder. It involves gradual and repeated exposure to feared stimuli, with resultant changes in the patient's cognitions, behaviours, emotional and physical responses (Boeldt et al., 2019). Similarly, XR interventions can be useful for people with neurological conditions, such as neurodevelopmental disorders and dementia, and persons recovering after a stroke or a traumatic brain injury. XR can become a tool for cognitive rehabilitation, a form of non-pharmacological therapy intended to improve everyday memory and motor/language functions (García-Betances et al., 2015). Virtual environments could evoke sensations or illusions, activating corresponding neural circuits and facilitating neural plasticity (Cao et al., 2021). XR also offers an interactive mean to train patients with prosthetics. For example, amputee patients with new leg prosthetics can train in locomotion in a XR environment, before using the prosthetics at home or outdoors (Porras, 2021). In turn, AR technology provides a way to help persons with visual impairments with navigation and obstacle avoidance. With the help of machine learning, a camera built into wearable devices can be used to detect surrounding objects, read out text, recognise familiar faces, etc. Eye-tracking technology has also been successfully incorporated into AR devices to help individuals with severe physical impairments control electric wheelchairs with gaze (Bona et al., 2021).

Finally, one of the most popular uses of XR technologies is to encourage a healthy lifestyle and improve the physical and psychological/emotional well-being of the general population. XR applications can improve psychological and emotional well-being by helping people to relax, relieve stress and anxiety, or simply improve their mood. VR systems may also help in countering loneliness and depression, improving connectedness and stimulating brain activity among older adults (Lin et al., 2018). XR can encourage physical activity, especially since some people find it hard to find the time or motivation to get the recommended amount of exercise every day. For instance, overweight children are more willing to walk in a virtual environment than they are in traditional form (Bond et al., 2021).

2.4 Manufacturing

The advent of virtual worlds within the Industry 4.0 ecosystem is poised to offer an abundance of opportunities for businesses, leading to enhanced industrial processes, the generation of new jobs and economic growth. For instance, as detailed in a 2022 market research report by The Brainy Insights[18], the global metaverses market is projected to experience significant expansion, growing from €36.26 billion in 2021 to €918.23 billion by 2030.

The industrial applications emerging from next generation virtual worlds are expected to extend across various sectors, including logistics, engineering and manufacturing, and are already providing real world benefits for companies (Leng et al., 2021). This comprehensive integration leads to improvements in design and simulation processes, augmented operational

18. Virtual Worlds fit for people | Shaping Europe's digital future (europa.eu).

efficiency (e.g., predictive maintenance, quality control, and supply chain management), and facilitates virtual training (Hupont et al., 2015) and remote collaboration. Moreover, these applications may contribute to a more sustainable European industry by promoting resource optimization and enabling innovative business models.

Digital twinning techniques are also being deployed in industrial settings. Digital twins are virtual replicas of physical objects or systems, and can be used to optimise product design, improve manufacturing processes, and enhance efficiency (Jiang et al., 2021). By integrating real-time data (e.g. from cyber-physical systems, the Internet of things) and advanced analytics (e.g. artificial intelligence, big data), digital twins enable proactive maintenance, monitoring, performance optimisation, and simulation-based decision-making, facilitating cost savings and increased productivity (Yao et al., 2022).

To harness the potential of these technologies of next generation virtual worlds, it is crucial for businesses to innovate, reshape their business models, and deliver customisable, personalised experiences to consumers. Supporting the development and growth of industrial virtual worlds is essential for fostering new business opportunities. Simultaneously, it is vital to ensure the widespread adoption of related technologies across industrial ecosystems, as this will drive efficiency gains and aid small and medium-sized enterprises (SMEs) in their pursuit of sustainability.

Future initiatives should bolster industrial virtual worlds by cultivating a market for emerging solution providers and raising awareness among industrial users about the potential of these transformative technologies. Continued engagement in ongoing dialogue with industry stakeholders will be key to ensuring that European companies can fully capitalise on open opportunities.

2.5 Public sector[19]

The implications of virtual worlds on the **public sector** and their role in public governance deserve particular consideration - in general and when it comes to the delivery of public services. Whereas in the real world, public sector organisations operate in public spaces, the situation changes when their presence extends into virtual worlds. Concepts of ownership, responsibility and accountability need to be re-assessed, especially considering the roles that public and private institutions might play in relation to the underlying infrastructures, enabling platforms

19. The content of this section originated from the initial discussions of the IFRAG, and was elaborated to match the scope of this report. We are grateful for the initial texts provided by our colleagues Andrea Halmos, Dylan Odini and Jose Fernandez-Villacanas (Pepe).

and applications. The mandate of the public sector to serve the public good, and the obligation to follow the rule of law need to be projected and extended into virtual worlds and hybrid realities.

Public services (e.g. in the domains of health, education, energy, transportation, and public administration) are services offered to create public value and to serve those members of the public that are in need of such services, without discrimination. Here, public value is considered as the total societal value that cannot be monopolised by individuals but is shared by all actors in society and is the outcome of all resource allocation decisions[20].

Public services that are accessible online (e.g. via virtual worlds) are also called digital public services. Following the eGovernment Action Plan 2016-2020[21], the Tallinn Ministerial Declaration on eGovernment[22] and the Berlin Declaration on Digital Society and Value-based Digital Government[23], these digital public services should also respect a set of principles. Those principles include, among others, human-centricity (people are empowered to decide their public service access and consumption, and the public services should serve people with minimised burden on them), the once-only principle (data that is requested from citizens or businesses by a public service once should not have to be requested again), and privacy-by-design (privacy is taken into account throughout the entire life-cycle of any public service).

According to the European Interoperability Framework[24], a *European public service* is any public sector service exposed to a cross-border dimension and supplied by public administrations, either to one another or to businesses and citizens in the EU. These services are characterised by legal, organisational, semantic and technical interoperability. If we consider the European Digital Rights and Principles[25] to prevail for the coming decades, we need to ensure that as technology evolves, European public services will remain 'seamless, secure and interoperable across the EU, designed to meet people's needs in an effective manner'.

The immediate impact of virtual worlds will most likely just provide an advanced delivery channel (an additional way of providing online access) for digital public services. Those services will be characterised by personalised

20. A vision for public services | Shaping Europe's digital future (europa.eu).
21. eGovernment Action Plan | Shaping Europe's digital future (europa.eu).
22. Ministerial Declaration on eGovernment - the Tallinn Declaration | Shaping Europe's digital future (europa.eu).
23. Berlin Declaration on Digital Society and Value-based Digital Government | Shaping Europe's digital future (europa.eu).

24. The New European Interoperability Framework | ISA² (europa.eu).
25. European Declaration on Digital Rights and Principles | Shaping Europe's digital future (europa.eu).

experiences tailored to an individual and the data to analyse patterns and behaviour changes. These developments will go hand-in-hand with already ongoing evolutions of public services to become more pro-active and transparent for the perceiving citizens or businesses. As the Web 4.0 capabilities improve with sensor technologies, these new types of data will improve the understanding of context, preferences and user needs, combining the physical and virtual worlds. In the long-run, as virtual worlds will eventually provide fully immersive experiences, we may sooner or later see complete socio-economic activities in the virtual worlds; buying property, socialising, running businesses, etc., which could lead to a completely new paradigm of public service delivery.

A particular facet of future virtual worlds that are highly relevant for the public sector are Citiverses[26]. A Citiverse facilitates policy-making with citizen participation using AR/VR and can be used in multiple ways, for example, to increase citizens' participation in decision-making, by letting them experience in the Citiverse different policy options; to model the possible consequences of certain policy choices; and to gather behavioural insights on how citizens would interact with changes in their local environment. A Citiverse can be useful at different scales, ranging from immersive visualisation of cities/communities for a specific short-term check, to more long-term visualisation and simulation of complex policy decisions that affect several interwoven sectors. All cases can potentially be used to include the participation of the citizens, getting their reactions as individuals or groups (with the emergence of collective opinions, strategies and norms), and even automatically reading their decisions via brain-interfacing technology.

An early example of delivering public services in the virtual worlds is the city of Seoul's plan to open a 'Metaverse 120 Centre'[27], which will allow civil servants to provide consultation in the form of their avatars. Residents will virtually access a city hall for any government service, including filing a civil complaint or speaking to the city's Mayor, using AR/VR technologies. Within the EU, Guichet.lu recently became available in a district of Luxembourg Megaverse, providing convenient access to administrative services related to Luxembourg[28].

With these emerging trends and existing legal and rights-based frameworks, many open questions remain, for example:

26. The European Commission is currently offering funding opportunities under the Digital Europe Programme (DIGITAL) to develop the Citiverse, and the first related info day was held on 23th of May 2023, https://digital-strategy.ec.europa.eu/en/events/info-day-developing-citiverse.
27. http://english.seoul.go.kr/seoul-first-local-govt-to-start-new-concept-public-service-with-metaverse-platform/.
28. https://luxembourg-megaverse.com/23052301/index.html.

- How do you deliver digital public services in potentially non-public spaces?
- Which jurisdiction would apply, that of the provider, the user, or the public body?
- How can we ensure the 'once-only-principle' in virtual worlds?
- Will users be able to 'teleport' from one virtual world to another carrying with them the data generated using public services?
- Given that virtual worlds will require high-speed internet connection and expensive equipment that is not available to all, how can we avoid the risk of amplifying the digital divide and ensure that all can access basic public services?
- How can we ensure that principles such as empowerment and participation exist in the digital public space, as well as foster a human centric digital transformation?

Related discussions are currently taking place in the above mentioned Expert Group Innovation Friendly Regulations Advisory Group (IFRAG), especially addressing (in the context of the EU) whether the existing body of EU legislation (including recent changes) is sufficient to deal with the emerging scenarios, and if there are regulatory loopholes to be taken into account. A report is expected in early 2024.

2.6 Other fields

Next generation virtual worlds will offer a groundbreaking wave of opportunities for education, medicine, manufacturing and public services, but many other fields and sectors might also greatly benefit from their adoption. In the following we elaborate on some areas we deem particularly promising because of their potential socio-economic impact:

Transport, hospitality and tourism. Virtual worlds have the potential to democratise travel, hospitality and tourism opportunities by breaking down geographical and socio-economic barriers and allowing individuals who may not have the means to physically visit geographically distant sites to experience them virtually (Gursoy et al., 2022). Although virtual worlds will not replace real-life hospitality and tourism experiences, they might modify the ways in which we consume related products and services (Go et al., 2023). For instance, travellers can plan more effectively a future trip by first exploring virtual representations of hotels and destinations, checking out accommodations, amenities and even interacting with virtual guides. This can help them make informed decisions and have a better understanding of what to expect before embarking on their journey. An additional benefit is that virtual tourism might help fighting environmental issues and concerns about the sustainability of popular mass tourism destinations (Go et al., 2023). Traveling and attending meetings, concerts, visiting museums, etc. in virtual worlds can contribute to sustainable tourism by reducing the carbon footprint associated with physical travel (cf. Section 3.1.4 'Sustainability'). Virtual travel experiences can provide an alternative for individuals who want to explore different destinations without contributing to greenhouse gas emissions. This can help mitigate the environmental impact of tourism and promote more eco-friendly practices.

Cultural heritage. The potential of virtual worlds to preserve and transform cultural heritage has been widely acknowledged (Magnenat-Thalmann et al., 2005; Cecotti, 2022). Virtual worlsd can serve as a vast digital repository allowing for the preservation and access to artworks, historical sites and other cultural elements. People from all over the world can virtually explore and experience cultural heritage that may be physically inaccessible or at risk of deterioration (Khorloo et al., 2022). It can also provide an immersive and interactive way to learn about different cultures and their history. Next generation virtual worlds will offer means of enhanced interactivity, such as engaging with virtual representations of historical figures, participation in re-enactments of significant events (Figure 6 left), or even simulation of experiences from different time periods. This interactivity enhances the educational and experiential aspects of cultural heritage, making it more engaging and memorable for users. Virtual worlds can also facilitate cross-cultural interactions and collaborations: people from different parts of the world might come together in virtual spaces to share and celebrate their cultural heritage, fostering understanding and appreciation for diverse cultures. Artists, historians, and experts can collaborate on virtual projects to recreate lost or damaged cultural artifacts, bringing together their knowledge and expertise. Augmented reality deserves particular attention, as it offers a way to the access cultural heritage content and information in real-world locations through AR overlays, providing a layered experience that blends the virtual and physical environments (Allal-Chérif, 2022). This integration can enhance site visits to historical landmarks and museums, providing contextual information and interactive elements (Buhalis et al., 2022). An interesting recent initiative for virtual cultural heritage is 'Time Machine Europe'[29], that focuses on the creation of AR/VR applications to simulate spatio-temporal 4D reconstructions with the aim of mapping the European social, cultural and geographical evolution across times.

29. Time Machine Europe. Available at: https://www.timemachine.eu/about-us/.

Figure 6

Left – Virtual recreation of the cultural experience of the pilar festivities in Zaragoza (Spain) during the pandemic period by the company IMASCONO[30]. Right - Virtual clothing for avatars in the Adidas Metaverse shop[31].

30. https://imascono.com/proyectos/ofrenda-de-flores-virtual-ayuntamiento-de-zaragoza/
31. https://www.adidas.com/metaverse/

Labour market. Virtual worlds can bring remote work to a whole new level (Popescu et al., 2022a). By creating virtual workspaces, individuals can collaborate and communicate with colleagues worldwide, opening new possibilities for global talent acquisition and providing more flexibility in terms of work-life balance. Additionally, a new range of skilled professionals will be required to design, develop and maintain virtual environments, as well as to create the assets and experiences within them. This could lead to the emergence of new job roles such as virtual architects, virtual designers or virtual event planners. Another benefit for the labour market is likely to come in the form of enhanced collaboration and creativity. For example, remote teams can boost creativity and innovation by sharing virtual spaces for brainstorming, ideation and prototyping. This will result in new virtual economies allowing individuals to monetise their creativity and skills in virtual environments, leading to the emergence of new business models and entrepreneurial ventures (Barrera et al., 2023). It is finally important to emphasise that virtual work has the potential to break down physical barriers and create more inclusive opportunities, e.g., for individuals with disabilities, limited mobility and neurodiversity (Brayou et al., 2022).

Retail and customer experiences. New highly immersive and social virtual shopping experiences are likely to emerge. In them, customers will be able to explore virtual stores, try on virtual clothing or accessories (both for physical persons and avatars – Figure 6 right), and interact with products before making a purchase (Popescu et al., 2022b). Additionally, customers could engage in social shopping experiences by virtually meeting with friends, family or even strangers while browsing products, sharing opinions and seeking advice (Billewar et al., 2022). This social aspect could simulate the real-world shopping experience. Enhanced product visualisation is another benefit, allowing customers to see products in 3D, explore different angles and interact with virtual models or simulations. This can help customers make more informed purchase decisions by giving them a better understanding of the products' features, functionality and aesthetics. Brands can also create virtual experiences that go beyond traditional retail environments. They can host virtual events, launch new products or offer exclusive content and promotions. These immersive brand experiences can deepen customer engagement and foster a stronger connection between customers and brands.

Entertainment. Future users of virtual worlds will be able to participate and engage in VR/AR games, concerts, movies, virtual parties, sport events and many other events. They will be empowered to create and share their own content, being able to contribute to the development of virtual worlds, design their own games or experiences, and share them with others. This democratisation of content creation allows for a diverse range of entertainment options and encourages creative expression. The interconnection of different platforms and devices will allow seamless integration across various media and entertainment channels. For example, a movie could have associated tie-in games, merchandising and interactive experiences, creating a more holistic entertainment ecosystem and opening new avenues for monetisation (Bonales-Daimiel, 2023). Again, virtual worlds also have the potential to improve accessibility in entertainment for people with physical disabilities or those living in remote areas, who will be able to access and participate in entertainment experiences that were previously limited to certain geographical locations or physical capabilities. Finally, cross-cultural exchanges enabling users from different regions and backgrounds to come together and share their cultures and perspectives will lead to the creation of diverse and inclusive entertainment content that appeals to a global audience.

Financial sector. If virtual worlds become widely adopted, financial service providers may be willing to jump on this emerging trend to exploit potential benefits and opportunities as a large portion of products and services might be moved to virtual worlds. Financial institutions could provide basic banking services in virtual worlds, such as lending to people to finance virtual goods, and at the same time banks could exploit alternative ways to connect with their customers. It is a fact that physical bank branches are closing down and younger generations might be reluctant to do things the old way, meaning going to a physical place or call a real person to make an appointment. The possibility to establish digital bank branches and offer customer services with real-time virtual content could strengthen the connections with their customers. Being already familiar with how technologies operate and living online most of their life, younger generations might feel more at ease in engaging with financial services in immersive digital environments. With 47% of retail bankers believing that about 20% of their customers will use virtual and augmented reality as an alternative channel to their daily transactions[32] it won't be long until other global banks will move into virtual reality marking the beginning of a new way of banking. Interestingly, BNP Paribas[33] launched few years ago (in 2017) a virtual reality app allowing retail banking users to access their account activity in a virtual environment, and recently HSBC[34] entered the metaverses by investing in a virtual real estate in SandBox.

32. https://thefinancialbrand.com/news/banking-trends-strategies/banking-future-projections-payments-technology-crypto-branches-competition-transformation-esg-124991/.
33. https://group.bnpparibas/en/press-release/bnp-paribas-contributing-development-virtual-reality.
34. https://www.reuters.com/business/finance/hsbc-buys-virtual-plot-land-digital-push-2022-03-17/.

3. Challenges

3.1 Societal challenges

While we acknowledge that the new generation of virtual worlds will bring unique opportunities for developments from multiple perspectives, as described in Section 2, the research community and civil society can already observe several emerging challenges at the societal level.

For the mitigation of the emerging challenges, the European Commission proposed a set of 'Digital rights and principles'[35], which function as an inter-institutional declaration that will complement existing rights, such as those of the Charter of Fundamental Rights of the EU, taking into account developments of the digital decade.

35. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en

Box 1

Digital Rights and Principles for the Digital Decade[36].

Putting people at the centre of the digital transformation: Digital technologies should protect people's rights, support democracy, and ensure that all digital players act responsibly and safely. The EU promotes these values across the world.

Solidarity and inclusion: Technology should unite, not divide, people. Everyone should have access to the internet, to digital skills, to digital public services and to fair working conditions.

Freedom of choice: People should benefit from a fair online environment, be safe from illegal and harmful content, and be empowered when they interact with new and evolving technologies like artificial intelligence.

Participation in the digital public space: Citizens should be able to engage in the democratic process at all levels and have control over their own data.

Safety, security and empowerment: The digital environment should be safe and secure. All users, from childhood to old age, should be empowered and protected.

Sustainablity: Digital devices should support sustainability and the green transition. People need to know about the environmental impact and energy consumption of their devices.

36. European Declaration on Digital Rights and Principles for the Digital Decade COM(2022) 28 final.

In this context, the European Commission organised in the first semester of 2023 'The European Citizens' Panel on Virtual Worlds'[37] which included a representative group of EU citizens at the centre of a

37. European Citizens' Panel on Virtual Worlds. Available at: https://citizens.ec.europa.eu/virtual-worlds-panel_en.

participatory process to reflect and develop recommendations on how to navigate safely, fairly and with trust in next generation virtual worlds. The Citizens' Panel shaped a set of guiding principles building on the European Declaration on Digital Rights and Principles, covering the eight fundamental dimensions depicted in Table 1[38].

1. Freedom of choice	2. Sustainability
The use of virtual worlds is a free choice for individuals – without disadvantages for those who are not participating.	The set-up of virtual worlds, implying an unprecedented use of interaction devices, servers, clouds and other computational infrastructures, is environmentally friendly.
3. Human centered	**4. Health**
Technological development and regulation of virtual worlds are serving and respecting the needs, rights and expectations of users.	Physical and mental human health as a fundamental pillar for the development and use of virtual worlds.
5. Education & Literacy	**6. Safety & Security**
Education, awareness-raising and skills on how to use virtual worlds are put in the centre of virtual worlds' development.	European citizens need to be kept safe and secure, including the protection of data and preventing manipulation and theft.
7. Transparency	**8. Inclusion**
1) Transparent regulations are protecting people, their personal data, and psychological and physical health. 2) The use of data (by third parties) is transparent.	Equal accessibility for all citizens is granted – regardless of age, income, skills, technological availability, country etc.

Table 1

Eight values and principles for desirable and fair next generation virtual worlds agreed on the large-scale citizens' panel organised by the European Commission in the first semester of 2023.

Guided by the above-mentioned principles, we review the current literature, and we elaborate on the anticipated possible societal challenges in relation to next generation virtual worlds, human rights, human health, cognition and psychology and the specific sectors. We conclude this section with the emerging challenges in terms of sustainability.

3.1.1 Ethics and human rights

Threats to human agency can lead to extreme surveillance capitalism (private sector) or government surveillance (authoritarian governments) (Anderson et al. 2022). Also amplified discrimination, changes/amplification in social order (inequalities), digital divides/

38. European Citizens' Panel on Virtual Worlds *Developing fair and desirable European Virtual Worlds*, Panel output https://citizens.ec.europa.eu/system/files/2023-04/Recommendations_Citizen%20Panel%20Virtual%20Worlds_0.pdf.

gaps, hate speech, harassment, misinformation and generally human rights need to be preserved online as in real life. There is a need for 'trustworthy virtual worlds'. It should be noted that it is beyond the scope of this report to thoroughly elaborate on human rights in the context of these new technological advances though it will form part of our future work. Below we provide some examples to illustrate emerging challenges in relation to human rights in the context of next generation virtual worlds.

Freedom of choice: as discussed in Section 2.1, the immersivity of the systems in next generation virtual worlds and the interconnectivity between virtual and physical environments is expected to impact the ways humans interact with machines and with each other. Perception systems are becoming increasingly capable of perceiving (and understanding) human behaviour by combining perception through different modalities. As machines can detect nuances of human behaviour in an increasingly more accurate way, humans might become more vulnerable to being affected by machines and controlled in their decision-making processes. In addition, the multiple modalities and the multifaceted nature of interactions in next generation of virtual worlds are expected to be a powerful tool for influencing and steering human decision-making towards desired directions. These developments might put one of the most fundamental human rights at risk, that of freedom of choice and free will particularly for vulnerable populations such as minors. One area of application in which this risk might be widely spread will be advertising, which will not be a distinct activity but will appear in the form of immersive experiences.

Privacy: with the advent of next generation virtual worlds, privacy and ownership issues seem to take on different forms than existing ones in current online settings. Invasive collection of personal and sensitive data and ubiquitous surveillance from public or private spaces can occur within both the virtual and the physical world. While current studies focus on how machines capture detailed information about the user's facial features, vocal qualities and eye motions along with information about the user's environment, a recent study by Nair et al. (2023) shows that the perception of human motion by AI systems based on wearables or other devices can result in the identification of the user in ways similar to fingerprints. The research analysed more than 2.5 million VR data recordings from more than 50,000 players of the Beat Saber app and found that individual users could be uniquely identified with more than 94% accuracy using only 100 seconds of motion data. In addition, motion data can be used to accurately infer a number of specific personal characteristics about users, including their height, handedness and gender. This means that with next generation virtual worlds the challenge of human privacy protection will become a complex issue to solve.

Safety and security: the protection of users' safety and security becomes challenging in the context of next generation virtual worlds. Abusive behaviours are not only limited to communication through text but they also appear with the use of multimodal features such as synchronous voice chat, heightened feelings of presence and embodiment, and avatar movements that can feel like violations of personal space (such as simulated touching or grabbing). Research shows that after training perceptual sensitivity in the virtual environments approached the erformance level of physical environments in diagnosis and training settings (Hupont et al., 2015). This means that experiences in immersive worlds might be perceived in a similar way as experiences in physical environments and consequently, perceived threats in virtual spaces may be interpreted by the user's brain as actual threats. Another example of emerging risks regarding safety and security in next generation virtual worlds is the new types of phishing techniques, which may become more sophisticated. In virtual worlds, users create their avatars and deal with other users' avatars representing actual humans. Pictures or 3D models are used to build avatars based on real or preferred appearance. These avatars can be easily copied and used in phishing like avatar acting like users' friends or family in the virtual space. Lastly, similar to the 'dark web', since interconnected virtual worlds are open to everyone, malicious users can create a so called 'darkverse' within the virtual worlds. The detection of illegal or criminal activities by law enforcement agencies will be more challenging because of the pseudo-physical presence of the users.

Accessibility and inclusion: ensuring inclusion, representation of people's diversity, accessibility to resources and services are among the fundamental human rights in the digital environments. In the design of next generation virtual worlds, or metaverses, a recent study found that potential users of virtual worlds require the equal representation of users with different ages, cultures, abilites, genders, languages and religions (Zallio et al., 2022). However, accessibility and inclusion should be accompanied by certain design decisions that respect the characteristics of specific users. For example, the design of virtual environments that are meant for or have the potential to be accessed by children, should integrate special safety measure for this specific population. The scientific community is becoming increasingly aware of the need to develop methods for the design of structures and content for next generation virtual worlds that are inclusive to people with physical and intellectual disabilities, and for interactions that minimise disadvantage (Parker et al., 2023).

To conclude, we observe that next generation virtual worlds will come with certain challenges regarding the protection of human rights, such as freedom of expression, safety and security, accessibility and inclusion. However, the psychological aspects of immersive advanced technologies and the blending of the physical and cyber worlds bring important distinctions and new challenges that need further considerations regarding the protection of human rights.

3.1.2 Challenges on human health, cognition and psychology

As mentioned in Section 2.1, the very nature of the next generation virtual worlds can have a powerful impact on human behaviour. Depending on the design decision of the applications in parallel with the positive effects of immersive technologies, there are indications of negative effects on human health, cognition and psychology. These might include effects of isolation from the real world, loneliness, digital twins connected to real persons, addiction and impact on vulnerable people (particularly children and teens), consequences for human intimacy and connection, changing morals, and cyberbullying[39]. While we can see certain changes in human behaviour, there is a lack of research in terms of the actual impact of next generation virtual worlds on human brain in terms of its function and structure, which would require further researh especial in long-term settings (Korte, 2022).

According to Gibson's theory of affordances, human behaviour and the corresponding psychological accounts depend on our interaction with the surrounding environment, our everyday experiences and the social interactions with other humans. The introduction of interconnected digital experiences, in the context of the next generation virtual worlds and their integration in people's everyday lives in a way that the movement between the virtual and physical world becomes increasingly seamless might transform human behaviour and psychology in unexpected ways. Research in the area of human behaviour and psychology already indicates that behaviours related to the virtual world affect those in the physical world and vice versa (Henz , 2022). In immersive interconnected environments with sustained long-term interaction, there is the risk that the user experiences difficulties in separating the virtual self and the objects of interaction. While effects of this powerful experience might be effective for certain contexts, like therapeutic experiences, it can prove more problematic in other virtual experiences, like gaming that involves committing acts of violence.

Human immersion within virtual environments mobilises multiple (targeted) channels of perception,

39. https://www.unicef.org/globalinsight/media/3056/file/UNICEF-Innocenti-Rapid-Analysis-Metaverse-XR-and-children-2023.pdf.

in a similar way as when navigating in the physical world. The fact that humans have evolved to trust our senses increases the risks of a negative impact on human health, cognition and psychology in not appropriately and well-designed virtual worlds. Oh et al. (2023) found that the social presence young users experience in virtual worlds predicts their social interactions and a general feeling of loneliness. In this context, there are aspects that require special consideration when designing virtual spaces for the minimisation of negative effects on human health, cognition and psychology. Some areas where we anticipate that next generation virtual worlds might bring certain challenges in terms of human psychology include the following:

- **Human cognition:** decision-making in the context of a fractured view of reality.
- **Social interaction:** digital escapism, cyberbullying through the use of avatars.
- **Affective engagement:** avatar-mediated communication, visually expressing emotions through avatars in VR (Bernal et al., 2017).
- **Human neuroscience** in the form of brain-to-brain individual attunement: VR and AR activate the same brain-to-brain individual attunement occurring during natural social interactions affecting empathy and the recognition of intentions (Ventura et al., 2020).
- **Self-awareness and perceived reality:** disconnection from the physical reality and construction of new types of realities.

In addition, issues of reading identity can impact people, especially teenagers who do not have yet mature cognition. A person's digital twin or virtual avatar may create a mismatch between the real identity of the user and the virtual world, both in appearance and internal mental status. Increased virtual involvement may blur the boundaries of both worlds, and malicious ideology may be easily instilled, such as bias, discrimination, violence, and even viral propaganda (Huang et al., 2023).

While research on the impact of next generation virtual worlds on human health, cognition and psychology is still in its infancy, there are indicators of the powerful nature of this technology which requires special considerations in the design for the minimization of negative effects through multidisciplinary approaches between designers, developers and specialists in human development. Towars this direction, further research is required in terms of the effects of next generation virtual worlds on human behaviour and cognition, especially with long-term studies.

3.1.3 Challenges in the field of education

While the field of education appears to be a promising area that can take advantage of the opportunities that will emerge from the advent of the next generation virtual worlds (see Section 2.2 'Education and training'), at the same time, the integration of immersive technology in education, especially at lower levels of primary and secondary education presents certain challenges. As described in previous sections, technical and societal challenges apply in this field too. For example, the challenges with the technical implementation might create inequalities and increase the gap among schools. The high computational requirements of next generation virtual worlds are also a technical challenge. If education is introduced into next generation virtual worlds, then the simulation and rendering of teaching scenes, the interaction between teacher and learner, and human-computer interaction are huge computational quantities, which pose major challenges to the throughput of the network and the computing power of cloud computing. Tlili et al (2022) indicate a set of education-specific challenges as they appear in the current literature. These challenges refer primarily to technological challenges such as network issues or the establishment of common rules among schools for digital coexistence. However pedagogical challenges, such as lack of pedagogical background in the design of activities in educational metaverses and the need for specific training for educators are urgent challenges that need consideration from education specialists. Other challenges include the cost for the development of the infrastructure of this technology and the current lack of robust analysis about the risks and the benefits for the educational community.

Even more importantly, with next generation virtual worlds, it is expected that the nature of education will no longer be limited to the physical classroom but will expand across various interconnected physical and virtual environments and might be blended with the entertainment or other activities. While this has a significant positive potential for the motivation of students and for new forms of learning, there are challenges that are connected to the need for a protected educational environment that proctects students' rights, such as the right of students not to share their personal data and to be forgotten, an element that is connected to students' data protection and privacy but also to safety for local off-line experimentation that a physical classroom provides. Furthermore, while virtual spaces have the potential to connect students from different countries and cultures in a synchronous way, which can be catalytic for the development of students' skills, this will raise issues of students' safety and security in cyber space. Thus, special measures are needed for their protection. Lastly the role of the educator might need to be reconsidered since educators could provide catalytic contributions for pedagogically-grounded content for the educational virtual worlds for the best interest of the students.

3.1.4 Sustainability

On the one hand, virtual worlds have the potential to positively impact different Sustainable Development Goals (SDGs)[40]. They could contribute to SDGs 'Climate Action' and 'Affordable and Clean Energy' by reducing

40. United Nation's Sustainable Development Goals: https://sdgs.un.org/es/goals.

the carbon footprint in several ways. They might narrow the frequency of physical commuting (e.g. through flight, train, personal transport) for meetings or touristic activities (Go & Kang, 2023). This would additionally contribute to the enhancement of work productivity by eliminating travel and other related resource and time consumption. Industrial XR applications, particularly digital twins, provide a valuable means to foster the 'Industry, Innovation and Infrastructure' SDG. Industrial XR has been successfully used to simulate different virtual scenarios in factories by Renault and PepsiCo to assess the impact on energy consumption, and to optimise production and supply chains (Kshetri & Dwivedi, 2023). Finally, as mentioned in previous sections, virtual worlds offer potential benefits to the SDGs 'Good Health and Well-Being' (cf. Section 2.3 'Health, Medicine and Well-Being') and 'Quality Education' (cf. Section 2.2 'Education and Training').

On the other hand, next generation virtual worlds risk negatively affecting key SDGs (Jauhiainen et al., 2023), and action should be taken to minimise this impact starting at the earliest stages of conception and development. For instance, the SDG 'Affordable and Clean Energy' could in turn be challenged. Virtual worlds will require energy-intensive computing and high broadband speed for real-time rendering, handling interactions with millions of simultaneous users, as well as the operation of servers and data centres (cf. Section 3.2.3 'Computational infrastructure'). If not managed appropriately and efficiently, this could lead to a significant increase in power consumption, primarily from non-renewable sources of energy (Dwivedi et al., 2022).

There is indeed a need to carefully consider that Web 3.0 and XR/AR/VR technologies might evolve at a much faster pace than the creation of clean, non-fossil energy. If current clean and non-fossil energy sources fail to keep up with the increasing energy demands of future virtual worlds, there could be a surge in carbon emissions which could exacerbate climate change (Liu et al, 2023). It could also provoke an imbalance in energy availability. The increased demand for energy from Web 3.0 applications may strain existing energy infrastructure, potentially leading to energy shortages or supply disruptions. Such inefficiencies could slow down the overall transition to a more sustainable energy system. The rapid evolution of these technologies should ideally come together with investments in the clean energy sector, particularly in the form of research and innovation on new renewable energy sources, energy storage solutions and energy-efficient technologies (Jamshidi et al., 2023), which is aligned with SDG 'Industry, Innovation and Infrastructure'.

In addition, as virtual worlds expand, so will electronic waste (Palak et al., 2023). There may be a rise in demand for hardware devices such as VR headsets, IoT devices, graphic cards and high-performance workstations. The production, disposal and recycling of these devices poses environmental challenges of utmost importance, negatively impacting the SDG 'Responsible Consumption and Production'.

Besides energy issues, the SDG 'Reduced Inequalities' could also be at high risk (De Giovanni, 2023). While virtual worlds might offer, e.g., more educational opportunities for all, this could be a dual-edged sword (Korkmaz et al., 2022). It must be considered that their widespread adoption may exacerbate existing inequalities in terms of access to technology and the internet. Ensuring equitable access to virtual worlds for all individuals regardless of their economic or geographical circumstances is essential to avoid creating a new form of exclusion and injustice.

3.2 Technical challenges

3.2.1 New technologies

Societal changes related to the next generation virtual worlds will inevitably come hand in hand with technological changes and emerging new technologies. Although there is some uncertainty as to how future virtual worlds will materialise from the technical perspective in the coming years, we can already anticipate some key technologies that are likely to be central to their implementation and will reshape the way we interact with them. Some will emerge as totally novel technologies, while others will require an effort to adapt from existing ones. In the following, we identify five technological fields that will play an essential role in the future development of virtual worlds:

- **Computer graphics** will allow the creation of increasingly immersive virtual, augmented and eXtended reality experiences and environments (Basdevant et al., 2022). Graphic engines will be used to animate expressive avatars in real-time, to facilitate the creation and navigation of original virtual worlds, to faithfully simulate the laws of physics (e.g. gravity, fluids, thermodynamics, natural phenomena), to develop data formats and compression methods for three-dimensional scenes, and to develop novel forms of visualisations such as 3D holograms.
- **Human-Machine Interaction (HMI) and Internet of things (IoT) devices** will be used to improve the way we perceive and interact with a virtual space from the physical world, and vice-versa. Specialised HMI hardware will include VR/AR headsets, haptic feedback devices, Brain-Computer Interfaces (BCIs) and motion capture systems. These interaction devices will allow for enhanced multimodal and real-time means of communication (e.g. users' avatars interacting with the environment through text, voice, gestures, motor movements, touch and even smell (Melo et al., 2020)). Similarly, IoT devices are smart connected sensors that will serve to communicate and transfer information between the real and virtual world through objects (e.g. a digital twin replica of an

industrial machine, a temperature sensor whose information is used to recreate the same weather conditions in the virtual world) (Barrera et al., 2023; Wang et al., 2022).

- **Artificial intelligence** will be needed to analyse and respond to the vast array of user interactions, data and personalized experiences created in virtual worlds. Technologies such as computer vision, machine learning and depth sensing will be essential to create realistic and immersive virtual environments, intelligent virtual agents, Non-Player Characters (NPCs) and autonomous systems within the virtual worlds (Barrera et al., 2023; Lee et al., 2021). These systems will need to understand/simulate human behaviour (e.g. actions, users' gestures, facial expressions), respond to users' inputs (e.g. in natural language), and learning and adapting over time. New forms of AI may emerge by extending existing forms to the virtual space. For instance, current *scene understanding* might evolve into *virtual scene understanding* (Park et al., 2022), current *affective computing* techniques (aiming at detecting and responding to users' emotions (Wang et al., 2022)) might evolve into *virtual affective computing* (e.g. detecting emotions from avatar data), and *generative models* might evolve into *3D generative models* to automatically generate 3D models of virtual scenes (Bautista et al., 2022).

- **Blockchain and cryptocurrencies** are likely to be the technological building blocks of a decentralized infrastructure (i.e. an infrastructure without the need of a centralised control) that will enable users to interact, buy, sell and trade virtual assets, as well as establish and enforce rules and regulations (Barrera et al., 2023; Lee et al., 2021). Blockchain would provide a trustworthy, transparent and verifiable mean of keeping a secure record of digital ownership of virtual assets (such as virtual real estate, avatars and virtual goods) which could be bought, sold or traded just like physical assets. This is particularly important for virtual economies, where users need to trust that their virtual assets and transactions are secure.

- **High-performance computing and high-speed networks** will be needed to provide the extensive computational power required by the ambitious architecture of next generation virtual worlds, which are expected to supply highly demanding functions in real-time, including visual rendering, data synchronisation, motion tracking and capturing (Ball, 2022; Duan et al., 2021). There will be a need to optimise and parallelise computations over complex and distributed architectures to minimise latency, data transfer and processor load. In this context, edge and cloud computing are likely to play a critical role in supporting the timely processing and system responses of relevant applications (Lee et al., 2021). Future mobile communications such as 5G/6G are also expected to facilitate ubiquitous services to users, making possible remote and real-time persistent connections between the real and the virtual worlds (Wang et al., 2022; Lin et al., 2022).

Nowadays the previous technological building blocks have varying levels of maturity and scalability, most of them being already present in the market in more or less sophisticated ways and scales. It is important though to understand that next generation virtual worlds will require to go a step further by handling these technologies altogether, at a very large scale and in real-time, to support the needs of millions of concurrent users each with their own unique interactions, data, virtual assets and experiences. Building a system that can handle this scale while maintaining high immersivity, low latency communications and high availability will be a significant challenge.

3.2.2 New types of data and digital contents

Users and connected devices (e.g. IoT devices) interacting, socialising and transacting in future virtual worlds will generate new types of data and contents that are likely to differ significantly and eventually extend those that can be found in current digital platforms. Below we discuss some illustrative examples and discuss their impact.

A prominent example of this possible data transition is **avatar data**. Being the representation of the user in the virtual world, avatars will generate data capturing user behaviour, actions, decisions, preferences, spending habits and interactions. For example, data on how a user interacts with objects, devices, other avatars and the virtual environment (e.g. paths they take to navigate the virtual world) could be collected and analysed. New ways of extracting **emotional data** (i.e. detecting whether the user is happy, sad, engaged, excited, etc.) could also possibly emerge from the study of avatars' behaviour. This first-hand data generated by users via avatars in virtual worlds can represent brand-new valuable information to enhance and further tailor user experiences.

Nowadays, the data generated by individual users in social networks are aggregated and analysed to extract higher-level information including friendship networks, patterns of interaction, preference similarity networks and user communities (Tabassum et al., 2018). It is reasonable to envisage an extension of this **social data** by further aggregating to these analyses the data generated by users' avatars in the virtual worlds.

New forms of **spatial and spatio-temporal data** are also likely to emerge from next generation virtual worlds. They would include the capture of the layout of virtual environments, the movement of avatars and other spatial features, e.g. related to spatial computing, navigation and geolocalisation within virtual worlds (Valaskova et al., 2022).

Regarding next generation **virtual contents**, their evolution is likely to be driven by advances in AR/VR/XR as well as artificial intelligence and blockchain technologies (cf. the previous Section on 'new technologies').

Nevertheless, besides technical aspects and concrete data format issues, it is important to understand the social change that may occur in the perception of the value of digital/virtual content. In future virtual worlds, digital fashion for avatars (Renault, 2023), virtual/digital art, assets and products, eventually registered as Non-Fungible Tokens (NFTs), may become as valuable as real-life objects (Baytaş et al., 2022).

Many open research questions and challenges arise from these novel data types and virtual contents: How to distinguish between real, digital and virtual data? Should they be analysed altogether or separately? How to fuse data generated from both real and virtual worlds concurrently (e.g. user/avatar data, digital twin data)? How different are user behaviours and social communities in real vs. digital vs. virtual worlds?

3.2.3 Computational infrastructure

The implementation of next generation virtual worlds will result in large-scale multimedia needs (e.g. for visual rendering, data synchronization, motion capturing), in addition to the management of a possibly unprecedented number of users and platforms. Therefore, **advanced and scalable computational structures** will be needed to make them function effectively and in real-time (Ball, 2022; Barrera et al., 2023; Duan et al., 2021).

This infrastructure will have to support and **combine efficiently different computation paradigms**, including high-performance computing, distributed computing, edge computing and cloud computing. While classic **high-performance computing** (e.g. clusters of servers and GPUs) will be undoubtedly essential to provide the significant processing power to support the management of complex virtual environments, **distributed computing** will also play an essential role towards the creation of a decentralised system that is not controlled by any single entity. Distributed computing systems can share processing power and data across multiple nodes, allowing for ubiquitous accesses and lower response times to complex problems.

Human-Machine Interaction (e.g. wearables), mobile and IoT devices generally have limited computational power. For instance, computing intensive tasks such as real-time 3D rendering cannot always be processed efficiently on a single resource-limited mobile device (Jiang et al., 2022). These devices are envisaged as key interaction technologies within next virtual worlds (cf. Section 3.2.1 'new technologies') and therefore **edge and cloud computing** are likely to be critical in supporting the timely processing and system responses of future virtual applications (Lee et al., 2021; Wang & Zao, 2022). Edge computing (Cao et al., 2020), a computation paradigm where data are processed closer to its point of origin, will allow to optimize processing speeds, minimize latency and tackle the trade-off between computation and communication. It will enable data to be processed closer to the user, reducing the need for data to be transmitted back and forth between central servers and users. Cloud computing will in turn be essential to store and manage the vast amounts of data generated by users. This will involve the use of cloud-based databases, file storage systems and other infrastructure to support the collection and processing of user-generated data.

Although virtual worlds provide the potential of decarbonisation through limiting physical activities (e.g. avoiding flying for physical meetings), it is important to highlight that building and operating this computational structure will also generate an extraordinary amount of carbon emissions (Liu et al., 2023). Therefore, the **carbon footprint** of virtual worlds will need to be carefully addressed from the earliest stages of development (cf. Section 3.1.4 'Sustainability').

3.2.4 Standardisation and Interoperability

Implementing a virtual world requires different technical building blocks to be interconnected in order to provide a flawless user experience. This, given its versatility and complexity of the necessary technical building blocks, would only be feasible through commonly agreed interoperability provisions.

There are already a plethora of normative and de facto standards that satisfy different virtual world requirements. However, bringing those together into a stack of commonly recognised and interconnected interoperability provisions is still in its early stages of conceptualisation. Open protocols, such as those that led to the creation of the HTTP protocol when the internet was conceived, are essential to establish the grounds for interoperable virtual world(s). A flawless cross-platform user experience would entail many different connected devices, interfaces, operating systems provided by different vendors to work together. Interoperability is an essential means to ensure compatibility of devices and platforms, thus helping to provide equal opportunities between different vendors (e.g., to avoid monopolies by big techs / 'more than one metaverse' (Breton, 2022) provide opportunities to SMEs to enter the virtual worlds, or the metaverses market).

Within this dynamic and complex context, the, Spatial Werb Foundation[41], the Open Metaverse Interoperability Group[42] and Metaverse Standards Forum[43] are online communities which bring together different actors who have interest in the topics of standardisation and interoperability of virtual worlds. The Metaverse Standards Forum

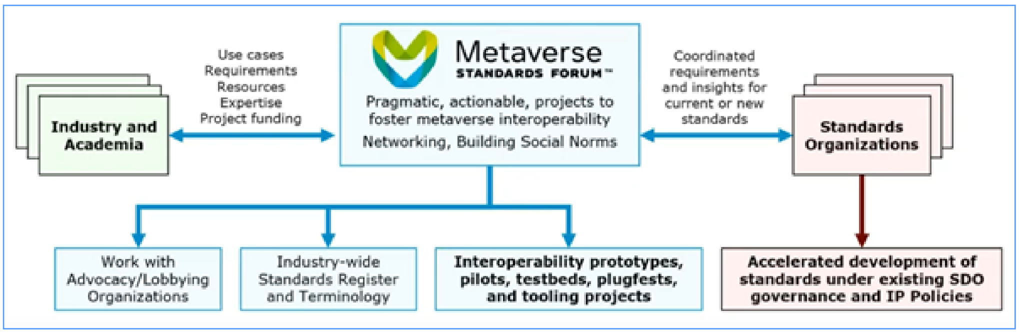
41. https://spatialwebfoundation.org/.
42. https://omigroup.org/.
43. https://metaverse-standards.org/.

is attended by standardisation bodies, industrial actors such as producers of hardware, software development companies, retailers, academia, and early tech adopters. Founded by 32 organisations (Figure 7) the Forum has a rapidly increasing number of participating organisations from around the world (2,255 as of 13/03/2023).

Figure 7

Founding members of the Metaverse Standards Forum.

The topics that are investigated (see Figure 8) range from (i) mapping of relevant standardisation initiatives to (ii) exploration of prominent technologies, and (iii) user requirements elicitation. The Forum is not a formal standards development organisation, and is therefore not expected to produce or adopt new standards. Nonetheless, with its vision towards a common understanding and agreement on open virtual world standards, the initiative is central to the efforts to ensure the interoperability of virtual world building blocks.



Source: Trevett, N. Khronos group

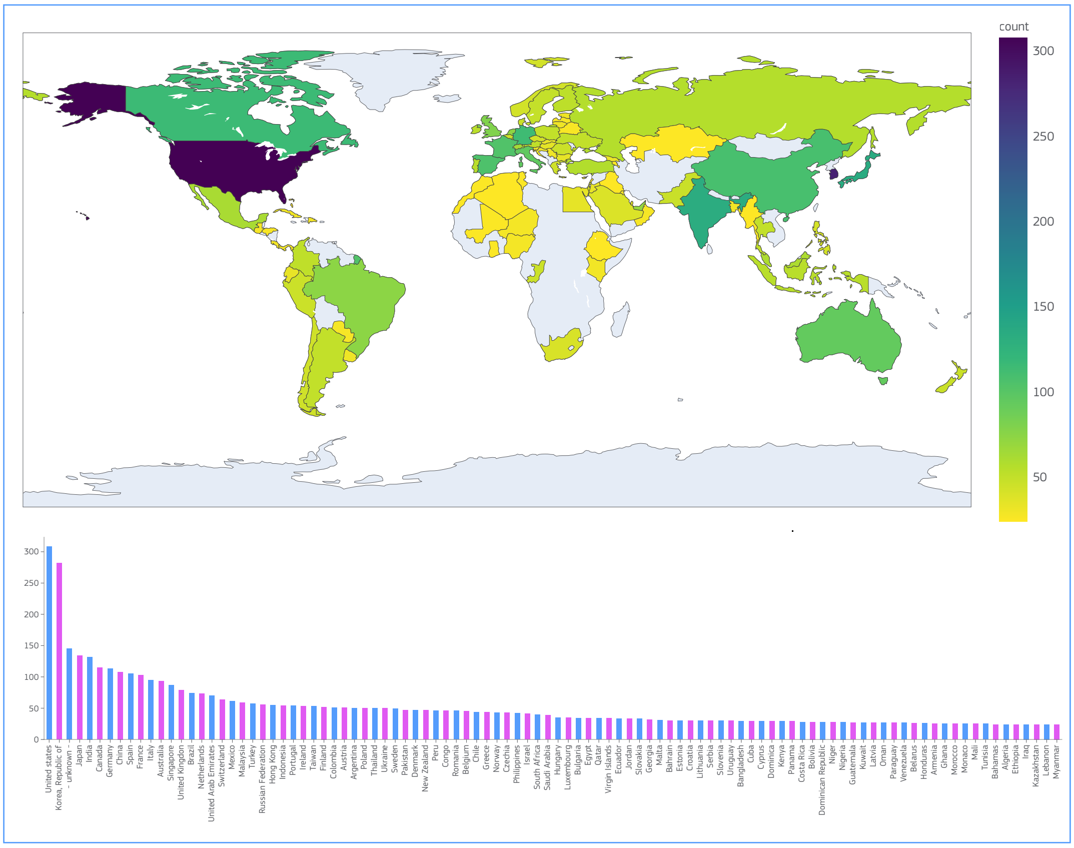
Figure 8

Metaverse Standards Forum scope of action.

Without being able to pinpoint precisely the origin of all participating organisations, we have harvested their homepages and extracted the mentions of countries. The highest number of country mentions on homepages (Figure 9), as an indirect proxy of the member origins, are from the USA, followed by Korea, Japan, India, Canada, Germany and China with European Union Member States comprising 27% of the total.

Figure 9

Frequency of countries mentioned on the hompages of the Metaverese Standards Forum members.



The profile of the members is also versatile. The word cloud (Figure 10), based on a web scraping of the homepages of Metaverse Standard Forum participants, illustrates the versatility of the types of activities that the participants are engaged with.

Figure 10

Grouping of Metaverse Forum participants by profile based on web scraping of their homepages.

There are different virtual world requirements (Table 2) that would benefit from standardisation, including at least the following[44].

Table 2

Standardisation requirements for next generation virtual worlds.

Virtual world requirements	Standardisation initiative
1. Representation and exchange of three-dimensional data assets	▪ Graphics Language Transmission Format - glTF (Khronos Group) ▪ GL Binary – GLB (Khronos Group) ▪ Universal Scene Description – USD (Pixar) ▪ COLLAborative Design Activity – COLLADA (Khronos Group) ▪ Virtual Reality Modeling Language - VRLM
2. Cross-platform data/asset exchange APIs	▪ MPEG-V ▪ Khronos 3D Commerce
3. Extended reality (XR), including virtual reality (VR), augmented reality (AR) and mixed reality (MR) APIs and SDK	▪ OpenXR (Khronos group) ▪ OpenVR (Valve corporation) ▪ WebXR (W3C groups)
4. Real/virtual world integration, including positioning and orientation in 3D and 4D space	▪ GeoPose (Open Geospatial Consortium - OGC)
5. Avatars/characters interoperability	▪ Avatar API (ReadyPlayerMe) ▪ HAnim (Humanoid Animation) ▪ VRM (Khronos Group)
6. Identity, cybersecurity and privacy preservation	▪ Decentralised Identifier - DID ▪ OpenID Connect – OIDC ▪ OAuth 2.0 ▪ InterPlanetary File System - IPFS
7. Networking protocols	▪ Hyperspace Modeling Language - HSML
8. Metadata and asset discoverability	▪ Cross-platform metadata – XMP (Adobe Systems) ▪ Dublin Core

Several observations are noteworthy based on the initial screening of the rapidly developing interoperability landscape around emerging next generation virtual worlds:

1. There is **no single metaverse but rather many virtual worlds** (VR, AR) that are being developed and are in a different level of maturity. They use various technologies, architectures and infrastructures. Therefore, at present, it is not possible to converge around a single reference architecture, set of interoperability standards and building blocks for virtual worlds.

44. Source: Metaverse Standard Forum and authors' own elaboration.

2. The standardisation landscape is still highly fragmented and is **rapidly evolving with multiple competing initiatives** (both open and proprietary) that are attempting to provide and promote interoperability solutions for the virtual worlds. As the topic is new, this is a normal evolutionary step with many actors and initiatives trying to position themselves. Clearly, as next generation virtual worlds technologies mature, some initiatives will be discontinued while others will be launched and gain momentum.

3. **Many European organisations participate in the Metaverse Standards Forum** which implicitly means that their voce can be heard in the debate around the conceptualisation of interoperable approaches and standards. The more experimentation and testing is conducted by European actors, the more concrete insights can be collected that would make their voice stronger in the debate around interoperability and standardisation on the global scale. In addition, a coordinated approach to standardisation and interoperability through (i) a common voice in existing initiatives such as W3C community groups and the Metaverse Standards Forum, as well as (ii) own European standardisation initiatives would provide multiple opportunities through reinforcing the EU position and tackling the fragmentation of the virtual world standardisation landscape.

4. Finally, achieving **higher level of interoperability**, leveraging on the opportunities created by the new Interoperable Europe Act[45] and the European Interoperability Framework[46], will likely contribute to the establishment of a **healthy ecosystem of developers and early adopters** who can build on top of each others work. If virtual worlds scale well, new emerging opportunities for cross-platform experiences, including commerce, will emerge which will allow end users to buy and sell their assets or services across different virtual worlds.

3.2.5 Privacy and security

Web 3.0 emphasises the protection of users' personal data as an increasing range of security breaches and privacy invasions emerge from the management of massive data streams, pervasive user profiling activities and the use of more and more powerful AI algorithms (e.g. recommender systems, content generation algorithms, chatbots) (Chen et al., 2022). Virtual worlds built upon the Web 3.0 will consequently inherit

45. COM(2022) 720 final.
46. https://ec.europa.eu/isa2/eif_en/.

these vulnerabilities and, in addition, new privacy and security threats are likely to breed (Wang et al., 2022). In the following we identify several key aspects that will challenge privacy and security in next generation virtual worlds.

Authentication and access control. Users may have multiple virtual identities, making it difficult to authenticate true identities. Ideally, users should be uniquely identified, which would imply to put in place interoperable mechanisms to ensure fast and trustworthy cross-platform identity authentication. If the identity of a virtual world user is stolen, her/his avatar(s), virtual assets and social life can be leaked and lost, which would have an even greater impact than on current digital platforms (Wang et al., 2022). Impersonation attacks, i.e. an attacker pretending to be another authorised entity to gain access to a service or data, might also lead to more dramatic consequences. For example, attackers could access a VR headset and exploit the behavioural data collected by the in-built motion-tracking system to create digital replicas of the victim in order to deceive, commit fraud or even cyber-crimes. A possible solution could be the use of biometric technologies as an added layer of security in virtual worlds. For example, face or voice recognition could ensure that only the authorised user has access to his/her virtual avatar. However, very recent advances in AI make it possible to generate highly realistic facial deepfakes and audios imitating a person's voice which opens new privacy breach issues (Westerlund, 2019).

Data privacy. While strong cross-platform authentication would significantly diminish the risks of impersonation, on the other hand it might pave the way to traceability, correlation and profiling, breaching the privacy of end users. Hence strong authentication will need to adopt the most stringent and modern *Privacy Enhancing Technologies (PET)*, possibly resilient to AI enabled data analysis and correlation.

The virtual worlds will be a vast repository of both the traditional and novel (c. f. Section 3.2.2 'New types of data and digital contents') user data and privacy will therefore be a significant concern. The challenge will be to protect users' information and ensure it is not misused. The data collected or generated by IoT, HMI devices and users/avatars may suffer from threats in terms of data tampering, false data injection attacks (Liang et al., 2017), ownership/provenance tracing and violation of intellectual property rights. The storage of particularly sensitive information (e.g. user profiling) of massive amounts of users in cloud servers and edge devices may also raise privacy disclosure issues (Wang et al., 2022). For example, attackers may deduce users' personal information by frequent queries via differential attacks (Wei et al., 2021) or compromise the cloud/edge storage via distributed denial-of-service (DDoS) attacks (Bertino & Islam, 2017). Data encryption, differential privacy, disclosure control and privacy-preserving data mining would need to be applied where possible to diminish the privacy exposure surface of end users.

Network-related threats. Classic attacks at the communication network level (e.g. DDoS, single-point-of-failure SPoF, Sybil attacks) are likely to perpetuate and even evolve, as new virtual worlds will build on the top of current Web 3.0 and existing wireless communication technologies. For instance, attackers may compromise IoT/HMI devices and make them part of a botnet (Bertino & Islam, 2017) carrying out DDoS attacks to cause network outages and service unavailability, to generate a huge amount of traffic, etc. Another example could be the creation of Sybil identities from fake/stolen ones and use them to out-vote genuine nodes in a blockchain network (Wang et al., 2022). Considering that many critical services will be delivered on top of the current Web 3.0 and the future Web 4.0, and that virtual worlds require near-to-real-time performance to guarantee an immersive experience, network resilience against DDoS attacks will become of extreme relevance to ensure a high level of quality of service. Moreover, network authentication, routing and DNS robustness and network anonymity schemes will also require enhancement to avoid the risk of network profiling, impersonation or data corruption.

Trust management. The hyper-spatiotemporality (Nevelsteen, 2018) that will result from the intertwining of virtual and real worlds greatly increases the complexity of managing trust. The deepening blurring of the boundary between the real and the virtual makes distinguishing fact from fiction more confusing. For instance, an evolution of current deepfakes could be in the form of fake virtual environments or events. It is essential to put in place mechanisms ensuring that the virtual content is not malicious or harmful, and to prevent the spread of malware, viruses and other forms of malicious software. As a relevant role will be played by AI-driven content, a special effort will need to be made to ensure the robustness of AI algorithms, in order to mitigate the effect of adversarial machine learning attacks.

Economy-related threats. As users will increasingly spend money on virtual goods and services, it will be essential to secure virtual assets. The challenge is to prevent hacking, fraud and theft of these virtual assets. Blockchain technology offers the promising NFT solution for virtual asset identification and ownership provenance tracing (Wang et al., 2021). However, NFTs are also vulnerable to threats such as ransomware, scams and phishing attacks. However, today, standards defining common minimum cybersecurity requirements for virtual assets are still lagging, while at world-wide level, only Europe started to regulate crypto-assets (a subset of virtual assets) through the 'Markets in Crypto-Assets (MiCA) Regulation'. Indeed, considering that virtual assets will become most probably the 'engine' of virtual worlds, their security should be addressed at architectural level, in the early stages of the virtual world design, to ensure a security by-design principle.

Threats to the physical world. Attackers can exploit system vulnerabilities and compromise IoT/HMI devices as entry points to invade real-world equipment, seriously threatening personal safety and causing material damage. For example, household appliances, industrial machines (e.g. via their digital twin replica) and critical infrastructures (e.g. power grid systems, rail systems, water supply systems) could be attacked by means of advanced persistent threat (APT) attacks (Hu et al., 2015). An injection of falsified messages or wrong instructions could also lead to bodily and equipment harm (Liang et al., 2017). For instance, falsified feedbacks sent to a wearable interaction device (e.g. excessive voltage) might cause its malfunctioning and harm on the user's body. Full immersivity can also raise concerns such as cyber-sickness. Attacks could modify VR environmental factors to deceive, disorient and control immersed human players and move them to other physical/virtual locations without consciousness (Casey et al., 2021).

With this potential increase in the scale of attacks, which might also provoke a dramatic harm at the societal level (cf. Section 3.1 'Societal challenges'), there is a need to improve existing countermeasures to face security and privacy threats in virtual worlds. Some solutions have been proposed such as AI-powered Intrusion Detection Systems. However, the ability of these solutions to provide a timely response and to scale to the very large needs of future virtual worlds is yet understudied and would require further research (Wang et al., 2022).

Security of handsets and sensors: to ensure the full and seamless integration between real world and virtual world, end-users' handsets and sensors will occupy increased relevance. These handsets and sensors can be divided today in two different classes: (a) high-end devices with sophisticated software and hardware, and (b) low-end, cheap sensors. While the first class is typically developed taking into consideration cybersecurity (even if, as every IT device, it can be anyway prone to vulnerabilities (see for example the Oculus handset vulnerability discovered in 2018), the second class of devices is quite often released with little attention to cybersecurity. The reason has its roots in the fact that low level sensors and devices have typically a noticeably short life cycle and need to keep their price low to succeed in the market, hence little resources are dedicated to cybersecurity aspects. While Europe, also in this case is at the forefront with the coming Cyber-Resilience Act regulation, still in general, ensuring an appropriate level of security for handsets and sensors used in virtual world represents today a global challenge.

Concrete examples of virtual world potential sources of vulnerabilities

- **Exploitable in-world objects:** virtual worlds often allow users to create and upload their own objects or assets. However, if the virtual world platform has insufficient security measures or inappropriate content moderation, malicious actors can create objects that contain malicious code or scripts. When other users interact with these objects, it can lead to unauthorized access, data breaches, or even malware infections.
- **Account credential theft:** cybercriminals can employ various techniques to steal user account credentials within virtual worlds. This can include phishing attempts, where users are tricked into revealing their login credentials through fake login pages or malicious links. Additionally, virtual world platforms with weak authentication mechanisms or poor password storage practices can be susceptible to brute-force attacks or credential stuffing.
- **Virtual world server vulnerabilities:** virtual world platforms rely on servers to host and manage the virtual environment. If these servers are not properly secured or maintained, they can become targets for hackers. Exploiting vulnerabilities in the server software or gaining unauthorized access to the server infrastructure can allow cybercriminals to manipulate the virtual world, compromise user data, or launch distributed denial-of-service (DDoS) attacks.
- **Avatar impersonation:** virtual worlds often feature avatars representing users. If there are flaws in the avatar authentication system or weak identity verification processes, it can enable impersonation attacks. Cybercriminals can create avatars that closely resemble other users or influential individuals within the virtual world, deceiving others and potentially engaging in fraudulent activities or spreading misinformation.
- **Malicious scripts or mods:** virtual worlds often support user-created scripts or modifications that enhance the user experience or introduce new functionalities. However, if the virtual world platform does not have strict controls or security measures in place, malicious actors can create and distribute scripts or mods that contain malware, keyloggers, or other malicious code. When users download and execute these scripts or mods, their devices can become compromised.
- **Social engineering and scams:** virtual worlds foster social interactions, making them ripe for social engineering attacks. Cybercriminals can exploit users' trust, manipulate in-world communications, or

set up fraudulent businesses or events to deceive others. This can include scamming users out of their virtual currency, tricking them into revealing personal information, or persuading them to download malicious files.

It is important for virtual world developers and platform providers to regularly assess and address these vulnerabilities through robust security measures, code audits, encryption protocols, content moderation, and user education, however, keep the pace with the enormous speed of proliferation of cyber-threats is a terrific challenge.

The challenge of crime prosecution in virtual worlds

Security-by-design, privacy-by-design, user awareness are clearly the fundamental pillars to ensure the security of virtual worlds. However, also the principle of deterrence, i.e. ensure that, if a crime is performed, a prosecution process will be triggered, plays a relevant role in discouraging criminals from performing cyber-attacks. Prosecuting crimes committed within virtual worlds presents today several challenges due to the unique characteristics and complexities of these environments. Here are some difficulties encountered in crime prosecution within virtual worlds:

- **Jurisdictional issues:** virtual worlds often transcend geographical boundaries, making it challenging to determine which jurisdiction has authority over criminal activities. Virtual world servers can be located in one country, while the users involved in criminal acts may be scattered across various jurisdictions. This jurisdictional ambiguity complicates the legal process, as different countries may have different laws and regulations regarding virtual worlds and their associated crimes.
- **Attribution and identification:** establishing the real-world identity of individuals involved in criminal activities within virtual worlds can be difficult. Users often operate under pseudonyms or avatars, making it challenging to link virtual identities to real-world individuals. Without reliable identification and attribution mechanisms, prosecuting individuals responsible for crimes becomes complicated.
- **Cross-border cooperation:** to prosecute crimes in virtual worlds effectively, international cooperation among law enforcement agencies becomes crucial. However, coordination and cooperation between different jurisdictions can be complex and time-consuming, involving legal frameworks, extradition processes, and cultural differences. These challenges can hinder the swift and efficient investigation and prosecution of virtual world crimes.
- **Technological complexities:** virtual worlds rely on complex technologies and platforms, making it challenging for law enforcement agencies to understand the intricacies of these environments. Investigating crimes within virtual worlds often requires technical expertise and specialized tools to gather evidence, analyse network traffic, or trace digital footprints. Law enforcement agencies may

face resource limitations or technical barriers that impede their ability to effectively investigate virtual world crimes.

- **Evidentiary challenges:** virtual worlds are digital environments where activities are recorded and stored in various forms, such as logs, chat transcripts, or in-world transactions. Gathering admissible evidence from virtual worlds and ensuring its integrity for legal proceedings can be difficult. The authenticity and verifiability of digital evidence, such as screenshots or chat logs, may be questioned, and establishing a chain of custody can be complex.
- **Legal ambiguities:** legal frameworks around virtual worlds and their associated crimes are still evolving. Many countries do not have specific laws addressing crimes committed within virtual worlds, leading to legal ambiguities and challenges in determining the appropriate charges and penalties. This can result in inconsistent application of laws and difficulties in holding perpetrators accountable.

Addressing these difficulties requires close collaboration between virtual world operators, law enforcement agencies, policymakers, and legal experts. Establishing clear legal frameworks, promoting international cooperation, developing specialised investigative units, and enhancing technological capabilities can all contribute to improving crime prosecution in virtual worlds. Additional and more broad policy and legal challenges can be found in Section 3.4.2.

Possible mitigation measures to improve the security of virtual worlds

As one can derive from what described in this section, the potential threats affecting the virtual worlds are multi-faced, covering technological, but also societal and regulatory aspects. As a natural consequence, to secure the virtual worlds, the society will need to put in place a manifold framework addressing in a consistent way all the dimensions of interaction and governance of virtual worlds. Here below, summarising what highlighted in the previous part of this section, we present a non-exhaustive list of possible area to cover:

1. **Robust authentication and access control:** implement strong authentication mechanisms, such as two-factor authentication, to ensure that only authorized individuals can access Virtual worlds platforms and accounts. Use secure access control measures to limit user privileges and prevent unauthorized activities.
2. **Secure software development practices:** follow secure coding practices during the development of Virtual worlds platforms and

applications. Regularly update software and promptly patch any identified vulnerabilities to prevent exploitation by malicious actors.

3. **Encryption and data protection:** employ encryption techniques to secure data transmission and storage within the virtual worlds. Ensure that sensitive user information, such as personal details and financial data, is properly encrypted to protect it from unauthorized access or disclosure.

4. **Content moderation and user safety measures:** implement effective content moderation systems to detect and remove malicious or harmful content within the virtual worlds. Enforce community guidelines and policies that promote user safety and discourage abusive or fraudulent behaviour.

5. **User education and awareness:** educate virtual worlds users about potential security risks, best practices, and guidelines for safe behaviour within the virtual environment. Encourage users to use strong passwords, be cautious about sharing personal information, and report any suspicious activities they encounter.

6. **Collaboration with security researchers:** establish bug bounty programs or collaborate with security researchers to identify and address vulnerabilities in virtual worlds platforms. Encouraging responsible disclosure of security flaws can help uncover and resolve potential issues before they are exploited.

7. **Incident response and monitoring:** develop robust incident response plans to address security incidents promptly and effectively. Implement monitoring systems to detect suspicious activities, unauthorized access attempts, or anomalous behaviour within the Virtual worlds environment.

8. **Privacy and data handling policies:** clearly communicate privacy policies and data handling practices to virtual worlds users. Ensure compliance with applicable privacy regulations and obtain user consent for data collection and processing activities.

9. **Legal and regulatory frameworks:** advocate for the development of legal and regulatory frameworks that address cybercrime, privacy, and security concerns specific to virtual worlds. Work with policymakers to establish clear guidelines and standards for security practices within virtual environments.

10. **Collaboration with law enforcement:** foster collaboration between virtual worlds platform operators, law enforcement agencies, and legal authorities. Establish channels for reporting and investigating virtual world crimes, and support law enforcement efforts to hold perpetrators accountable.

By implementing these mitigation solutions, stakeholders in the virtual worlds can enhance security, protect user data and privacy, and create a safer virtual environment for users to explore and interact within.

3.3 Economic challenges

3.3.1 Virtual worlds economy

Virtual worlds or metaverses will change the ways in which goods and services are produced, advertised, transacted, distributed and consumed. These changes could be massive, but it is premature to tell what the final shape of economics in metaverses will be. Looking at emerging trends, this section provides several highlights of what the economic activity in virtual worlds might look like.

Virtual worlds might transform the way people work, shop or entertain on the internet into immersive, engaging and more valuable online experiences. E-commerce is the main area where this is already happening. Some fashion and home décor brands are already experimenting with 3D virtual stores as a new marketing and distribution channel. Virtual stores may add value to buyers' purchasing experience thus translating into concrete benefits for vendors who enter the realm of virtual and extended reality. A visitor of such store can try new clothes on her avatar and see in 3D how an object fits in her private space. The virtual shopping experience is richer and more comprehensive. Shoppers can interact with product creators and trendsetters, play thematic games and ultimately order a product. Thanks to this new level of buyer engagement, companies can boost brand awareness; reinforce loyalty and steer shoppers towards buying a real product. Finally, virtual shops are becoming a novel experimentation tool for testing new product designs and eliciting extensive information about consumer beliefs, values and preferences. If 3D virtual stores and shopping malls attract buyers on a mass scale, metaverses could become a transformative innovation for e-commerce. From an economic viewpoint, this transformation of e-commerce would not necessarily bring a huge increase of GDP, because it will, in part, crowd out sales in existing marketing and distribution channels. Nevertheless, in some cases vendors could benefit from market expansion effects and efficiency-related secondary effects. This can be illustrated by the recent example of innovation in distribution channels in the music industry. Digital music streaming via apps contracted business of brick-and-mortar media stores, but at the same time, it broadened access to music, facilitated artist discovery and entry of independent record labels. Metaverses will further change patterns of music consumption by boosting demand for concerts and live events on virtual platforms, such as Roblox or Fortnite.

The transformative potential of virtual worlds is not limited to new ways of selling and marketing existing physical products as described above. Virtual worlds have a potential to create an economy with digital products for use only in virtual spaces. Examples of genuinely new virtual objects include in-game items and collectibles, avatar skins, digital artwork or land. Currently, virtual versions of objects constitute ony a small niche for enthusiasts. This niche may quickly expand into a multibillion-euro business, if more people start to visit virtual worlds and spend there more time. Some luxury brands already have begun experimentation with virtual fashion, designing outfits and luxury wearables for avatars. These objects are released in limited editions and use non-fungible tokens (NFTs) to certify their ownership. Virtual goods and services have practically unlimited scope and may include everything that is needed to function in parallel planes of reality, from avatar wearables, real estate, homes, businesses, vehicles, weapons, tools and utilities to transportation services. All these virtual objects have one interesting element in common: zero or very low fixed cost of production, which is very different from the cost structure of their real-world equivalents. For example, a virtual house or vehicle does not require physical materials that are scarce and thus expensive. This difference creates some interesting implications for the contestability of markets in virtual worlds. Because of low fixed cost, providers of virtual goods and services could face more entry and possibly fiercer competition than in the real world. In the absence of economic barriers to entry, incumbents may create artificial restraints (technical or contractual) to protect their market position. This potential challenge is discussed in the competition section below.

It is commonly agreed that the payment infrastructure underlying the virtual worlds economy will be based on blockchain technology. Already most transactions involving virtual goods and assets, such as land are stored on Ethereum blockchain and carried out in cryptocurrencies, usually stablecoins. Transactions on blockchain are processed in seconds and involve a commission for validating nodes. Distributed ledger technology (DLT) ensures transparency and decentralised governance of transaction register. The main benefit from such distributed transaction records is that they are reliable and tamper-proof, which eliminates the need for intermediation or custody by banks. Despite the above-mentioned advantages, there are also well-known challenges associated with blockchain, which include scalability, interoperability and environmental footprint. Moreover, security of transactions on blockchain can sometimes be compromised, because of possible software bugs and hacking. Although stablecoins eliminate excessive volatility vis-à-vis government-issued money, cryptocurrencies are generally less trusted than the fiat money. These problems will need to be solved to enable transactions on a mass scale in the metaverses economy, as well as providing a solution that does not depend solely on private crypto currencies providers. The issue of trust is closely related to the potential convertibility to fiat money, and the subsequent reserves that a stablecoin provider should hold. In addition, stablecoins might be also subject to liquidity runs[47]. One way of addressing the issue of trust could be switching from private stable coins to government-backed currencies, such as Central Bank Digital Currencies (CBDC). The use of smart contracts and DLT technologies would allow, for instance, to program conditional payments and executable contracts. Given the actual payment infrastructures and the centralized authority (the ECB) that manage the payment system, technical solutions and standard must be developed to allow an effective and safe communication between the DLT world and the financial system. In addition, this solution would also facilitate the introduction of a tax regime harmonized across virtual and real-life assets, goods and services. Still, tax collection in the metaverses economy poses specific challenges for public authorities, related to the scalability of infrastructure and institutional arrangements. To carry out automated tax deduction, tax authorities will need to be connected to a distributed ledger as a monitoring node and have an active role in a smart contract governing each blockchain-based transaction.

Expansion of the metaverses economy will boost demand for connectivity technologies, access devices, visualisation and interfacing technologies and spatial computing. Among economic actors that will become winners if metaverses become the next 'big thing' are producers of virtual reality headsets and sensing gloves (Meta, HTC), semi-conductor and chip companies (Nvidia), platform providers (Roblox, Epic Games, Meta), 3D content developers, creators of immersive marketing campaigns and developers of anthropomorphic AI solutions that will power humanlike interactions of avatars with real users.

The value of the virtual worlds economy is determined by the interplay between supply and demand for related goods and services and measured by their trade volumes. To date, metaverse economy grows mostly in hardware and software segments: infrastructure, platforms and access devices. Trade of virtual objects is still in a nascent phase, characterised by low demand and mostly speculative purchases. Creators and developers tend to release virtual objects in limited editions to maintain high prices. Economic scarcity is obtained with NFT technology that transforms possibly unlimited digital commodities into a

47. One example is the collapse of the Terra stablecoins on May 2022. See the ESMA report on Crypto-assets and their risks for financial stability for further details.

limited number of unique objects. With the development of new use cases, applications and services value creation will gradually shift to the demand side. A growing user base of virtual spaces will release network effects, which have been a powerful factor of growth in the digital economy. Network effects will also remain the key for value creation on metaverse platforms. Network effects in the virtual worlds economy will be the largest if users could interact across virtual worlds and not just within a single virtual space. Hence value maximization requires virtual worlds to develop as an open ecosystem of interoperable platforms, which will enable differentiated users to collaborate, form groups, create tools, share content and exchange resources in the most unconstrained way possible. In this context, portability of virtual items across digital worlds and interoperability across platforms should remain focal points of regulation.

3.3.2 Competition

Market structures with one or a few providers gaining the most users and market value are common in the digital economy. Large concentration is an outcome of competition for the market – a specific model of rivalry that arises due to economies of scale, switching costs and network effects. In combination, these three factors create a strong incumbency advantage, protecting dominant firms from new market entrants. Prominent examples of winner-takes-most markets include search engines, social media, e-commerce marketplaces and mobile operating systems. These markets display competition problems related to the exploitation of business users, self-preferencing and foreclosure behaviour. Dominant firms can utilise network effects to expand into adjacent markets through envelopment. The envelopment attack is a hostile type of entry whereby an entrant leverages its market power from the core market and offers a bundled service. Envelopment strategy can be effective in case of a significant overlap of user bases and strong complementarities from product integration. Drawing on the complementarity between a secondary service and the core functionality, multi-product entrant generates superior value for users and may compete away a single product provider (Eisenmann et al., 2011). Using network externalities, big technological firms have built digital ecosystems spanning across several markets. Ecosystem orchestrators set access and pricing rules for different groups of users in order to maximise profit. A common monetisation strategy rests upon tight control over data generated from use of various platform services. This quasi-closed, platform-centric model offers high degree of commoditisation and security but is detrimental to innovation and economic welfare. Adding a metaverse layer to closed digital ecosystems of the big technology firms triggers certain privacy and competition concerns. A standard worry highlights the risk of exclusionary and exploitative conduct inside the centralised metaverse platform. The second concern points to a lack of contestability and a risk of envelopment of emerging, independent metaverse ecosystems. A final concern relates to abusive data collection, which has already been the cause of numerous lawsuits against big tech firms in the past. Metaverses, as a rich data environment, would amplify aggressive exploitation of user data for steering economic choices or political opinions. Ways of addressing some of these concerns are discussed below.

Abusive conduct, such as exclusion and exploitation of platform users, is a major concern on winner-takes-most markets. Recently in the European Union, Digital Markets Act (DMA) entered into force. It is a first-ever piece of regulation targeted at gatekeeper platforms - big technology companies operating core platform services, which hold an entrenched and durable position. DMA provisions act as necessary safeguards if for example a gatekeeper engages in abusive vertical behaviour against business users. Prohibitions and obligations enshrined in the DMA remain relevant for metaverse platforms due to the possibly frequent use of marketplace monetisation on various levels. As already noted, virtual objects have different cost structure than their real-life counterparts. Economic barriers to entry are low, which normally leads to intensified competition. However, in most cases supply of these objects will remain under the control of individual artist, space creators or a platform provider. The controlling entity can choose to monopolise provision of these items, leading to restricted offer and inferior welfare outcome. Alternatively, provision of differentiated virtual objects can effectively organised through downstream competition and marketplace monetisation, especially for large and heterogeneous demand. Vertical relations between the platform or space creator and providers of tradable virtual items will require competition scrutiny. As many of these markets can be small-scale, the open question remains whether the current DMA threshold levels are not too high. The DMA regulation also addresses issues stemming from de facto control of user data. For example, combining data from different sources is prohibited and gatekeepers are obliged to provide limited access to user and business data for third parties. The above provisions weaken but do not eliminate incumbency advantage from exclusive access to data (Cabral et al., 2021). Firms will still leverage data-driven network effects to lock-in or capture users. Although the DMA can be adapted to changing technological and market circumstances, it is not designed to loosen a platforms grip on different types of data.

A dedicated regulation is needed, addressing access and portability of data generated by avatars, users and devices across centralised and decentralised platforms.

Mitigation of envelopment risk is necessary for the sustainable coexistence of open and closed ecosystems. Virtual worlds platforms can be designed in accordance with a centralised (closed) and a decentralised (open) model. Firms that grew on Web 2.0 applications, including the big tech platforms, steer towards the former model (Roblox, Fortnite, Meta). Companies with blockchain origins (Sandbox and Decentraland) follow the latter model. The open model is compatible with the decentralisation principle, which postulates a lack of single point of control or ownership. Open metaverse platforms claim to adhere to user-centric governance, enabling users to control data and content. Decentralised governance limits rulemaking of the orchestrator in two important aspects. It introduces permissionless access and changes the ownership structure of digital assets in a way that has implications for competition and welfare generation. By enabling cross-platform exchange and collaboration positive network effects are lifted to the global level of interconnected networks instead of remaining condemned within a single closed ecosystem. This induces more entry, promotes innovation and enhances economic wealth in the open ecosystem. Drawing from past mistakes, namely a domination of walled garden platforms, regulators need to ensure conditions for co-existence of centralised and open ecosystems in the metaverses. This requires striking a right competitive balance between both types of ecosystems, without a threat of foreclosure on either side. Network effects will continue to play a paramount role on either type of metaverse platform, driving market outcomes in accordance with winner-takes-all logic. Dominant walled garden ecosystems have already accumulated large proprietary pools of user data. Adding a metaverse layer will radically increase economies of scope in data and consequently amplify data-driven network effects generated inside these walled gardens. This in turn will increase their envelopment potential vis-à-vis smaller providers operating in emerging market niches. To overcome the increased data advantage, a competing rival would have to release a highly innovative, if not revolutionary product. Although some metaverse use cases are sufficiently novel, none of them in isolation could induce consumers to switch from a multi-product platform. However, disruption may also stem from opening of the ecosystem, that is allowing users to interact, combine novel services, and port content and data across different platforms. Gains from amplified network effects could potentially outweigh the benefits generated in the closed ecosystem. Innovation in metaverse by incumbent platforms can be considered as a countermeasure to potential envelopment threat from large and diverse open ecosystem (similarly to killer acquisitions). This inverted envelopment scenario is less likely than ordinary envelopment, given the active monitoring of the market by walled garden platforms. To prevent ordinary envelopment, closed metaverse ecosystems should not exercise de-facto ownership rights over user data. Activity on virtual worlds platforms will generate a plethora of valuable user information about interests, emotions, behaviours, moods, used products, read books, etc. These new insights, pooled with other proprietary data, will boost data-driven externalities and increase the risk of foreclosure on product or service markets. To prevent competition risks and improve economic efficiency from data reuse, the new data governance is needed. All user, business and machine data generated during use of a service should be available in full scope to third parties subject to consent from the party that generated it. Although distributed ledgers are not fit for purpose of storing large amounts of data, they can be very useful for distributed management of access rights, including real-time data access for authorised parties.

3.3.3 Taxation

There is no doubt that with the success of metaversese the volume of purchases of virtual objects will increase, such as in-game items and collectibles, wearables, digital artwork or land. Most of these items can be classified either as digital assets or durable consumables for future resale. What makes them suitable for investment purposes is scarce quantity and unique, individual attributes. Virtual assets are represented as non-fungible tokens (NFTs) and are traded for cryptocurrencies on blockchain. Unlike other types of digital crypto assets, most notably stable coins, utility and security tokens, issuance and circulation of NFTs is will not be regulated in the forthcoming Markets in Crypto-assets Regulation (MiCA). MiCA is the first EU regulation of the crypto asset sector, covering issuers, crypto wallets and exchanges. It targets money laundering and increases protection of investors and consumers. Although NFTs are excluded from this comprehensive framework, they are already subject to standard capital gains tax (for investors) or income tax (for creators).

The fiscal regime for crypto assets is heavily fragmented across the EU. Taxation rules within national jurisdictions are largely the same for NFTs as for other classes of asset categories. Some Member States apply linear tax while others use progressive taxation, often with a tax-free allowance functioning as partial exemption of income from cryptocurrencies from tax. Because of these various regimes, the effective tax rates on crypto assets vary from 0 to 33% across the EU. There is a broad consent that capital gains from NFTs should be taxed in the same way as income generated from sales of crypto currencies on crypto exchanges. The current approach to taxation of crypto assets will change in the coming years due to increasing acknowledgement of their cross-border and cross-jurisdictional nature. The EC has started to work on a proposal for a single EU tax regime for crypto assets. The proposal puts forward new requirements for establishing simple, fair and efficient taxation rules for the entire crypto asset sector, including NFTs. The proposal will address the anonymity of transacting parties. Individual and corporate investors who own digital assets across the EU, will be required to share detailed records with tax authorities.

As already noted, issuance and circulation of the NFTs are not currently regulated or scrutinised by financial authorities. This fact together with some technical features make NFTs susceptible to money laundering. The main features facilitating money laundering include the parties' pseudo-anonymity, a lack of account of cross border and cross jurisdictional transactions on public blockchains as well as volatile pricing. The comprehensive regulation of NFTs needs to address other specific vulnerabilities. It should put forward Intellectual Property (IP) protection safeguards for creators and increase security of transactions for buyers, given the recurring cases of theft and frauds involving NFTs. Regarding IP protection, an NFT may grant only selected rights to the buyer such as the right to use, copy, modify or display. The licensed rights can be encoded in a smart contract that provide for automatic monitoring, enforcement and billing in certain cases. Misuse of NFTs can take the form of trademark and copyright infringements and should be sanctioned under IP protection laws. However effective digital IP enforcement is also technically challenging. It requires access to highly specific technological instruments from IP rights holder to monitor the conduct of legitimate buyer and marketplaces for NFTs, as well as unauthorised issuers. It is important that conceptualisation of the comprehensive regulation and technological means of enforcement and monitoring of contractual obligations between the transacting parties come in due time. Otherwise, confidence in NFTs may be undermined due to their susceptibility to criminal practices and weak IP enforcement. This could seriously hinder the development of the metaverse ecosystem.

Looking beyond taxation of capital gains from crypto assets, in the future metaverses economy there will be a massive circulation of digital products and services which will be used as input (intermediary) goods for productive economic activity carried out via the Web 3.0. For example, a firm planning to open a sales channel in a metaverse will need to purchase virtual land from the creator of a universe and contract a digital architect to design a virtual building and then a digital developer to create it. Alternatively, the firm may rent a commercial space in a virtual shopping mall. Such transactions generate a series of taxable events that need to be properly registered and reported for the purpose of accounting (individual and corporate) income tax. Crypto assets should be recognised as a legitimate fixed asset from the accounting viewpoint. For example, investment in productive virtual asset should be subject to amortisation rules, while leasing should be recorded as an operating cost. Lack of objective and stable price benchmarks for traded objects could make them potentially attractive instruments for tax evasion or tax optimalisation instrument. These challenges will have to be addressed by future accounting standards and technological solutions, e.g., through the introduction of digitally signed electronic invoices, tamper-proof electronic sales registers, automatic transmission of information to tax authorities, and exchange of data between tax jurisdictions.

3.3.4 New business models

The Web 2.0 gave rise to many new business models such as e-commerce, sharing economy or online marketplaces, which disrupted the traditional retail industry, transport, hospitality and many other sectors of the economy. Next generation virtual worlds could potentially further transform ways in which companies create, deliver and capture value. It will take at least 10-15 years until the technology reaches market and business readiness. As new virtual worlds use cases emerge every day, the outcomes of the business model innovation are yet unknown. This section offers some early highlights about how metaverses could potentially disrupt business activity and value creation.

In the B2C and C2C contexts, the so-called 'creator economy' comes to the fore front. It offers new possibilities to professional creators to develop and monetise virtual creations. Artist, writers, architects, musicians or game developers can build virtual objects and offer them for purchase or lease for use in virtual spaces. Thanks to the availability of tools that assist content and experience creation, it will also be possible for the ordinary users to become co-creators and co-investors in collaborative projects powered by decentralised autonomous organisations. The creator economy is underpinned by NFTs and blockchain technology. Together they allow for object ownership verification and transacting. An NFT can store enormous amount of static and dynamic properties related to the object, including copying, editing or transfer history. Importantly, tokens also store IP and licensing rights, including exclusive rights to the inventor, use restrictions, etc. For example, many original creators can claim economic benefits upon every resale of their creation. NFT-based royalties are settled automatically by the smart contract on blockchain. The creator economy leverages the decentralisation principle of virtual worlds, eliminating the need for intermediation and related costs. This may jeopardise selected existing online platforms, such as ETSI or Amazon Handmade.

In the B2B context, often called the 'industrial metaverse', the concept of digital twins has gained significant attention. Digital twins are virtual representations of machinery, industrial plants and other complex physical objects. Such models populated with data coming from the real environment, allow for experimenting, learning and discovering which changes to the physical system would be beneficial (or harmful) and their implementation. Learning from digital twin models can accelerate the evolution of complex objects like cars and rockets. For example, Tesla trains AI system for autonomous driving in virtual environments with purposefully high exposure to unusual situations. BMW has a virtual factory to simulate a real-life production in search of efficiency gains. The application of digital twins is becoming widespread in energy system management, and building management to assess the feasibility of a project prior to spending the first euro on construction. In retail store design, it allows to simulate the flow of customers and test graphical layout and article placement. Digital twins are also increasingly used in the public sector, leveraging rich governmental databases to design resilient infrastructures and mitigate climate change.

The ad-based business model, which prevails in the current online platform economy, will most likely retain its prominence in the metaverse-based social networks. However, marketing and in particular advertising in metaverses will be disrupted by the plethora of new data collected from users. New forms of ad placement, such as virtual billboards and new forms of AI-powered user targeting, such as mood discovery, will emerge. Sensing devices and headsets will enable new pricing instruments and campaign efficiency measures based for example on tracking users' eye movements and sight.

The intensity of business model innovation will be fuelled by increasing activity in virtual worlds. Whether the trade of virtual objects and the number of virtual headsets in use will approach the scale of e-commerce transactions and smartphone adoptions is yet unknown. It will depend on whether the metaverse technology will deliver on its promise of an enhanced, immersive experience and whether users will ultimately enjoy using virtual and extended realities. Hardware improvement is one of the prerequisites for massive participation in virtual worlds, as currently available headsets are expensive and provoke fatigue effects.

3.4 Governance and policy challenges

3.4.1 Governance

Metaverse is still in its nascent stage; however, the developed virtual worlds, technological maturity and growing investments already call for more attention to be devoted to the issue of governance. In this document, governance for virtual worlds (or metaverses) is understood as a dedicated form of internet governance. It is therefore considered as the 'development and application by governments, the private sector, civil society and the technical community, of shared principles, norms, rules, decision-making procedures, and activities that shape the evolution and use of virtual worlds.'[48]

As mentioned above, virtual worlds and metaverses pose a broad spectrum of challenges ranging from issues of a purely technological nature to economic, legal, ethical and ontological questions. The creation of an appropriate governance scheme is necessary to handle these challenges and orchestrate value creation and distribution of the benefits in society. The creation of such a governing structure will be a result of a consensus-forming among a number of stakeholders. Ultimately, this consensus will be recorded in technology standards, policies, industry codes of conduct, binding laws, and other types of rules.

So far, there is no complete understanding of what kind of governance structure will be optimal for the functioning of virtual worlds. As different stakeholders have different rights and interests, relevant public bodies, including governments, will need to guard the process of the formation of the governing structure in a way to balance the rights and maximise the benefits for society at large. Of, course, this structure must not be a rigid one. It needs be agile and flexible to continuously respond to changing societal needs and challenges.

As the metaverse and virtual worlds are primarily technical phenomena, their technical architecture has a direct impact on the functioning of the governing structure or, vice versa, the governing structure must be reflected in the technical setup to be effective. This alignment of structures is an important aspect of the effective governance of technology-enabled phenomena, including virtual worlds. Discrepancies in this context may translate into rather impulsive governance model primarily driven by the ad hoc technical developments and not by values or societal needs.

The two basic governance models that are widely discussed in the context of virtual words are centralised and decentralised models.[49] We

48. Internet Governance is 'development and application by governments, the private sector, civil society and the technical community, of shared principles, norms, rules, decision-making procedures, and activities that shape the evolution and use of the Internet' (COM/2014/072 final).
49. See for example: Dwivedi, Y.K. et al. Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. Int. J. Inf. Manag. 2022, 66, 102542.

will briefly reflect on these two models but argue in favour of the hybrid structure and then consider a metaverse nation-state scenario.

3.4.1.1 Centralised model

A centralised governing structure implies a single entity or a small group of entities that hold authority and decision-making power over the network of virtual worlds. This could be a central organisation, a government, or a large tech company.

A centralised governance structure resembles the current model, where a service provider is in control of a virtual environment and the services are governed by the terms of service in accordance with existing horizontal and sectorial laws. From a governance perspective, virtual worlds and the metaverse do not really disrupt the existing governing structure. Metaverses are yet another layer added to the current model. The main challenge for policymakers in the centralised model is to identify new risks for users and society at large and navigate the process of adapting appropriate policies.

Efficiency and consistency are important advantages of the centralised model. A centralised governance structure can be more efficient in decision-making, implementation of policies and law enforcement. It allows for quicker responses to issues and greater control over the development of the virtual worlds.

A major disadvantage is the potential for the abuse of power resulting from the asymmetry of information and control of the infrastructure. The concentration of power in a centralised governance structure can lead to concerns regarding the lack of effective competition, transparency, and limited user influence over decision-making.

3.4.1.2 Decentralised model

A decentralised governing structure implies distributed self-governance. In this structure, decision-making power is distributed across multiple entities or individuals. In principle, it is the users and communities who navigate the challenges and organically respond to the issues emerging in virtual worlds. Governments rather assume a role of the guardians of the decentralised system with focus on the adoption of relevant technologies such as decentralised protocols or distributed ledgers.

Participation in decision-making processes and access to information are big advantages of this model. Decentralised governance often emphasises user empowerment, giving individuals more control over their digital identities, data, and participation in metaverse. A decentralised structure allows for greater resilience and flexibility, as decision-making is distributed and not dependent on a single authority. It also encourages diverse perspectives and innovation.

Nevertheless, decentralised governance faces challenges related to coordination, consensus-building, scalability and law enforcement. It will require robust protocols and mechanisms for effective decision-making and resolving conflicts.[50] Distributed self-governance does not provide an obvious recourse system in cases when a virtual environment run by a decentralised autonomous organisation (DAO) becomes harmful. In such cases, jurisdiction and governing laws may be difficult to identify, and assigning and enforcing liability may be challenging. Moreover, the use of AI on top of distributed ledger technology may make this type of governance susceptible to spinning out of human control.

The main challenges for policymakers in this model include the development of an agile checks and balances system that distributes power and responsibility throughout a community of users and stakeholders as well as the establishment of ways to enforce law and enable human oversight.

3.4.1.3 Hybrid model

A hybrid structure combining decentralised and centralised elements seems to be the most realistic approach to the governance of virtual worlds. Both models in their perfect versions have strengths and weaknesses. Combination of them could be used strategically, depending on the context and needs. User empowerment, digital identity, and future digital rights can benefit greatly from a generally decentralised architecture. On the other hand, certain aspects, such as law enforcement or targeted policies, may be more effectively addressed through the centralised structures. The hybrid model allows for better mitigation of the associated risks while profiting from the strengths of both models.

3.4.1.4 Digital nation-state scenario

A uniform type of governance for virtual worlds on a global scale is unlikely. The social constructionism perspective suggests that digital representations can be seen as social phenomena, influenced by the collective knowledge and perceptions of individuals and communities.[51] As national political and cultural systems and values vary across the world, governments may decide to introduce into virtual worlds governing frameworks that reflect or are continuations of the real systems. Some countries may opt for centralised models that promote strict control over user data, identity, the clothing

50. ERA: Academy of European Law, 'Legal challenges of the metaverse and its implications for the criminal justice system', Trier & Online, 23-24 March 2023.

51. Peter L. Berger and Thomas Luckmann 'The Social Construction of Reality: A Treatise in the Sociology of Knowledge', Penguin Books, 1966; On the relation between technology and society see for example: Poel, Ibo van de. 'Three philosophical perspectives on the relation between technology and society, and how they affect the current debate about artificial intelligence' *Human Affairs*, vol. 30, no. 4, 2020, pp. 499-511. https://doi.org/10.1515/humaff-2020-0042.

for avatars, and social rankings. Some may adopt more democratic systems that allow for the functioning of different types of stakeholders within a democratically accepted framework. It is possible that, eventually, a bundle of interconnected virtual worlds will start acting like a nation-state. Strategic alliances between digital worlds may be formed, which would result in a relationship that is more interoperable. Virtual worlds governed by different values and principles may choose to stay less interoperable or interoperable under specific conditions. In a way, access to the bundle of interoperable virtual worlds may mirror crossing the nation-state border. Eventually we may end up creating digital representations or continuations of our own societies and governance structures that to large extent mimic the real world.

3.4.2 Policy and legal

Although the existing legal corpus extends its applicability to virtual worlds, the specific characteristics and nature of virtual worlds may entail its adaptation. Certain laws may require reinterpretation for the purposes of the metaverse. Do murder or rape can exist in the metaverse? Do human rights extend to avatars? How to gather evidence in the metaverse or pursue investigations? The advent of the metaverse may necessitate the creation of new rules in instances where the current framework fails to address the unique attributes associated with this virtual realm. What are the rights of avatars in the metaverse? Will avatars keep identity when entering different virtual worlds? These are only examples. We may soon discover many metaverse-enabled legal gaps across the whole body of law and legal procedures. In the context of cyber crime, specific challneges are introduced in Section 3.2.5, notably on jurisdictional, attribution and identification issues, cross-border cooperation, technological complexities, evidentiary challenges and legal ambiguities.

While the above-mentioned issues will need to be addressed at some relevant point, the focus of the EU policymaker today is to first enable the technical functioning of virtual worlds in a secure and value-driven way. The current legal focus is on the following areas:

- Data protection.
- Intellectual property rights.
- Regulation of virtual assets.
- Rules on competition, e-commerce and advertising.
- Technology and interoperability standards.
- Standards for avatar conduct and behaviour.
- Human vs. avatar rights.
- Cybercrimes.
- Jurisdiction and governing laws.
- Innovation policy.

- Law enforcement.
- Legal barriers to the rolling-out of the enabling technologies.

Enabling the safe use of virtual worlds is primarily based on the continuation of the current policies as they have qualities necessary to tackle many immediate issues linked to virtual worlds. The GDPR[52] sets out rules for the processing of personal data in the EU, the Digital Services Act[53] introduces layered system of responsibility for service providers in the context of content moderation, Markets Act[54] upholds competition in digital markets, InfoSoc Directive[55] harmonises certain aspects of copyright and related rights in the information society, Cybersecurity Act[56] and Network and Security Directive (NIS2)[57] establish the governance framework and the baseline measures for the cybersecurity. The proposed Data Act[58] encourages more actors to participate in a data-driven economy and proposed AI Act[59] deals with the responsible use of AI. These horizontal laws are accompanied by sectorial rules that have a strong focus on enabling the value-driven use of digital services in the specific sectors such as health, energy, telecommunications or financial sector. Moreover, the Commission is currently building a regulatory framework for technologies such as AI, distributed ledger technology and crypto assets. All these laws are not only applicable to metaverse, but they enable its use and development.

Next generation virtual worlds have a potential to transform how we interact, communicate and work. The governance framework and law are ways to navigate this change. It is difficult to precisely assess how the existing laws will apply to metaverse and how the current understanding of legal concepts will be influenced by metaverse in the long-term perspective. It is clear, however, that not only the rules but also the judicial system, law enforcement and eventually legal education will need to adapt to the possible technological advancements in the context of virtual worlds.

52. REGULATION (EU) 2016/679.
53. REGULATION (EU) 2022/2065.
54. REGULATION (EU) 2022/1925.
55. Directive 2001/29/EC.
56. REGULATION (EU) 2019/881.
57. DIRECTIVE (EU) 2022/2555.
58. COM(2022) 68 final.
59. COM(2021) 206 final.

4. The techno-economic ecosystem of next generation virtual worlds

The Digital Techno-Economic ecoSystem (DGTES) maps and analyses the worldwide digital ecosystem, based on the Techno-Economic ecoSystems (TES) analytical approach. DGTES takes account of policy relevant and forward-looking digital activities (therefore, some more consolidated activities in the domain of digital are excluded). The flexibility of DGTES allows zooming in on a specific digital domain. Here the focus is placed on the next generation virtual worlds, describing and commenting on the related activities and players that shape the virtual worlds subdomain. In DGTES, subdomains are defined by the activities (business, innovation and research[60]) identified by a list of keywords. In the case of virtual worlds, a list of 215 keywords (see Annex) has been compiled and classified with the help of expert, bibliographic repositories and on the basis of a repeatable approach consistent with the TES methodology (Calza et al, 2022). These keywords allow exploring the virtual worlds subdomain within the digital ecosystem, considering both virtual worlds as an ecosystem on its own and as intersection with the entire digital ecosystem. Once activities have been detected, player(s) performing each activity can be identified.

Composition of the virtual worlds subdomain in the DGTES global digital ecosystem

With about 27,000 activities, the subdomain of virtual worlds entails about 4% of all activities in the entire digital ecosystem (which in total count more than 600,000 activities). Among the 333,000 players identified in the entire global digital ecosystem, almost 15,600 are engaging in activities related to virtual worlds (5% of all players in the digital ecosystem). If we include also activities related to EU funded projects (FP7, Horizon 2020, Horizon Europe) and respective players, these figures rise to 27,500 activities and about 18,000 players (including also players located in non-EU countries but participating in virtual worlds related EU funded projects).

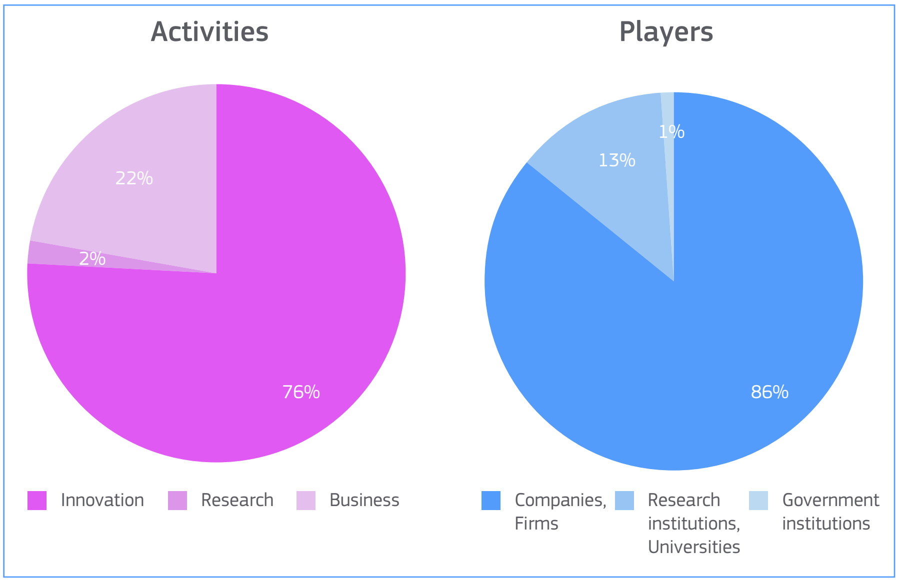
60. DGTES considers businesss activities (firms' declared activities, venture capital deals), innovation activities (submission of prioirty patent applications, participation in EU funded research projects), and research activities (publication in academic journals). It makes use of a number of micro level data sources (BvD Orbis, Crunchbase, DowJones, DealRoom, EPO Patstat, Cordis, Scopus, among the horizontal ones).

Looking at the composition of activities (Figure 11), research and innovation (R&I) activities represent almost 80% of activities in the virtual worlds subdomain. This share of R&I activities is larger than that observed over the entire digital ecosystem (71%). In particular, the share of innovation activities is larger in the virtual worlds domain than in the entire digital ecosystem (76% versus 66%), while the shares of research and business activities are lower (2% versus 5% and 22% versus 29%, respectively). This stronger-than-average weight of activities related to patents suggests an **'innovation-oriented' character of the virtual worlds subdomain with respect to the overall digital domains**.

When looking at the composition of players (Figure 11), firms represent 86% of all players in the virtual worlds subdomain. Although being the large majority, this share is smaller than what is observed over the entire digital ecosystem, where firms correspond to 94% of all players. The larger share of research institutions and universities represent a significant difference in terms of players' composition with respect to the entire digital ecosystem, as these players correspond to 13% of all players in the virtual worlds domain (slightly above 5% in the whole digital ecosystem). Government institutions play a marginal role, in line with average figures.

Figure 11

Players and activities in the virtual worlds subdomain, composition by type (2009-2022).



In terms of the geographical distribution of players (Figure 12), the subdomain of virtual worlds closely reflects the geographical composition – and concentration - of the global digital ecosystem: three geographical areas – China, the US and EU – host about 70% of all players (65% of players in the overall digital ecosystem). The share of Chinese players is double that of US players, which is double that of EU players.

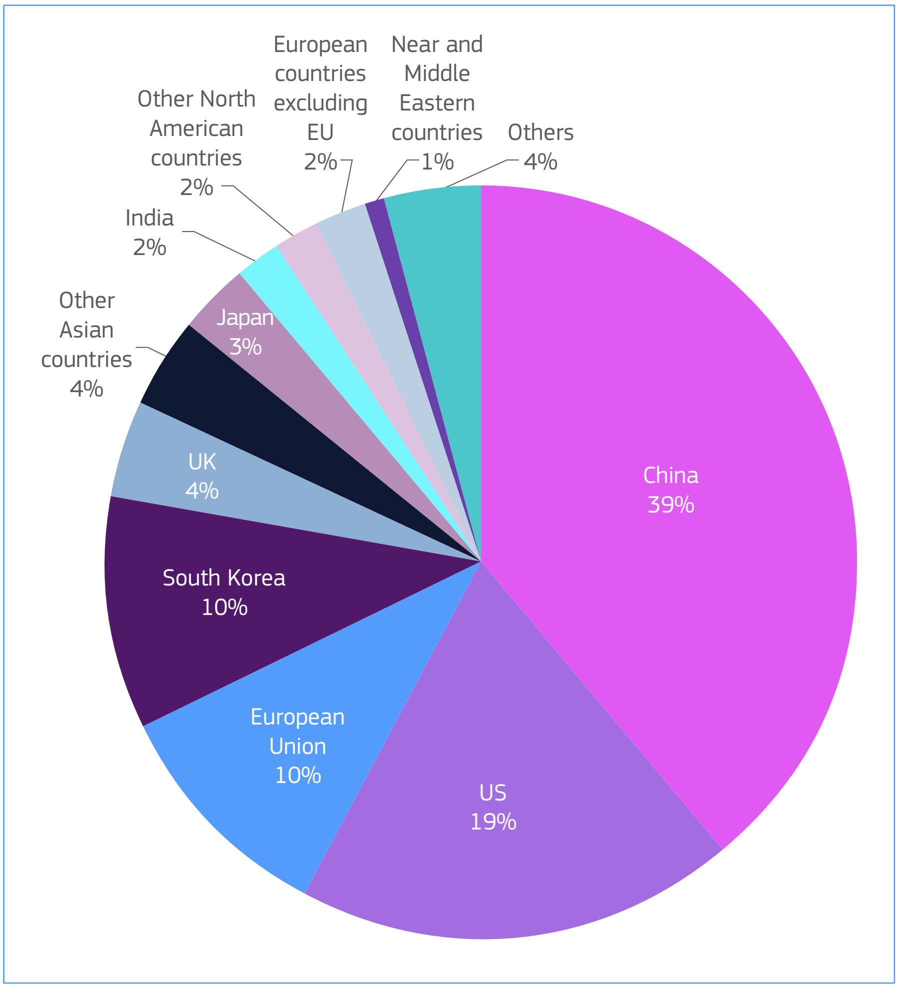


Figure 12

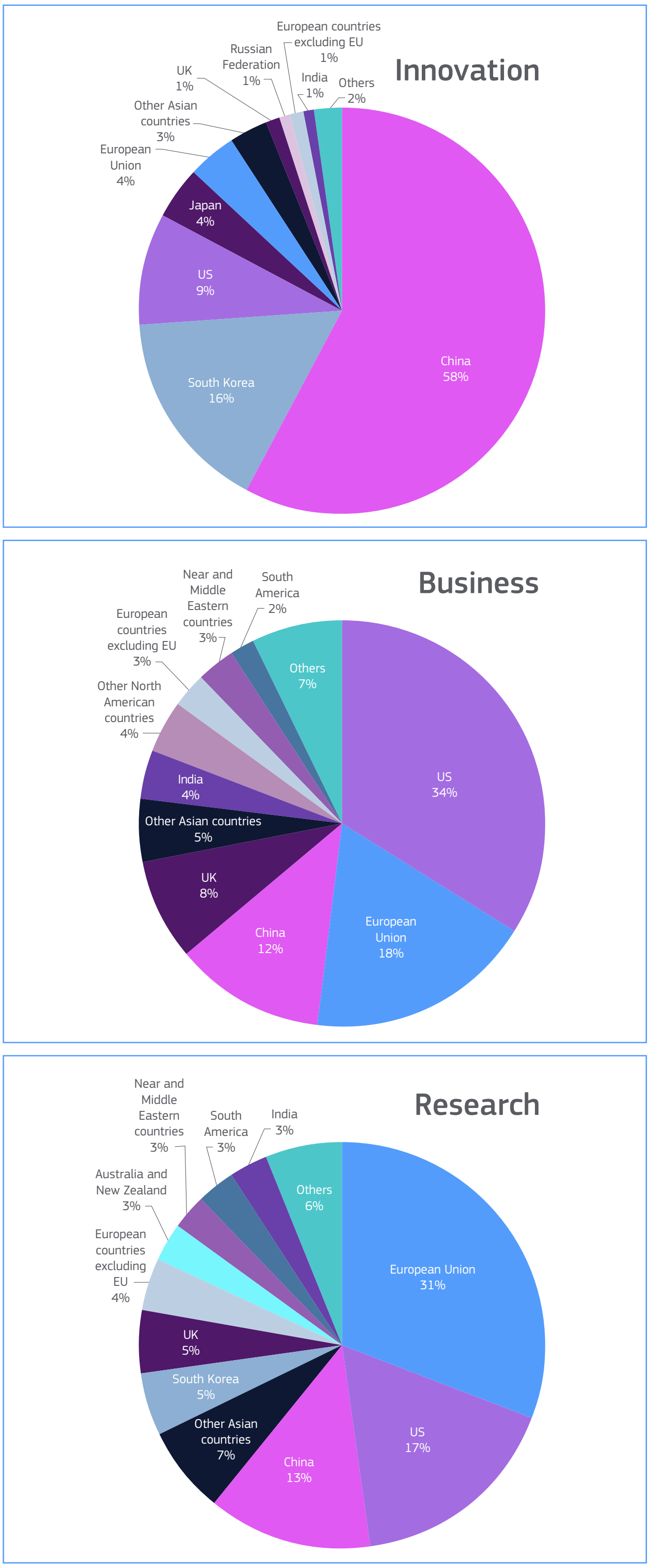
Players in the virtual worlds subdomain, composition by geographical area (2009-2022).

However, the figure of regional composition of players as well as of the relative ranking of the three main geographical areas (China, US and EU) varies remarkably depending on the type of activity (Figure 13). China hosts almost 60% of all players engaging in virtual worlds related innovation activities (patent applications), followed by South Korea (16%), the US (9%) and Japan (4%)[61]. Players engaging in business activities present a rather different geographical distribution: the raking of the three main geographical areas is reversed, as the US accounts for 34% of players, the EU for 18%, China for 12%. In research activities, the EU leads with 31% of players, followed by the US (17%), China (13%). Other Asian and South Korean players also play a relatively larger role in research activities.

61. This is fully in line with the large share of innovation activities performed by players located in China observed when considering the entire global digital ecosystem (Calza et al., 2023).

Figure 13

Players in the virtual worlds subdomain in different activities, composition by geographical area (2009-2022).



Focus on EU27

We now look at the composition and features of the virtual worlds subdomain in the EU. Here we include the activities identified through EU funded projects (FP7, Horizon 2020, Horizon Europe) and the respective players (Figure 14). The EU27 accounts for about 3,700 players (about 24% of all players in the virtual worlds subdomain) performing about 2,500 activities (about 9.4% of all virtual worlds related activities). Among these, EU funded projects correspond to 496 activities (20% of activities in the EU virtual worlds subdomain). This implies that the share of activities associated with EU funded projects in the virtual worlds subdomain is significantly larger than the share of EU funded projects when the entire EU digital ecosystem is considered (that is 17%) (Calza et al., 2023). To be noticed is the larger share of research activities in the EU virtual worlds subdomain (9%) with respect to the global virtual worlds subdomain (2%). The European virtual worlds subdomain also displays a relatively larger share of business activities (42%).

In terms of players, the EU virtual worlds subdomain presents a smaller share of firms (63%) and a much larger share of research institutions and universities (29%) than the global virtual worlds subdomain (see Figure 14). Also government institutions engage relatively more in virtual worlds related activities than what they do in the entire digital ecosystem. This is in line with the relevant contribution of EU funded projects to shaping the EU virtual worlds ecosystem. In this respect, it is worth noticing that the EU funded projects involve 2,065 players, implying that more than half (55%) of the European players in the virtual worlds subdomain are involved in a virtual worlds related EU funded project.

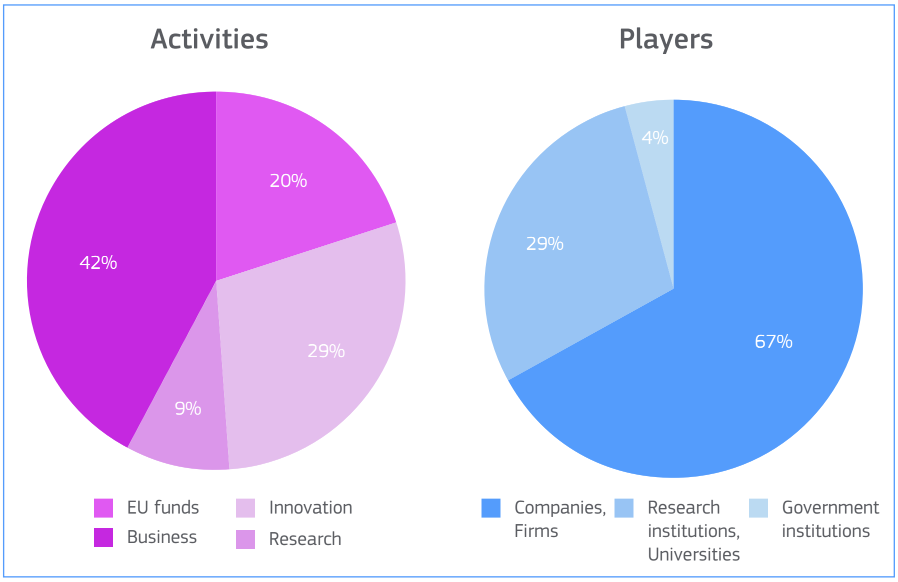


Figure 14

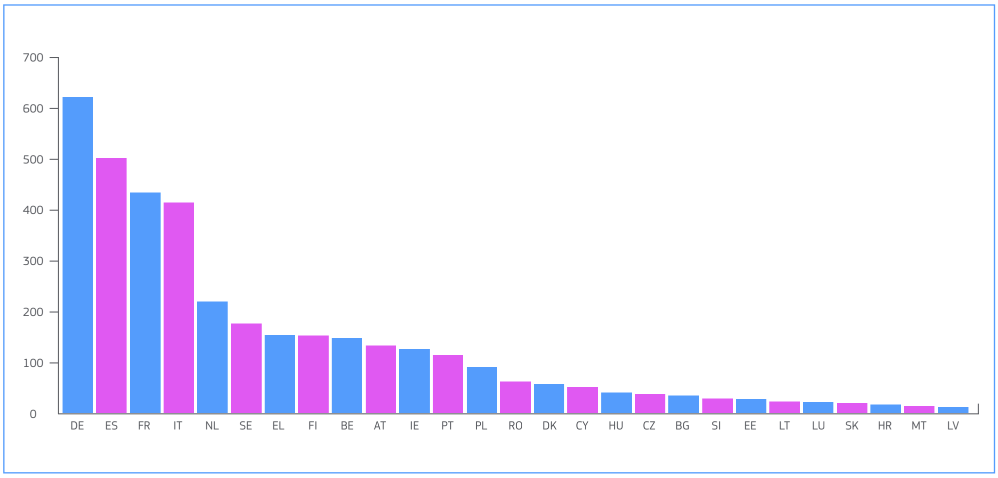
EU27: players and activities in the virtual worlds subdomain, composition by type (2009-2022)

In terms of number of players (including players involved in relevant EU funded projects), five countries occupy top positions: Germany, Spain, France, Italy, the Netherlands (Figure 15). Together these countries account for ~60% of players in virtual worlds subdomain in the EU. These are the same countries occupying the top 5 positions per number of players when the entire digital ecosystem is considered (Calza et al., 2023).

The composition of the digital ecosystem varies from country to country, and a deeper analysis may reveal useful information to better understand country-level features of the European virtual worlds subdomain. Moreover, given the importance of EU funded projects with respect to specific domains and areas of development of the virtual worlds ecosystem, it is also advisable to focus on the analysis of the collaborations across EU countries.

Figure 15

EU27: players by country in the virtual worlds subdomain (2009-2022).



Digital areas and sector composition in the virtual worlds subdomain

In DGTES, digital areas correspond to consistent techno-economic categories used to cluster digital technologies that relate to the same technological domain (Calza et al., 2022). 15 digital area (domains) constitute the DGTES digital ecosystem. Table 3 displays the 'technological composition' of the virtual worlds subdomain, revealing how virtual worlds related activities are related to 8 digital domains. Not surprisingly, the digital domain of 'extended reality, virtual reality, augmented reality, mixed reality, metaverse' entails most of retrieved activities.

Table 3

Activities by digital area in the virtual worlds subdomain

Extended reality, virtual reality, augmented reality, mixed reality, metaverse	93.958%
Infrastructure, cloud computing, digital platforms, online platforms, IaaS, SaaS, Paas, social networks, internet	2.314%
Internet of things, AIDC (automatic identification and data capture)	1.164%
Artificial intelligence	1.500%
Blockchain, distributed ledge	0.907%
5G and beyond, autonomous networks, communications, telecommunications and connectivity	0.111%
Verticals	0.043%
3D printing, additive manufacturing	0.004%

Looking at the distribution by economic sector of all types of players engaging in the virtual worlds subdomain (Table 4), 'Information and Communication' and 'Manufacturing' comprise the majority of players (52%). Several other sectors host players active in virtual worlds related activities, in particular 'Education' and 'Professional and scientific activities' (with about 10% each), 'Wholesale and retail trade' (7%) and 'Administration' (5.5%). Exploration of the specific activities may help in building a picture of the types of application of virtual worlds in sector other than the ICT related ones.

Sector	%
Information and communication	42.33%
Manufacturing	10.13%
Education	9.91%
Professional, scientific and technical activities	9.76%
Wholesale and retall trade, repair of motor vehicles and motocycles	7.14%
Administrative and support service activities	5.52%
Financial and insurance activities	**3.40%**
Public administration and defence, compulsory social security	3.02%
Other service activities	2.34%
Arts, entertainment and recreation	**2.15%**
Human health and social work activities	1.65%
Accomodation and food service activities	0.97%
Transportation and storage	0.59%
Agriculture, forestry and fishing	0.34%
Construction	0.28%
Real estate activities	0.28%
Activities of households as employers	0.06%
Mining and quarrying	0.06%
Water supply; sewerage, waste management and remediation activities	0.06%

Table 4

Players by sector in the virtual worlds subdomain (2009-2022).

Figure 16 crosses the information provided in Table 3 and Table 4. Colours reveal the concentration of players (the higher the concentration, the darker the colour) in a given combination of sector and digital domain. As already shown in Table 1, the majority of players engage in activities falling under the digital domain of 'extended reality, virtual reality, augmented reality, mixed reality, metaverse', but these do not reveal a clear sectoral concentration and are scattered around several sectors.

Figure 16

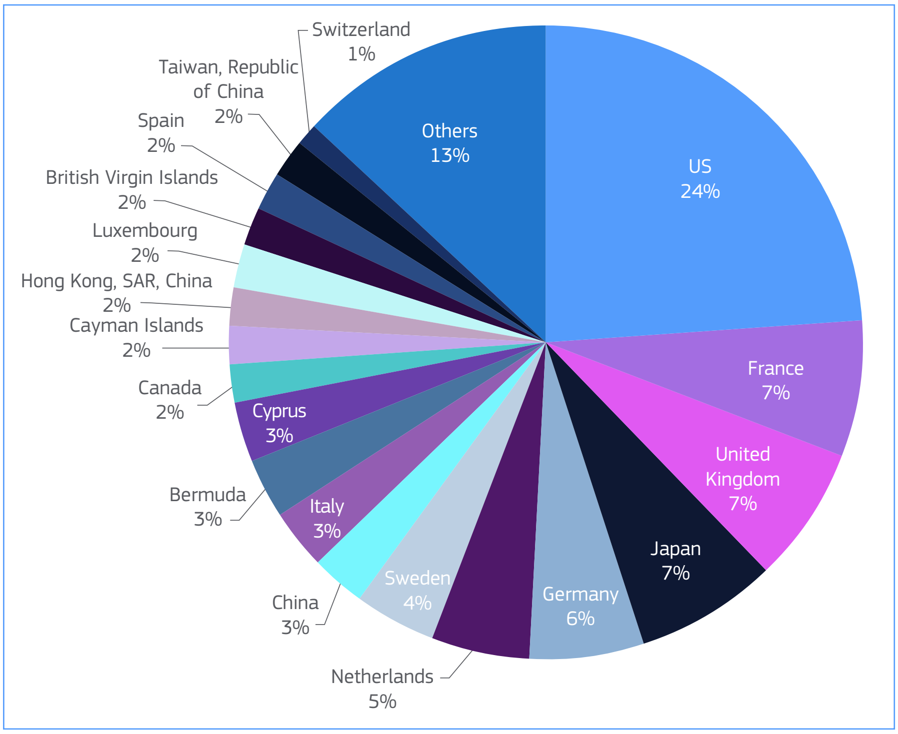
Players by sector and digital area in the virtual worlds subdomain (2009-2022).

Foreign ownership

The information contained in the DGTES graph database allows representing the virtual worlds subdomain as a web of ownership relations across companies located in different countries. From a worldwide perspective, the US is in first place (about 24%) per number of owned foreign companies that engage in virtual worlds related activities in the worldwide DGTES digital ecosystem, followed by France (7%), the UK (7%), Japan (7%) and Germany (8%) (Figure 17).

Figure 17

Foreign ownership of players in the virtual worlds subdomain, by owner's country (2009-2022).



Focusing only on the foreign ownership of players in the EU virtual worlds ecosystem (Figure 18) the US hold 20% of these owned firms, followed by France (10%), the UK (10%), the Netherlands (7%), Germany (7%) and China (6%).

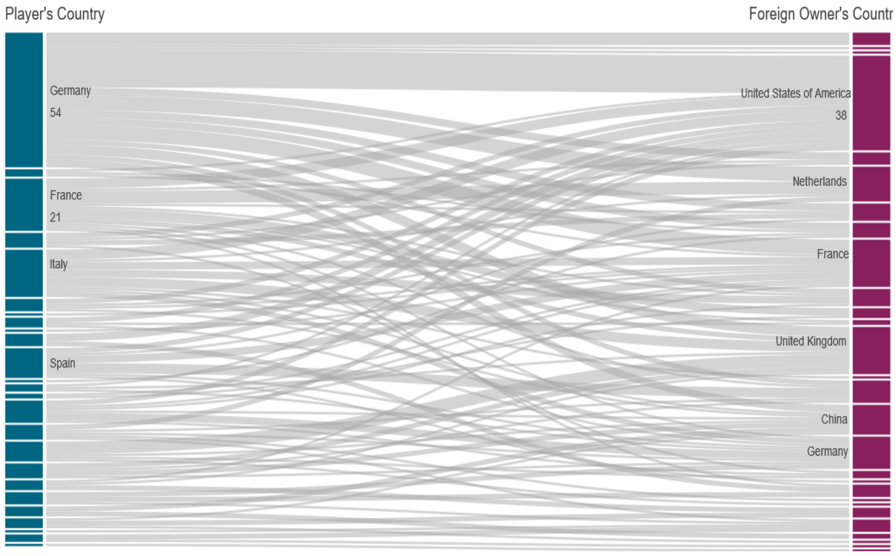


Figure 18

Foreign ownership of EU27 players in the virtual worlds subdomain (2009-2022).

Box 2

About DGTES.

The rapid evolution of digital technologies is catalysing the digital transformation, not only in the traditional information and communication technologyICT sector, but in all industrial ecosystems, reshaping the global horizon of technological, social and economic development and triggering several challenges for EU competitiveness. Reaching and enhancing digital leadership has become an essential driver of EU competitiveness as well as the condition for the successful implementation of the twin transition and for future prosperity in the EU. In this regard, the mastering of critical and emerging digital technologies is considered critical for the EU's strategic autonomy.

A related challenge is the need for updated indicators suitable to properly capture these rapidly evolving digital technologies and the pervasiveness of digital transformation. The JRC developed the Techno-Economic ecoSystems (TES) methodological approach to be able to map and analyse complex and rapidly evolving technology driven ecosystems. The TES approach may target any ecosystem, and has already been applied to several techno-economic segments expected to play a key role in digital transformation, such as photonics, earth observations technologies, and artificial intelligence (AI), powering the EC AI Watch worldwide landscape.

DGTES is the comprehensive application of TES to map, in a forward looking and policy-relevant way, the digital ecosystem. DGTES provides a graph dataset allowing to flexibly study the key elements of the digital worldwide ecosystem: the actors, their activities, their interlinkages of geographical, technological, financial and structural nature, as well as to investigate at different level of granularity flows of knowledge, gatekeepers, hubs, latent communities, hidden patterns, and emerging clusters of excellence. Based on a number of micro-level databases covering business, innovation and research activities (including EU funded projects), it provides both aggregated data at country and regional levels, and micro level information for specific actors allowing the construction of an extremely wide range of quantitative indicators, including network indicators to account for the detection of vulnerabilities and dependencies.

DGTES is the comprehensive application of TES to map, in a forward looking and policy-relevant way, the digital ecosystem. DGTES provides a graph dataset allowing to flexibly study the key elements of the digital worldwide ecosystem: the actors, their activities, their geographical interconnectedness, technological, financial and structural nature, as well as to investigate at different level of granularity flows of knowledge, gatekeepers, hubs, latent communities, hidden patterns, and emerging clusters of excellence. Based on a number of micro-level databases covering business, innovation and research activities (including EU funded projects), it provides both aggregated data at the country and regional levels, and micro level information for specific actors allowing the construction of an extremely wide range of quantitative indicators, including network indicators to account for the detection of vulnerabilities and dependencies.

DGTES offers quantitative indicators and metrics appropriate to map the spatial distribution, technological development, and evolution of a complex and dynamic industrial ecosystem. It allows the provision of novel insights and analysis targeting Europe's competitiveness and leadership, strategic autonomy and technological sovereignty aspects, knowledge flows, excellence in research networks, regional technology clusters, innovation performance, investments, and the development of the technological and industrial capabilities.

First report in a series of two, the JRC Technical Report 'An analytical approach to map the digital ecosystem (DGTES)' focuses on the methodological aspects, explaining the methodology and the steps leading to the construction of the DGTES database, and introducing metrics and indicators, also suggesting analytical avenues to directly address relevant policy questions.

The second report 'A DGTES-based analysis of the digital ecosystem' (forthcoming) presents a first overview of the global digital ecosystem over the period between 2009 and 2022, looking at the digital ecosystem from multiple analytical perspective and at the EU's digital leadership, integrating its technological and industrial nature, looking at competitiveness, resilience, strategic autonomy and capabilities, also considering critical digital subdomains of the digital ecosystem.

Sources: Calza et al., 2022 and Calza et al., 2023.

5. Conclusions

Next generation virtual worlds are related to a general-purpose multi-disciplinary paradigm intertwining virtual, digital and physical realities. They will bring ground-breaking technical, economic and societal shifts that are hard to predict as their future strongly depends on key technologicaldrivers, industrial stakeholders, and adopters.

In recent years, many highly innovative and transformative technologies have rapidly emerged and are currently being integrated in the Web 3.0 at an unprecedented rapid pace. These include VR, AR, blockchain, cyber-physical systems, advanced HMI interfaces, AI, cloud/edge computing, IoT and 5G networks. Computational and network infrastructures are only now starting to allow for ubiquitous access with very low latency, paving the way for unprecedented large-scale social and interactive virtual experiences. These, together with other novel technologies that will possibly appear in the near future, are likely to be the central technological building blocks of next generation virtual worlds.

While offering many open opportunities, future virtual worlds also come with many challenges including technical, societal, economic and legal ones. The opportunity vs risk trade-off must therefore be carefully addressed from the earliest stages of development and deployment. Regarding opportunities, the field of education deserves a particular mention. Next generation virtual worlds are expected to bring changes in teaching and learning dynamics. First, in terms of the introduction of new modalities for learning through virtual, shared, distributed experiences learners will have the possibility for self-regulated exploratory learning in contexts that are not restricted by the current limitations in education. The idea of the 'classroom' will be expanded, which will bring new opportunities for collaborative learning especially benefiting learners in situations where collaboration is difficult'. However, the design of such an educational cyber-physical meta-space needs to be structured around educational principles based on the vast knowledge from the fields of developmental psychology and education sciences with the inclusion of practitioners. Most importantly, the design and use of next generation virtual worlds in education should incorporate human rights such as privacy, safety and non-discrimination including the right of the learner to be forgotten. Nevertheless, scientific evidence regarding the impact of next generation virtual worlds on human behaviour, cognition and development is still limited and further research is required especially in long-term settings.

Health and manufacturing are also among the sectors that have the highest potential to proit from the advent of future virtual worlds. These sectors are already benefiting from previous education opportunities in the form of professional skills training. In medicine, virtual environments are likely to lead to improved surgical techniques, medical analysis and diagnosis, and new types of therapies. Industry 4.0 will probably bring important real-world benefits such as better product design, increased productivity, quality and logistics management through simulations and digital twins, and new business models.

When it comes to challenges, all these rapidly evolving technological advances will need to be carefully introduced into society, both for the sake of smooth adoption and trustworthy technical deployment. Putting in place standards and interoperability mechanisms would help to ensure technological robustness and security. Nevertheless, related standards and architectures for these technologies sometimes provide overlapping functionality. The ability to interoperate between different platforms and interconnect different components through the adoption of common standards is still challenging and will become increasingly important as a means for improving user experience and as a driver for new business opportunities.

Policy interventions in the EU will likely need to react to this rapidly evolving paradigm in the future, therefore it is important to create an environment that, on the one hand, stimulates the economy and evolution of players in the digital technology ecosystem, and on the other hand, fosters responsible and fair virtual worlds.

Addressing the challenges of next generation virtual worlds will require a common effort from both public and private stakeholders, as well as the participation of civil society.

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List of abbreviations and definitions

AI	Artificial Intelligence
APT	Advanced Persistent Threat
AR	Augmented Reality
CAGR	Compound Annual Growth Rate
DDos	Distributed Denial of Service
EC	European Commission
ECB	European Central Bank
EU	European Union
DSA	Digital Markets Act, the EU regulation
glTF	Graphics Language Transmission Format
HMI	Human Machine Interaction
IoT	Internet of Things
IP	Intellectual Property
MiCA	Markets in Crypto-assets, the EU regulation
NFT	Non-Fungible Token
NPC	Non-Player Character
OGC	Open Geospatial Consortium
PET	Privacy Enhancing Technologies
R&D	Research and Development
SPoF	Single Point of Failure
SDG	Sustainable Development Goal
USD	United States Dollar
VR	Virtual Reality
W3C	World Wide Web Consortium
XR	eXtended Reality

List of boxes

List of figures

List of tables

Annexes

Annex 1. Next generation virtual worlds digital ecosystem

	Keyword	Digital area
1	3D graphics	3D Printing, Additive manufacturing
2	3D computer graphics	3D Printing, Additive manufacturing
3	afterlife	Extended / Virtual / Augmented / Mixed reality, Metaverse
4	afterworld	Extended / Virtual / Augmented / Mixed reality, Metaverse
5	agent persona modelling	Extended / Virtual / Augmented / Mixed reality, Metaverse
6	augmented reality	Extended / Virtual / Augmented / Mixed reality, Metaverse
7	AR	Extended / Virtual / Augmented / Mixed reality, Metaverse
8	avatar	Extended / Virtual / Augmented / Mixed reality, Metaverse
9	blockchain	Blockchain, Distributed Ledger
10	blogging	Extended / Virtual / Augmented / Mixed reality, Metaverse
11	blogsphere	Extended / Virtual / Augmented / Mixed reality, Metaverse
12	chaingaming	Extended / Virtual / Augmented / Mixed reality, Metaverse
13	chat room	Extended / Virtual / Augmented / Mixed reality, Metaverse
14	computer generated imagery	Extended / Virtual / Augmented / Mixed reality, Metaverse
15	cosmoplastic	Extended / Virtual / Augmented / Mixed reality, Metaverse
16	cosmos	Extended / Virtual / Augmented / Mixed reality, Metaverse
17	cryptocurrency	Blockchain, Distributed Ledger
18	crypto	Blockchain, Distributed Ledger
19	Cyber world	Extended / Virtual / Augmented / Mixed reality, Metaverse
20	cyberculture	Extended / Virtual / Augmented / Mixed reality, Metaverse
21	cyberpunk	Extended / Virtual / Augmented / Mixed reality, Metaverse
22	cyberspace	Extended / Virtual / Augmented / Mixed reality, Metaverse
23	cyborg	Extended / Virtual / Augmented / Mixed reality, Metaverse
24	decentralized finance	Blockchain, Distributed Ledger
25	DeFi	Blockchain, Distributed Ledger

26	disembodiment	Extended / Virtual / Augmented / Mixed reality, Metaverse
27	education	Extended / Virtual / Augmented / Mixed reality, Metaverse
28	embodied_interaction	Extended / Virtual / Augmented / Mixed reality, Metaverse
29	entertainment	Extended / Virtual / Augmented / Mixed reality, Metaverse
30	extended reality	Extended / Virtual / Augmented / Mixed reality, Metaverse
31	facebook	Infrastr, Cloud Cmpg, Dgtl Pltf, IaaS, SaaS, PaaS, Social Ntws, Internet
32	first person	Extended / Virtual / Augmented / Mixed reality, Metaverse
33	game	Extended / Virtual / Augmented / Mixed reality, Metaverse
34	game controllers	Extended / Virtual / Augmented / Mixed reality, Metaverse
35	gamefi	Blockchain, Distributed Ledger
36	gamification	Blockchain, Distributed Ledger
37	gaming	Extended / Virtual / Augmented / Mixed reality, Metaverse
38	glasses	Extended / Virtual / Augmented / Mixed reality, Metaverse
39	graviton	Extended / Virtual / Augmented / Mixed reality, Metaverse
40	habitat	Extended / Virtual / Augmented / Mixed reality, Metaverse
41	hand based input device	Extended / Virtual / Augmented / Mixed reality, Metaverse
42	haptic feedback devices	Extended / Virtual / Augmented / Mixed reality, Metaverse
43	head mounted display	Extended / Virtual / Augmented / Mixed reality, Metaverse
44	headsets	Extended / Virtual / Augmented / Mixed reality, Metaverse
45	holographic	Extended / Virtual / Augmented / Mixed reality, Metaverse
46	humanoid	Extended / Virtual / Augmented / Mixed reality, Metaverse
47	hyperreality	Extended / Virtual / Augmented / Mixed reality, Metaverse
48	hyperspace	Extended / Virtual / Augmented / Mixed reality, Metaverse
49	imaginary place	Extended / Virtual / Augmented / Mixed reality, Metaverse
50	immanency	Extended / Virtual / Augmented / Mixed reality, Metaverse
51	Immersion	Extended / Virtual / Augmented / Mixed reality, Metaverse
52	Immersive	Extended / Virtual / Augmented / Mixed reality, Metaverse
53	immersive device	Extended / Virtual / Augmented / Mixed reality, Metaverse
54	immersive multimedia	Extended / Virtual / Augmented / Mixed reality, Metaverse

55	immersive technologies	Extended / Virtual / Augmented / Mixed reality, Metaverse
56	immersive virtual world	Extended / Virtual / Augmented / Mixed reality, Metaverse
57	information superhighway	Infrastr, Cloud Cmpg, Dgtl Pltf, IaaS, SaaS, PaaS, Social Ntws, Internet
58	infosphere	Extended / Virtual / Augmented / Mixed reality, Metaverse
59	integration optimisation	Artificial Intelligence
60	interactivity	Extended / Virtual / Augmented / Mixed reality, Metaverse
61	interconnected world	Extended / Virtual / Augmented / Mixed reality, Metaverse
62	intermundane	Extended / Virtual / Augmented / Mixed reality, Metaverse
63	interoperability	5G & beyond, Autonomous Ntws, Comms, Tele-comms, connectivity
64	interplanetary	Extended / Virtual / Augmented / Mixed reality, Metaverse
65	jabber	Infrastr, Cloud Cmpg, Dgtl Pltf, IaaS, SaaS, PaaS, Social Ntws, Internet
66	keyboards	Extended / Virtual / Augmented / Mixed reality, Metaverse
67	live action role playing game	Extended / Virtual / Augmented / Mixed reality, Metaverse
68	LARP	Extended / Virtual / Augmented / Mixed reality, Metaverse
69	linden	Extended / Virtual / Augmented / Mixed reality, Metaverse
70	machinima	Extended / Virtual / Augmented / Mixed reality, Metaverse
71	marketing	Blockchain, Distributed Ledger
72	marketplace	Blockchain, Distributed Ledger
73	massively multiplayer online games	Extended / Virtual / Augmented / Mixed reality, Metaverse
74	meta	Extended / Virtual / Augmented / Mixed reality, Metaverse
75	microblog	Extended / Virtual / Augmented / Mixed reality, Metaverse
76	microblogging	Extended / Virtual / Augmented / Mixed reality, Metaverse
77	mmorpg	Extended / Virtual / Augmented / Mixed reality, Metaverse
78	motion controllers	Extended / Virtual / Augmented / Mixed reality, Metaverse
79	motion input device	Extended / Virtual / Augmented / Mixed reality, Metaverse
80	motion rendering	Extended / Virtual / Augmented / Mixed reality, Metaverse
81	multi agent optimisation	Artificial Intelligence
82	multimodal content representation	Extended / Virtual / Augmented / Mixed reality, Metaverse
83	multimodal entity expansion	Extended / Virtual / Augmented / Mixed reality, Metaverse
84	multimodal inference	Artificial Intelligence

85	multimodal interaction	Extended / Virtual / Augmented / Mixed reality, Metaverse
86	multimodalentity linking	Extended / Virtual / Augmented / Mixed reality, Metaverse
87	multiplatform	Extended / Virtual / Augmented / Mixed reality, Metaverse
88	multiplayer	Extended / Virtual / Augmented / Mixed reality, Metaverse
89	multi task interaction	Extended / Virtual / Augmented / Mixed reality, Metaverse
90	multiverse	Extended / Virtual / Augmented / Mixed reality, Metaverse
91	mundivagant	Extended / Virtual / Augmented / Mixed reality, Metaverse
92	neocosmic	Extended / Virtual / Augmented / Mixed reality, Metaverse
93	nexus	Extended / Virtual / Augmented / Mixed reality, Metaverse
94	non-fungible token	Blockchain, Distributed Ledger
95	NFT	Blockchain, Distributed Ledger
96	object generation	Extended / Virtual / Augmented / Mixed reality, Metaverse
97	object recognition	Artificial Intelligence
98	omniverse	Extended / Virtual / Augmented / Mixed reality, Metaverse
99	Online_multiplayer	Extended / Virtual / Augmented / Mixed reality, Metaverse
100	otherworld	Extended / Virtual / Augmented / Mixed reality, Metaverse
101	pachinko	Extended / Virtual / Augmented / Mixed reality, Metaverse
102	panopticon	Extended / Virtual / Augmented / Mixed reality, Metaverse
103	Persistent universe	Extended / Virtual / Augmented / Mixed reality, Metaverse
104	portlet	Infrastr, Cloud Cmpg, Dgtl Pltf, IaaS, SaaS, PaaS, Social Ntws, Internet
105	reality capture	Extended / Virtual / Augmented / Mixed reality, Metaverse
106	realm	Blockchain, Distributed Ledger
107	Reinforcement learning based approach	Artificial Intelligence
108	RLB	Artificial Intelligence
109	sandbox	Extended / Virtual / Augmented / Mixed reality, Metaverse
110	scenario evaluation	Extended / Virtual / Augmented / Mixed reality, Metaverse
111	scenario generation	Extended / Virtual / Augmented / Mixed reality, Metaverse
112	scenario population	Extended / Virtual / Augmented / Mixed reality, Metaverse
113	scene generation	Extended / Virtual / Augmented / Mixed reality, Metaverse
114	scene recognition	Artificial Intelligence
115	screens and display technologies	Extended / Virtual / Augmented / Mixed reality, Metaverse

116	sims	Extended / Virtual / Augmented / Mixed reality, Metaverse
117	singularity	Blockchain, Distributed Ledger
118	smalltalk	Extended / Virtual / Augmented / Mixed reality, Metaverse
119	Smart contract	Blockchain, Distributed Ledger
120	Social media	Extended / Virtual / Augmented / Mixed reality, Metaverse
121	social space	Extended / Virtual / Augmented / Mixed reality, Metaverse
122	software agent	Artificial Intelligence
123	sound recognition	Artificial Intelligence
124	sound synthesis	Extended / Virtual / Augmented / Mixed reality, Metaverse
125	spacetime	Extended / Virtual / Augmented / Mixed reality, Metaverse
126	spectacles	Extended / Virtual / Augmented / Mixed reality, Metaverse
127	speech recognition	Artificial Intelligence
128	speech synthesis	Extended / Virtual / Augmented / Mixed reality, Metaverse
129	strong interaction	Extended / Virtual / Augmented / Mixed reality, Metaverse
130	superstruct	Extended / Virtual / Augmented / Mixed reality, Metaverse
131	teleport	Extended / Virtual / Augmented / Mixed reality, Metaverse
132	teleportation	Extended / Virtual / Augmented / Mixed reality, Metaverse
133	telepresence	Extended / Virtual / Augmented / Mixed reality, Metaverse
134	terraforming	Extended / Virtual / Augmented / Mixed reality, Metaverse
135	transhuman	Extended / Virtual / Augmented / Mixed reality, Metaverse
136	transhumanism	Extended / Virtual / Augmented / Mixed reality, Metaverse
137	unreality	Extended / Virtual / Augmented / Mixed reality, Metaverse
138	urban area	Extended / Virtual / Augmented / Mixed reality, Metaverse
139	user senses	Extended / Virtual / Augmented / Mixed reality, Metaverse
140	Virtual advertising	Blockchain, Distributed Ledger
141	Virtual alerts	Blockchain, Distributed Ledger
142	Virtual art	Extended / Virtual / Augmented / Mixed reality, Metaverse
143	Virtual banking	Blockchain, Distributed Ledger
144	Virtual blogs	Extended / Virtual / Augmented / Mixed reality, Metaverse
145	Virtual business	Blockchain, Distributed Ledger
146	Virtual chat room	Extended / Virtual / Augmented / Mixed reality, Metaverse
147	Virtual cinema	Extended / Virtual / Augmented / Mixed reality, Metaverse

148	Virtual class	Extended / Virtual / Augmented / Mixed reality, Metaverse
149	Virtual coaching	Extended / Virtual / Augmented / Mixed reality, Metaverse
150	Virtual conference	Extended / Virtual / Augmented / Mixed reality, Metaverse
151	Virtual consulting	Extended / Virtual / Augmented / Mixed reality, Metaverse
152	Virtual counseling	Blockchain, Distributed Ledger
153	Virtual discussion board	Extended / Virtual / Augmented / Mixed reality, Metaverse
154	Virtual economy	Blockchain, Distributed Ledger
155	Virtual education	Extended / Virtual / Augmented / Mixed reality, Metaverse
156	Virtual entertainment	Extended / Virtual / Augmented / Mixed reality, Metaverse
157	Virtual environment	Extended / Virtual / Augmented / Mixed reality, Metaverse
158	Virtual event	Extended / Virtual / Augmented / Mixed reality, Metaverse
159	Virtual fashion	Extended / Virtual / Augmented / Mixed reality, Metaverse
160	Virtual forum	Extended / Virtual / Augmented / Mixed reality, Metaverse
161	Virtual gallery	Extended / Virtual / Augmented / Mixed reality, Metaverse
162	virtual good	Blockchain, Distributed Ledger
163	Virtual marketing	Blockchain, Distributed Ledger
164	Virtual museum	Extended / Virtual / Augmented / Mixed reality, Metaverse
165	virtual object	Extended / Virtual / Augmented / Mixed reality, Metaverse
166	Virtual property	Blockchain, Distributed Ledger
167	Virtual reality	Extended / Virtual / Augmented / Mixed reality, Metaverse
168	VR	Extended / Virtual / Augmented / Mixed reality, Metaverse
169	Mixed reality	Extended / Virtual / Augmented / Mixed reality, Metaverse
170	MR	Extended / Virtual / Augmented / Mixed reality, Metaverse
171	virtual self	Extended / Virtual / Augmented / Mixed reality, Metaverse
172	virtual service	Blockchain, Distributed Ledger
173	Virtual shopping	Blockchain, Distributed Ledger
174	Virtual socializing	Extended / Virtual / Augmented / Mixed reality, Metaverse
175	Virtual tourism	Extended / Virtual / Augmented / Mixed reality, Metaverse
176	virtual training	Extended / Virtual / Augmented / Mixed reality, Metaverse
177	Virtual tutoring	Extended / Virtual / Augmented / Mixed reality, Metaverse
178	Virtual world	Extended / Virtual / Augmented / Mixed reality, Metaverse

179	visor	Extended / Virtual / Augmented / Mixed reality, Metaverse
180	vrchat	Extended / Virtual / Augmented / Mixed reality, Metaverse
181	working group	Extended / Virtual / Augmented / Mixed reality, Metaverse
182	workspace	Extended / Virtual / Augmented / Mixed reality, Metaverse
183	extended reality	Extended / Virtual / Augmented / Mixed reality, Metaverse
184	5G	5G & beyond, Autonomous Ntws, Comm, Tele-comms, connectivity
185	5G connectivity	5G & beyond, Autonomous Ntws, Comm, Tele-comms, connectivity
186	internet of sensing	IoT, AIDC (autom idn & data capture)
187	internet of thing	IoT, AIDC (autom idn & data capture)
188	machine learning technique	Artificial Intelligence
189	computer-controlled machinery	3D Printing, Additive manufacturing
190	human-machine interaction	Artificial Intelligence
191	machine learning	Artificial Intelligence
192	deep Learning	Artificial Intelligence
193	online learning	Verticals
194	virtual_learning	Extended / Virtual / Augmented / Mixed reality, Metaverse
195	e-learning	Extended / Virtual / Augmented / Mixed reality, Metaverse
196	second life	Extended / Virtual / Augmented / Mixed reality, Metaverse
197	blockchain technology	Blockchain, Distributed Ledger
198	motion recognition	Artificial Intelligence
199	bio-inspired sensors	Autonomous Systems, Robotics
200	distributed sensors system	Autonomous Systems, Robotics
201	Connected sensors	IoT, AIDC (autom idn & data capture)
202	embedded sensors and wireless systems	IoT, AIDC (autom idn & data capture)
203	remote sensors	IoT, AIDC (autom idn & data capture)
204	sensors (IoT)	IoT, AIDC (autom idn & data capture)
205	wireless sensor technologies	IoT, AIDC (autom idn & data capture)
206	simulation	Extended / Virtual / Augmented / Mixed reality, Metaverse
207	connected devices	IoT, AIDC (autom idn & data capture)
208	cyber-physical systems	IoT, AIDC (autom idn & data capture)
209	distributed sensor networks	IoT, AIDC (autom idn & data capture)
210	embedded systems	IoT, AIDC (autom idn & data capture)
211	implanted/wearable medical devices	IoT, AIDC (autom idn & data capture)
212	industrial IOT	IoT, AIDC (autom idn & data capture)
213	smart devices	IoT, AIDC (autom idn & data capture)
214	smart home	IoT, AIDC (autom idn & data capture)
215	web of things	IoT, AIDC (autom idn & data capture)

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