The Role of Blockchain Interoperability for a Sustainable Metaverse: A Research Agenda

Abstract—**The metaverse is increasingly finding its way into our lives, for example through its application in the medical field, which makes a solid technical basis important. Blockchain technology can ensure the immutability and uniqueness of avatars and digital assets in metaverses. Interaction between different metaverses requires the blockchains they run on to be interoperable. Lack of interoperability can lead to user isolation and lock-in, winner-takes-all effects and adverse outcomes for citizens as well as societies, which ultimately render a metaverse unsustainable. In contrast, blockchain interoperability and open standards could enable a multi-metaverse ecosystem that promotes UN Sustainable Development Goals. Based on a literature review, a research agenda is proposed that promotes a sustainable metaverse.**

Index Terms—**Blockchain Interoperability, Metaverse, Research Agenda, Sustainability, UN Sustainable Development Goals**

I. Introduction

Metaverse-like applications have existed for almost two decades in the gaming industry, starting with *Second Life* in 2003 [1]. As the technological foundations mature, the scope for realistic and value-adding use cases for metaverses expands [2] [3]. Aside from gaming, new use cases are being developed in the domains of education [4], healthcare [5] [6], work [7] and collaboration [8]. Blockchain is suggested as an enabler technology of metaverses [2] [3] [9], for example, to improve data privacy and security in these use cases. Blockchain can also facilitate fighting poverty and reduce resource consumption by minimizing distances in the virtual space [10].

Metaverses merge the physical with the virtual world by facilitating and combining technologies that allow to augment and extend reality [4]. They enable virtual real-time interactions between users and their virtual representations, called avatars, with digital assets or digital twins of physical objects [2] [11] [12]. Digital twins represent unique physical objects in the virtual space. In a metaverse, two users might trade a physical object by selling its digital twin for digital money. Engaging in such transactions is only reasonable, for an honest user, if avatars and digital twins are unique, unalterable and secure: blockchain-based non-fungible tokens (NFTs) can be used to enable these properties [2] [9] [13].

Transactions between metaverses are only possible if the blockchains they run on are interoperable [2] [3], for instance, to enable NFT trading between avatars from different metaverses [13]. In addition to private transactions, some application areas such as healthcare might be subject to country-specific laws and regulations that require medical records to be shareable [14]. However, from the point of view of companies developing metaverses, isolated metaverses promise the highest profits: by locking in their users, isolated metaverses effectively become monopolies. This is a particularly promising avenue for today's internet and social media giants, who can leverage their existing networks and ecosystems to facilitate such monopolies [4] [15]. Indeed, current blockchain-based metaverses lack openness and interoperability [9]. At present, several mutually incompatible metaverse ecosystems are under development [16]. From the point of view of users and societies, the monopolistic structures of isolated metaverses are likely to yield less benefits than interoperable metaverses.

Metaverse isolation exacerbates another important barrier to metaverse access: the extent to which access to high-quality metaverses depends on financial resources. If high-quality metaverses are isolated and access is pricey, large parts of society, and even entire nations, are likely to be disadvantaged [17]. This directly undermines the expectation that metaverses can help poorer countries, particularly underserved social classes, achieve better outcomes in education, health and sustainability, and is contrary to the UNSDGs. We follow the calls to investigate how metaverses could help promote the UNSDGs [18]. Specifically, we investigate the role of blockchain interoperability (BCI):

- RQ: **How can BCI promote metaverse alignment with the UNSDGs?**

This work introduces a research agenda towards a theoretical foundation for future research and development towards a sustainable metaverse. Current research and market developments show increased interest, relevance and capitalization but also a threat from isolated metaverses. As an isolated metaverse may violate multiple UNSDGs, ways of connecting metaverses with each other must be found, promoted and perhaps even legislated. Since literature proposes metaverses to be based on blockchain technology, this study describes how BCI can be used to develop multi-metaverse ecosystems by connecting metaverses and their blockchains with each other to serve as a foundation for a sustainable metaverse.

II. Metaverse Applications

The metaverse was first described in the 1990's [19]. Despite a lack of clear definition and future shape [3], the purpose of metaverses is generally understood as enabling social interaction in a dynamic virtual environment [20]. Virtual (VR) and augmented reality (AR) technology innovations render virtual interactions increasingly realistic [3]. The purpose of the metaverse to enable social interaction in a virtual space is also reflected by the strategic decisions of *Meta*, one of the largest social media platforms in the world [21] with almost three billion active users. Meta changed its name in 2021 to emphasize its focus on the metaverse and related technologies such as augmented reality. At the time of writing, Meta is running large losses on its metaverse-developing unit and laid off many of its employees in 2022 [22]. Meta has not been able to leverage the positive network effects [23] of Facebook to make its metaverse a commercial success yet. Still, analysts attribute great potential and strong growth to the metaverse market in the coming years, with industry value forecast to grow to $50 billion by 2026 [24] and up to $5 trillion by 2030 [25].

Existing metaverses are often used for gaming and entertainment purposes and, as in the case of Pokémon Go, can even promote physical exercise [26]. Pokémon Go was one of the first globally successful AR-based games, released in 2016 and played by millions of users worldwide [26]. Users would scan their physical environment with their smartphone cameras to detect and collect virtual monsters, or Pokémons. The Pokémons were displayed as overlays on top the physical environment on the smartphone screen. In a blockchain-based Pokémon metaverse, Pokémons could be stored as digital assets. This would guarantee their uniqueness and immutability [3] [9] and protect them from centralized control [27]. Pokémons could then be traded among users on an internal market or externally [28] on decentralized exchanges or NFT market places as OpenSea.

In the workplace, the Covid-19 pandemic boosted demand for remote work [29]. Online collaboration platforms and video conferencing providers benefited greatly [29], but after the pandemic was deemed to be over, many employers are looking for ways to make working in the office more attractive in order to encourage their employees to return to the physical workplace [30]. Remote work has been linked to many benefits for employers and employees alike - lower costs for office space and less time spent commuting, for instance [31] - but also to negative effects like increased social isolation [32]. Metaverses could offer the same benefits as remote work via videoconferencing and fewer disadvantages, offering a more immersive and engaging user experience and strengthening social ties [33].

In the healthcare domain, metaverse applications have been praised for providing easier access to better healthcare services to underserved and disadvantaged population groups [34], contributing to UNSDG Goal 3 “Ensure healthy lives and promote well-being for all at all ages”. For instance, the UAE-based *Thumbay Group* has implemented a hospital metaverse including virtual reality and other technologies [35] to facilitate virtual doctor visits and diagnostics. Medical services in the metaverse can benefit from the use of artificial intelligence (AI) applications, such as more accurate cancer diagnoses through improved image recognition [34].

Recent developments in AI are expected to speed up the evolution of the metaverse [36] in terms of auto-generating content [37] like 3D background visuals or computer-generated metaverse inhabitants to converse with. This raises new challenges for authentication and access control, fraud detection and privacy preservation [38] that require new AI safety measures [39]. These safety measures are particularly important when AI simulates human-like behavior, interacts with human agents and potentially conducts Sybil attacks or other malicious behavior [**?**].

Use cases for the metaverse are also emerging in the financial sector. *JPMorgan*, for example, identified a large opportunity in the virtual real estate market and was the first bank in the world to open its own metaverse office [40]. Future scenarios have users walk through the investment objects, sign legally binding contracts, and pay for real estate - physical or digital real estate - in the metaverse. Such a metaverse might have an independent token-based economy [41].

III. Blockchain Interoperability

Literature suggests blockchain as one of several technologies that provide the foundation for metaverses [2] [9]. Blockchains are distributed ledgers stored and maintained by a network of participants, each of whom holds a copy of the same information. Interactions of participants are governed by rules in such ways that participants, although they do not know or trust each other, can still securely interact [42]. Blockchains can be public or private and implement different consensus mechanisms such as Proof of Work (PoW), Proof of Stake (PoS) or Byzantine fault tolerance (BFT) [43]. The two largest blockchains in terms of market capitalization, *Bitcoin* and *Ethereum*, are both public and permissionless. While Bitcoin facilitates a computationally heavy PoW consensus mechanism [44], Ethereum has recently switched to a PoS consensus mechanism [45]. This drastically reduced Ethereum’s energy consumption [45] and contributes to the efforts of blockchain providers and researchers to find ways of reducing the energy requirements and carbon footprint of blockchain solutions [46] [47].

Communication between blockchains – or metaverses running on different blockchains – is enabled by blockchain interoperability mechanisms [48]. Public blockchains can be connected with the BCI mechanisms sidechains & relays [49], notary schemes [48] [50], and hashed time-lock contracts (HTLCs) [48] [50] [51]. In contrast to these public connectors, hybrid connectors and Blockchains of Blockchains can also establish interoperability between public and private blockchains, but are in an earlier development stage [51].

BCI mechanisms are facilitated by BCI solutions that can be classified and compared on a technical layer [51]. They can also be compared on their developer community based on publicly available source code [52]. BCI solutions allow BCI functions [50] such as atomic swaps [53] or token transfers [54]. BCI functions serve as the foundation for interactions within a multi-metaverse ecosystem.

A key BCI function and arguably a requirement for a multi-metaverse ecosystem is the *token transfer*, which enables token transfers between blockchains [54], or the move of an avatar or a digital asset from one metaverse to another

[2]. In order to achieve token transfers, many BCI solutions create a virtual version of the original token on the recipient blockchain, while the original token is made inaccessible. A well-known example is *Wrapped Bitcoin (WBTC)*, which allows the transfer of Bitcoin from the Bitcoin blockchain to the Ethereum blockchain by creating a *virtual* version of Bitcoin on its new destination in form of a wrapped token, as its name implies. A token is created or minted on the recipient blockchain, while being locked or destroyed on the sender blockchain [55]. The function of making assets from one blockchain transferable to another blockchain could be regarded as an *adapter* [23].

Moving avatars from one metaverse to another [56] would also require moving their online reputation [57], for instance using a universal wallet [58]. The online reputation of an avatar could be stored in the form of a soulbound token [59], which is tied to the identity of the user and cannot be transferred to another user. Soulbound tokens are a special kind of NFTs derived from the *ERC-721 token standard*.

While many BCI solutions focus on the transfer of fungible tokens from one blockchain-based system to another [60], the transfer of NFTs [61] is rarely discussed in literature by the time of writing. Transfers of NFTs between blockchains are more challenging and still face issues [62]. Still, the implementation of such a solution is necessary in a sustainable metaverse, as it would allow to transfer a digital twin from one metaverse to another or enable people to travel between metaverses using their avatars.

An avatar transfer within a multi-metaverse ecosystem is shown in Fig. 1. This would, for example, allow Alice to see a doctor in a metaverse that is focusing on diagnosing seldom diseases. As in the physical world, where Alice would not be able to exist in two places at the same time, the BCI solution locks or destroys the NFT which represents Alice in metaverse A and unlocks or creates the NFT in the medical metaverse B. The BCI solution ensures consistency, and other metaverse participants can be sure that Alice's avatar is genuine.

Consistency is a particularly important feature for blockchain-based metaverses [63]. They rest on the assumption that avatars and digital twins are unique, tamper-proof and immutable within and across multiple blockchains [9]. Avatars and digital twins that represent unique assets in the real world must not exist more than once within a multi-metaverse ecosystem and its interconnected blockchains, and must not be duplicated. The most important aspect of token transfers is that the original token stays locked or is irrevocably burned on the original blockchain if there exists a virtual or wrapped version of it on another blockchain. Otherwise, the NFT might be copied and so-called Doppelgangers created to conduct Sybil attacks on other users or illicitly selling a specific digital asset multiple times.

As security is a key argument for the use of blockchain technology for the metaverse [9], BCI can only contribute to improve the technical foundations of the metaverse if BCI solutions are decentralized, robust and secure. The blockchain-based metaverse builds on the assumption that avatars and digital twins are unique, tamper-proof and immutable, also across multiple blockchains [9]. A high level of security for BCI solutions providing BCI functions for those digital representations must be guaranteed. Yet, security aspects of BCI are one of the most important open issues [51] and challenges [60] in the field. Even for stand-alone blockchains, where no BCI functions are involved, security is an aspect that still needs to be improved [64]. Multi-metaverse ecosystems enabled by BCI solutions may inherit risks if implemented without diligent security considerations. Recent attacks on BCI solutions led to large financial losses, as the prominent examples of *Wormhole* and *Ronin* show [65]. As metaverse use cases become more relevant and sophisticated, BCI solutions implemented in the metaverse can become a lucrative target for hackers as well.

Vulnerabilities in BCI solutions could enable attacks [66]. For example, by manipulating a BCI solution and its token transfer function, a hacker could attempt to illicitly mint and use a token on a new blockchain that has not been locked on the original blockchain. This could enable Sybil attacks in which the attacker uses an avatar that should currently be locked and inaccessible in this metaverse as the avatar is currently being used by its real owner in another metaverse. As mentioned above, attacks on BCI solutions to manipulate the lock-mint and burn-release mechanisms have already been conducted, for example, in the Wormhole bridge attack [67]. In this example, attackers exploited a software bug in the source code of this BCI solution to release tokens on the recipient blockchains which have not been locked on the sender blockchain [67].

The attacks mentioned above result in an inconsistent state across blockchains, as the token illegally circulates on multiple blockchains. In the metaverse, this could lead to avatars that are active on multiple blockchains and their metaverses, although one human can only use one avatar at a particular point in time. While the damage in the Wormhole and Ronin attacks was of a financial nature [65], the impact and potential damage in the metaverse could be higher. For example, in a medical metaverse, sensitive patient data could be exposed when a Sybil attacker pretends to be a doctor by falsely using their avatar, which should currently be locked and inactive in this particular medical metaverse. This attack could even be performed by a generative AI agent, if no appropriate AI safety measures are in place.

To tackle these problems, security aspects of BCI in the metaverse must be studied and continually improved [38]. Literature lays the groundwork by classifying attacks on BCI solutions and proposing tools to detect security weaknesses [67]. To prevent attacks on BCI solutions and other blockchain applications, security measures for storing keys should be improved and secure mechanisms for transferring data outside the blockchain to the blockchain should be provided [68]. Furthermore, security vulnerabilities in smart contracts, which are blockchain-based programs that, for example, allow converting an NFT into a soulbound token, should be identified and their operation continuously monitored [68]. A test bed

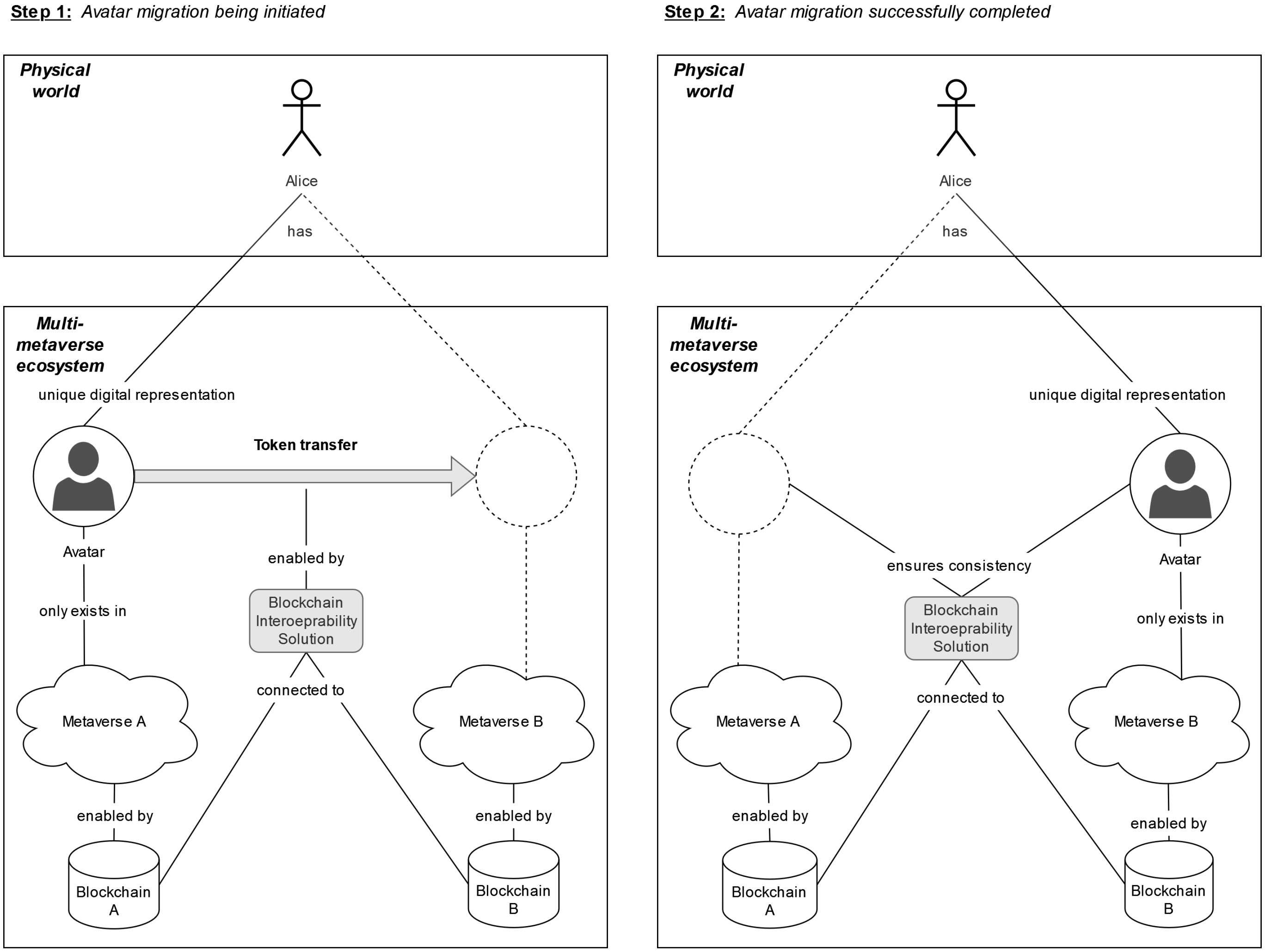

Fig. 1. Avatar migration in a multi-metaverse ecosystem.

for identifying vulnerabilities in BCI solutions, which are also depicted as smart contracts, is proposed [69]. In case of BCI solutions, it would be necessary to test and monitor its smart contract code on all connected metaverses and their respective blockchains, which makes them more difficult to secure [69]. In addition, the security level of a BCI solutions can be increased by utilizing multiple BCI mechanisms [51]. While BCI analysis and defense methods are proposed, secure BCI in the metaverse remains an open challenge [65].

IV. Historical Parallels to Isolated Societies

Although the open challenge of implementing secure BCI solutions in the metaverse persists, it is essential to create an open multi-metaverse ecosystem. The importance of an open and fair metaverse is illustrated by a historical example. Analogies serve as a method in science to understand and reason by drawing parallels between historical cases and new concepts [70]. The consequences of being trapped in an isolated metaverse could be similar to living and working in a totalitarian regime like East Germany from 1949 to 1990. Berlin was separated into two blocks by a heavily guarded physical wall from 1961 to 1989. Attempts to cross the wall were forcibly prevented. This separation tore families apart, as people could not choose on which side of the wall they wanted to live [71]. They also had no choice on which side of the wall to see the doctor, go to school, or go to work. The separation of the city harmed multiple UNSDGs. Interaction between the two parts of the city was almost non-existent and severely limited the freedom of the inhabitants and their quality of living.

The isolation resulted in economic problems. Trading between people living on different sides of the wall was impossible and the Eastern part of the city could not participate in international trading [72]. In the end of 1989 the wall that separated the city was demolished, finally allowing people to freely move between and interact with people from both parts of the city of Berlin. The German reunion facilitated economic growth, higher real income and investments in East Germany, at least in the short-term [73].

As the metaverse increasingly enables essential use cases in the virtual world, care must be taken to ensure that history is not repeated in that new realm. In the future, applications in healthcare, education, work and other highly relevant areas of life will be brought into the metaverse. It can be particularly problematic if a single entity controls an isolated metaverse. Analogous to the East Germany example, a central institution - an internet giant, for example - can prevent its users from leaving its territory - symbolically their avatars from leaving the specific metaverse of the internet giant - and prevent them from interacting with users of another domain. This can exclude users from accessing the best possible healthcare, education system or work environment. The latter can also have consequences on the innovation capabilities of users and their isolated community, resulting in economic disadvantages.

Connecting previously isolated metaverses can have similar effects on virtual worlds as demolishing the wall in the physical world had on Berlin in 1989. The resulting multi-metaverse ecosystem could allow users to change their virtual residence, temporarily visit another metaverse for a specific purpose, for example, to see a virtual doctor or allow interaction with users residing in other virtual worlds. As a result, the connection of metaverses using BCI can enable a sustainable multi-metaverse ecosystem which is in line with the UNSDGs.

V. Metaverse and UNSDGs

Literature suggests the adoption of blockchain to promote sustainability in the field of health care, education and work [10], but lacks an analysis in the context of metaverse. As the metaverse market grows rapidly and its use cases increasingly permeate important areas of life, a sustainable development of the metaverse is essential. To establish a sustainable research agenda for a multi-metaverse ecosystem, the Goals of the 2030 Agenda for Sustainable Development of the United Nations (UNSDGs) [74] are analyzed in this context. While an isolated metaverse risks violating several UNSDGs, a multi-metaverse ecosystem of interconnected metaverses can help to fulfill selected UNSDGs. For blockchain-based metaverses, BCI is key to a sustainable metaverse by enabling a multi-metaverse ecosystem. In this context, Table I summarizes the threats posed by isolated metaverses and points out the requirements for aligning with selected UNSDGs.

Within the healthcare sector (UNSDG Goal 3), integration of advanced technologies in the metaverse promises to enhance clinical practices and patient outcomes [34]. This leads to improved quality, accessibility and cost-effectiveness within the field [75]. The use of blockchain technology enables applications in healthcare to enhance data integrity and decentralized trust. However, challenges such as scalability, privacy, compliance and security with healthcare regulations must be considered in order to prevent malicious behavior of metaverse users [14]. The metaverse in healthcare offers an approach that promises to reduce costs, increases the inclusion of poorer social classes and offers earlier access to medical innovations [34].

In an educational context (UNSDG Goal 4), the metaverse transforms learning experiences and provide equal opportunities [76]. Through the extension of the internet into an interactive virtual world, the metaverse introduces the potential to deliver educational content on a global scale by breaking geographical barriers while reducing costs [77]. This is especially beneficial for poorer social classes and offers personalized learning experiences in a universal context. While the metaverse offers numerous advantages for educational applications, it also poses potential threats including weaker social connections, privacy concerns, or potential new forms of cyber crime. Furthermore, since users in school-age are still in the process of building their identities, it can be challenging to adapt to real-world social interactions [78].

The metaverse can also have an impact on the job market (UNSDG Goal 8), for instance, concerning potential virtual employment opportunities. The need for physical office spaces is reduced due to the establishment of remote and virtual work environments [79]. In addition, the introduction of a metaverse for teleworking can reduce population pressure, as residents can move from mega cities to less populated areas without suffering work-related disadvantages. As a result, travel-related environmental pollution can be reduced [80] (UNSDG Goal 13).

The metaverse also offers a digital environment that promises a transformative social landscape that promotes inclusion, diversity and accessibility, and enables a broad spectrum of individuals to interact [81] (UNSDG Goal 10). For this purpose, digital twins are used in the metaverse that necessitate identifying and testing solutions with regards to security and privacy challenges [82] (UNSDG Goal 11). Through the implementation of blockchain-based solutions, features such as high transparency and accountability through decentralized and tamper-resistant ledgers are introduced. This can enhance the security, privacy and trustworthiness of the metaverse [83] [9] (UNSDG Goal 16).

There are currently several initiatives aimed at developing interoperable metaverses, even if they are not specifically aimed at sustainability. The *Open Metaverse Alliance for Web3 (OMA3)* [84] aims to create a large metaverse consortium whose participating organizations implement agreed-upon standards to promote interoperability and facilitate different kind of interactions between their metaverses. Other initiatives focus on enabling certain BCI functions between metaverses, such as *cross-chain messaging* [85], or certain interoperable assets, such as *multi-metaverse wearables* [86].

OMA3 is one of the first efforts to make the metaverses of participating organizations compatible with each other through a common product standard [23]. *Inclusiveness, transparency and decentralization* are the fundamental principles of the alliance. OMA3 emphasizes that users have sovereignty over their digital identities and assets, which they can move between participating organizations and their metaverses. Multi-metaverse functions should remain under the control of the users. However, by its own description, the alliance forms a *consortium*, which may make interoperability with non-consortium members difficult.

An example of a practical approach of enabling interop-

TABLE I
UNSDGS IN THE METAVERSE

Selected UNSDGs	Relevance	General metaverse threats	Threats of isolated metaverses	Interoperability: the solution?
Goal 3. Ensure healthy lives and promote well-being for all at all ages	Easier access for people with reduced mobility, remote populations, poorer populations; Access to better services than available in a region or country; Reduced costs for public health [75] systems; Better life outcomes through early and regular care [34]	Fraud and malicious behavior of healthcare service providers or patients facilitated by remote setting [14]	Lock-in into low-quality metaverses; Inaccessibility of certain services; Data theft by metaverse owner; Overcharging by metaverse owner or healthcare service providers; Worse health outcomes	Partially: less threat of lock-in; In theory, no more overcharging; In practice: will require regulation to curb monopolistic tendencies
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Easier access for people with reduced mobility, remote populations, poorer populations [76]; Access to better services than available in a region or country; Reduced costs for public education systems [77]; Better life outcomes through early and regular education	Fraud and malicious behavior of education service providers or students facilitated by remote setting [78]		
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Better matching of jobs and applicants through reduction of geospatial barriers [79]; New jobs; Less travel and less office space required [80]; Better employment opportunities for less mobile people; More stringent policing of "indecent work"	Fraud and malicious behavior of employees or employers facilitated by remote work		
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	More idea and information exchange between more diverse population groups [81]; Greater audience for innovations	Intellectual property rights theft made easier by remote setting	Less of an innovation boost	Partially: more exposure to diverse populations, more audience for innovations
Goal 10. Reduce inequality within and among countries	By giving more populations easy access to good-quality education [76], health [75], and employment opportunities	High-quality metaverses only available in high-GDP countries or for high-net worth individuals; Exacerbating disparities	Exacerbates these issues	Partially
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable	Leverage digital twin concepts to identify issues and test solutions [82]	Fraud and malicious behavior of city planners, magistrates or citizens facilitated by remote setting	Lock-in into low-quality, unsafe metaverses	Partially
Goal 13. Take urgent action to combat climate change and its impacts	Reduced travel (education, healthcare, employment, justice) [80]; Less office space [80]	Design choices regarding consensus mechanisms of the blockchain, for instance PoW vs. PoS, have an impact on the energy consumption [46] [47].	Parallel metaverses implementing the same use cases increase energy demand further	Yes
Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	Transparency and accountability through blockchain [83] [9]; Easier access to justice for people with reduced mobility, remote populations, poorer populations	Fake news dissemination, pervasive discrimination, little accountability of metaverse provider or malicious actors, lack of governmental oversight and resources to enforce justice	Fewer avenues for recourse	Partially

erability between metaverses is *Metalinq* [86]. This project aims to create NFTs which are compatible across different metaverses. A user could transfer and use the same virtual good in different virtual worlds. This is achieved by integrating NFT standards from different blockchains into an overarching multi-metaverse protocol.

VI. Research Agenda for a Sustainable Metaverse

While the technological foundations for the metaverse continue to mature, the embedding of these innovations in a sustainable sociotechnical context is a suitable task for research [87]. High commercialization drives technological developments suggesting mass adoption in the foreseeable future [3], but may result in isolated metaverses [4]. Since the metaverse could have an important role in our future society, the research community is committed to shape the topic from a sociotechnical perspective, taking into account the UNSDGs. In order to create the research basis for a sustainable metaverse, a research agenda regarding interoperability in the metaverse [3] is specified and extended by sustainability aspects:

The impact of BCI on the metaverse in relation to selected UNSDGs is outlined in Table II. Each goal is analyzed for its socioeconomic and technical implications. The socioeconomic and technical impact is explored from multiple perspectives. Based on the socioeconomic and technical impact on individuals, firms, society, governance and regulators, at least one research question is proposed for each.

From a *socioeconomic* view, the metaverse affects different actors. For *individuals*, the metaverse could provide access to better healthcare, global education resources and remote work opportunities. It could also facilitate access to more innovative solutions and resources. The metaverse could also have a positive impact on an individuals' living conditions and the transparency of virtual interactions while reducing carbon emissions. However, user adoption depends on social networks where network effects and social pressure could push users into a certain metaverse. Concerns also include ensuring safe interactions in the virtual world and preventing crimes such as sexual harassment in a metaverse [94].

For *firms*, the discussion centers on the competitive advantages that can be achieved through extensive investment in the metaverse. High investment costs can be justified by high expected returns. Network effects within social networks play an important role here and favor firms with large existing networks. Another consideration is whether market forces could encourage the creation of isolated metaverses and the economic consequences of such a development, including the impact on market efficiency.

For *society*, the research questions relate to the implications of isolated metaverses, in particular how such a scenario can be aligned with the UNSDGs. Other considerations include the use of energy-efficient consensus mechanisms within the metaverse and how to support open and fair participation. This could promote a more equal distribution of wealth.

Governments and regulators influence the impact of market dominance and competition between different metaverses. The extent to which policy makers should advocate for a multi-metaverse ecosystem should be discussed. Public actors can promote competitive balance by enforcing legal frameworks and promoting multi-metaverse ecosystems.

From a *technical* point of view, the investigations are concerned with the most suitable BCI mechanisms that enable interoperability between different metaverses. The resulting multi-metaverse ecosystem requires sufficient security while potential trade-offs, for instance between carbon footprint and performance [90] or security and performance [91], must be considered. For firms, governments and regulators, the technical research questions extend to the accountability of metaverses [101] including potential crimes [100] and which institutions should oversee these platforms. In addition, the question of how to prevent attacks on the infrastructure of the metaverse must be answered to ensure the integrity, security and long-term viability of the metaverse. Especially with regard to new forms of attacks enabled by advanced technologies, including the prevention of Sybil attacks in the virtual space by generative AI agents. Within the broader framework of technical challenges, the focus is on designing a multi-metaverse ecosystem that is robust, inclusive and sustainable while supporting the UNSDGs.

VII. Conclusion

The prospective metaverse can have such a profound impact on people's lives that research should guide sociotechnical developments as early as possible. A fair and open access to and between metaverses is of vital importance. As argued in this paper, BCI is necessary to create a sustainable multi-metaverse ecosystem, by connecting blockchain-based metaverses which may each be specialized for a specific purpose and created by a specific organization. BCI facilitates the alignment of metaverse with selected UNSDGs, as it enables users to transfer their avatars from one virtual world to another, allowing people to choose where to virtually live, work and go to a digital doctor. Such avatar migrations are based on token transfers enabled by BCI solutions, which must be improved and monitored constantly to guarantee a high level of security. A sustainable metaverse can only be based on a robust technical infrastructure.

TABLE II
RESEARCH AGENDA TABLE

Selected UNSDGs	**Impact**		**Research Questions**
Goal 3. Ensure healthy lives and promote well-being for all at all ages; Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all; Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for al; Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; Goal 10. Reduce inequality within and among countries	Socio-economic	Individuals	How does the underlying social network influence user adoption of the metaverse through bandwagon pressures [88]?
		Firms	How do large investments in the metaverse and positive network externalities [23] in social networks affect competition? How does market pressure affect the emergence of isolated metaverses [8]? How do isolated metaverses impact market efficiency?
		Society	How do isolated metaverses impact society in relation to the respective UNSDGs?
		Governments & regulators	What is the impact of market dominance and competition between metaverses and their organizations, as addressed by the by the European American Chamber of Commerce that attempts to understand metaverse from a competitive perspective [89]? To what extent should policy makers advocate for a multi-metaverse ecosystem?
	Technical		Which BCI mechanisms are best suited to enable the necessary BCI functions between metaverses? How does the possible participation of private and public blockchains in the multi-metaverse ecosystem affect the choice of BCI solution, especially with regard to Hybrid Connectors [51]? How do trade-offs, for instance between carbon footprint and performance [90] and security and performance [91], affect the choice of the BCI mechanism and solution for the metaverse? Concerning scalability [92], how does the interconnection of numerous metaverses and their underlying blockchains affect performance? For example, in medical applications, how can it be ensured that a patient's avatar, including their medical data, is transferred between metaverses without the medical data being duplicated, stolen, lost or transferred to another person or their avatar?
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable	Socio-economic	Individuals	How to engage in digital twins of cities to increase citizen participation [93]?
		Firms	How to create useful digital twins of cities for sustainable planning and inclusive city design [93]?
		Society	How to prevent offenses such as sexual harassment in a virtual world [94]? How to design civic metaverses to promote democratic values and human rights [95]?
		Governments & regulators	How to police metaverses [96]? How to enforce laws in metaverses [97]?
	Technical		*see above*
Goal 13. Take urgent action to combat climate change and its impacts	Socio-economic	Individuals	How does participation in metaverses change the value placed on healthy environments and the climate?
		Firms	How to measure ESG goal achievement in metaverses [98]?
		Society	Which energy-efficient consensus mechanisms can be considered open and fair, guaranteeing equal participation and distribution of wealth?
		Governments & regulators	What is the impact of metaverses on climate change indicators [99]?
	Technical		Which energy-efficient consensus mechanisms can be considered open and fair, guaranteeing equal participation and distribution of wealth? How does a multi-metaverse ecosystem that connects different metaverses affect the ecological footprint - also taking into account different network components and underlying technologies [90]?
Goal 16. Promote peaceful and inclusive societies for sustainable development provide access to justice for all and build effective, accountable and inclusive institutions at all levels	Socio-economic	Individuals	How to reduce barriers to access and reduce costs for participation in society?
		Firms	To which institutions should a metaverse be *accountable* [100]?
		Society	How to establish societal norms in accordance with real-world societal norms and values in metaverses [101]?
		Governments & regulators	Should access by government agencies be required by law for any metaverse to *provide access to justice for all*, similar to the proposal of the *European Commission* on artificial intelligence in the *Liability rules for artificial intelligence* [102]?
	Technical		How can attacks on a multi-metaverse ecosystem and its underlying interconnected blockchains be prevented [38]? How can generative AI agents be prevented from carrying out Sybil attacks in the metaverse [9]? How can inconsistencies regarding avatars and digital goods be mitigated, recognized and resolved in interconnected metaverses also with regards to potential blockchain hard forks [103]?

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