ITUPublications

International Telecommunication Union

Standardization Sector

# ITU Focus Group Technical Specification

**(10/2023)**

ITU Focus Group on metaverse (FG-MV)

## FGMV-08

## Design criteria and technical requirements for sustainable metaverse ecosystems

*Working Group 8: Sustainability, Accessibility & Inclusion*

# Technical Specification ITU FGMV-08

## Design criteria and technical requirements for sustainable metaverse ecosystems


### Summary

Metaverse holds promises on accelerating progress towards the UN Sustainable Development Goals (SDGs), for instance, in health, biology computation, automotive, aerospace, education, and mitigation of the effects of extreme climate events. However, digital spaces have inherent costs and pose new environmental, social, and economic risks. If not properly governed, the rise of metaverse could amplify adverse environmental consequences inherent to its enabling technologies (e.g., AI, A/R, blockchains, IoT and digital twins) leading to increased CO2-emissions, e-waste, and resource consumption, harming local ecosystems, communities, and their businesses.

Moreover, emerging AI risks related, for instance, to manipulation, disinformation, isolation, echo chambers, and amplification of individual/group discriminations can be amplified by the metaverse. In business, high-performance hardware and costly resources needed to develop, test and maintain metaverse applications could be an economic barrier for SMEs, start-ups and non-profit organizations, thus deepening influence and power gaps. Moreover, the development of resource-intensive metaverse can amplify long-term rebound-effects risks, leading to a substantial increase in CO2 emissions and resource consumption.

The contributions of this document are threefold:

1. A definition of a sustainable metaverse ecosystem;
2. Design criteria to integrate at design environmental, social and economic sustainability needs;
3. System requirements for sustainable metaverse ecosystems.



### Keywords

Metaverse, system design, sustainability, UN SDGs, energy efficiency, CO2 emissions, carbon footprint, e-waste, responsible design, sustainability risks, risk assessment.


### Note

This is an informative ITU-T publication. Mandatory provisions, such as those found in ITU-T Recommendations, are outside the scope of this publication. This publication should only be referenced bibliographically in ITU-T Recommendations.

### Change Log

This document contains Version 1.0 of the ITU Technical Specification on "*Design criteria and technical requirements for sustainable metaverse ecosystems*" approved at the third meeting of the ITU Focus Group on metaverse (FG-MV), held on 3-5 October 2023 in Geneva, Switzerland.


### Acknowledgments

This Technical Specification was researched and written by Daniela Tulone (Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT)), Hoang Dinh (University of Technology Sydney, Australia), Antonio Puliafito (CINI Smart Cities Lab), Wei Yang Bryan Lim (Nanyang Technological University, Singapore) and Patrick Henz (Primetals Technologies, USA) as a contribution to the ITU Focus Group on metaverse (FG-MV).

Special thanks to Siyue Zang (Nanyang Technological University Singapore), Amr Hashem (Policy Advisor, AHC Egypt), Symeon Papavassiliou (School of Electrical and Computer., Eng., National Technical University of Athens, Greece), Sebastiano Panichella (Zurich University of Applied Science (ZHAW), Switzerland), Roberto Saracco (IEEE Future Directions Committee), Paolo Gemma (Huawei, Italy) for their helpful reviews and contributions.

Additional information and materials relating to this report can be found at: https://www.itu.int/go/fgmv. If you would like to provide any additional information, please contact Cristina Bueti at tsbfgmv@itu.int.

**Editor**: Daniela Tulone
CNIT
Italy
E-mail: tulone@csail.mit.edu

## Table of contents

# Technical Specification ITU FGMV-08

# Design criteria and technical requirements for sustainable metaverse ecosystems

## 1 Scope

This document defines technical requirements and design criteria for designing metaverse ecosystems that are sustainable from the environmental, social, and economic perspectives. It defines a sustainable metaverse ecosystem, and provides sustainable design criteria to guide practitioners during the technical design and align it with ethical principles, system requirements for sustainable metaverse ecosystems.

## 2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of these Technical Specification. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Technical Specification are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Technical Specification does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T L.1420] Recommendation ITU-T L.1420 (updated), Methodology for energy consumption and greenhouse gas emissions impact assessment of information and communication technologies in organizations.

## 3 Terms and definitions

### 3.1 Terms defined elsewhere

This Technical Specification uses the following terms defined elsewhere:

**3.1.1 Artificial Intelligence**

**3.1.1 Artificial Intelligence (AI)** [b-ITU-T M.3080]: Computerized system that uses cognition to understand information and solve problems.

**3.1.2 Augmented Reality (AR)** [b-ITU-T P.1320]: An environment containing both real and virtual sensory components. The augmented reality continuum runs from virtual content that is clearly overlaid on a real environment (assisted reality) to virtual content that is seamlessly integrated and interacts with a real environment (mixed reality).

**3.1.3 Digital Twin** [b-ITU-T Y.4600]: A digital representation of an object of interest.

**3.1.4 Internet of Things (IoT)** [b-ITU-T Y.4000]: A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.

**3.1.5 Interoperability** [b-ITU-T Y.101]: The ability of two or more systems or applications to exchange information and to mutually use the information that has been exchanged.

**3.1.6 Mixed Reality (MR)** [b-ITU-T P.1320]: An environment containing both real and virtual components that are seamlessly integrated and interact with each other in a natural way (one end of the augmented reality continuum).

**3.1.7 Virtual Reality (VR)** [b-ITU-T P.1320]: An environment that is fully generated by digital means. To qualify as virtual reality, the virtual environment should differ from the local environment.

## 3.2 Terms defined here

This Technical Specification defines the following terms:

**Sustainable metaverse ecosystem:** [1] a metaverse ecosystem that is designed and operated:

1. to address present environmental and societal needs without compromising the ability of future generations to meet their own needs and
2. to harness system benefits for the environment, people and stakeholders while preventing any type of harm to them and mitigating unintended sustainable impacts.

# 4 Abbreviations and acronyms

This Technical Specification uses the following abbreviations and acronyms:

| | |
|---|---|
| HMD | Head-Mounted Display |
| IoT | Internet of Things |
| AR | Augmented Reality |
| VR | Virtual Reality |
| MR | Mixed Reality |
| AI | Artificial Intelligence |
| NLP | Natural Language Processing |
| ML | Machine Learning |
| SME | Small and Medium Enterprise |
| SDGs | UN Sustainable Development Goals |
| LoD | Level of Details |
| GHG | Greenhouse Gases |
| NFT | Non-fungible token |

# 5 Conventions

In this Technical Specification:

The keyword "is required" indicates a requirement that must be followed strictly and from which no deviation is permitted if conformance to this document is to be claimed.

The keyword "is recommended" indicates a requirement that is recommended but not absolutely required. Thus, this requirement needs not be present to claim conformance.

The keywords "optionally" and "may" indicate an optional requirement that is permissible, without implying any sense of being recommended.

These terms are not intended to imply that the vendor's implementation must provide the option and that the feature can be enabled optionally by the network operator/service provider. Rather, it means that the vendor may provide the feature optionally and still claim conformance with the specification.

[1] The definition contained in this document may be revised if the FG-MV develops and approves a definition of metaverse.

## 6 Sustainability risks and opportunities

The term metaverse was coined in 1994, describing a virtual reality (VR) space that incorporates the internet and augmented reality (AR) via avatars and software agents. Recent advances in AI, digital twins, IoT, 5G and blockchains have made its development more feasible, capturing the interest of businesses, academia, and institutions.

The metaverse can amplify the physical world with AR and VR, enabling seamless interactions in both real and simulated settings through avatars and holograms. This results in more immersive and spatially interactive digital experiences than conventional online platforms.

These enhanced perceptions of reality can significantly contribute to the UN Sustainable Development Goals (SDGs). For example, they can revolutionize education by offering innovative learning methods in interconnected cyber-physical spaces. They also present opportunities for advancements in health, well-being, public sectors, smart cities, and manufacturing, culminating in reduced resource consumption and increased productivity [b-Hupont].

In education and training, the metaverse can provide more realistic experiences than traditional ones, replacing costly or hazardous physical experiences. It can improve medical treatments [b-Logeswaran] and training, for instance, providing surgical trainees with authentic experiences in a 3D operating room. For mental health and neurological diagnoses, it can simulate real scenarios, allowing observation of patient reactions [b-Garcia-Betances]. Additionally, in public sectors and urban environments, the metaverse can boost citizen involvement, model intricate policy decisions, and enhance certification processes for autonomous systems like self-driving vehicles.

However, to advance SDGs through the metaverse, it's vital to:

I. Prioritize solutions addressing environmental and societal challenges (*metaverse for sustainability*).

II. Make metaverse ecosystems *sustainable by design* from the environmental, social and economic perspectives (*sustainability of metaverse*).

This document addresses point II as mentioned above. As pointed out in [b-Tulone Samuel], it is paramount to adopt a comprehensive design approach that is able to 1) integrate environmental, social and economic needs/costs into the system model and system’s building blocks and 2) evaluate multi-dimensional sustainability impacts of the system along with their inter-linkages. Indeed, *single-path design approaches* pursuing only technical enhancements or business growth or individual sustainability issues without considering the bigger picture often led to system inefficiencies and sustainability drawbacks, sometimes exacerbating existing sustainability issues or even creating new ones [b-Tulone Samuel].

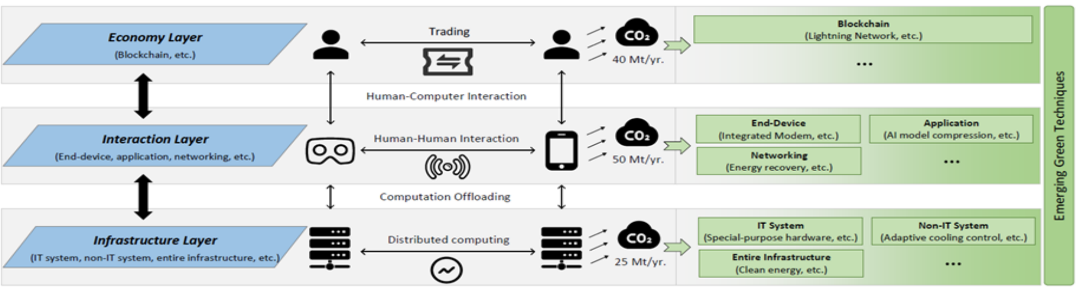


**Figure 1: Key energy-hungry components in the metaverse [b-Liu]**

While the metaverse is claimed to substantially cut CO2 emissions by replacing physical goods with digital ones, reducing physical mobility, and conducting simulations in cyberspace, metaverse ecosystems themselves are resource-intensive with a high carbon footprint. Paradoxically, they can lead to an overall increase in $CO_2$ emissions due to infrastructure expansion rather than a decrease. As a result, it is crucial to invest efforts in designing environmentally sustainable metaverse ecosystems to minimize energy consumption and the system's negative environmental impacts [b-Zhang]. Figure 1 shows the main energy-hungry system components proposed in [b-Liu] that need to be considered at design:

- ***Economic layer***. It provides a trading and operation platform for users, service providers, application developers, and infrastructure providers. Blockchain, with its attributes of transparency and security, is a robust option for handling trading transactions. Yet, it's important to note that blockchain technology is energy-intensive. Hence, exploring innovative, cost-effective, and energy-efficient consensus mechanisms is essential.
- ***Interaction layer***. The energy consumption resulting from human-to-human, human-to-machine, machine-to-human, and machine-to-machine interactions across software and hardware, including internet services, is the most power-intensive aspect. Given the Metaverse's anticipated large user base, it's vital to minimize energy usage in devices, software, and network components.
- ***Infrastructure layer.*** It encompasses the creation and maintenance of Metaverse activities, spanning IT systems (e.g., computing, networking, data centers) and non-IT systems (e.g., cooling systems) crucial for virtual environments, avatars, interactions, and smart contract execution.

The Metaverse risks resource duplication as operations can span both virtual and physical realms, potentially elevating $CO_2$ emissions and resource consumption. To counteract this, activities shall shift predominantly to digital spaces. While the development of the metaverse should prioritize energy efficiency, it's essential to weigh this against individual, community, and business benefits. For example, while virtual interactions can save energy, they might compromise mental health and relationships.

Moreover, an energy-intensive metaverse could inadvertently neutralize efficiency gains and the benefits of renewable energies, resulting in increased $CO_2$ emissions and resource consumption. Beyond these concerns, the metaverse introduces challenges like increased e-waste (from HMDs, sensors, servers), augmented resource consumption (like water and rare metals), and potential threats to ecosystem biodiversity due to infrastructure growth.

The Metaverse's potential societal risks include fostering isolation, particularly among the young and vulnerable, distorting human relationships and decision-making through an idealized reality, and perpetuating harmful biases and stereotypes. Applications within the metaverse could further intensify risks linked to enabling technologies like AI, generating echo chambers and misinformation.

Furthermore, the metaverse could exacerbate power gaps and inequalities among developed and developing regions, rural and urban areas, large and small enterprises. In developing countries, system requirements for high-performance networks (e.g., throughput, latency) can be difficult to meet because of the high variability of broadband services. Unreliable broadband services can hinder access to metaverse ecosystems, potentially leading the metaverse to primarily serve developed countries and exacerbating existing disparities. Additionally, the metaverse's demand for costly high-performance hardware and computational resources can negatively affect SMEs, startups, and non-profits organizations, favouring larger ones.

In conclusion, the design of sustainable metaverse ecosystems should follow a comprehensive design approach, integrating environmental, social and economic sustainability considerations, and evaluating sustainability system impacts, as highlighted in [b-Tulone Samuel].

## 7 Metaverse functional components

This section illustrates metaverse functional components used in the following sustainability analysis and adapted from [b-Ning] [b-Xu]. Table 1 summarizes them

The functional component considered in this technical specification are here listed and detailed in the following part of this section:

- Data
  - Dataset for model training
  - Data Representation & Management system
- Content creation
- Infrastructure & third party services

**Dataset for Model Training**

- Sensor data from the physical world;
- Unstructured data (e.g., private/public data, web data and social media);
- Synthetic (model-generated) datasets;
- Data from avatars, digital objects, and virtual services.

**Data Representation & Management Systems**

- Data models representing avatars and scenes;
- Data linking and semantic alignment technologies;
- Data storage and analysis techniques, including unstructured data sources, graph-based data storage, and analysis components;
- Fusion of heterogeneous data from various digital and physical entities leveraging ML techniques (e.g., Natural Language Processing).

**Content Creation**

- **Virtual Environments and Scenes:** Simulated environments with 3D digital objects and their attributes, virtual IoT device representations, and edge virtualized functions. Discover hidden, causally linked relationships and develop narratives based on them. Virtual spaces might have unique spatio-temporal dimensions, organically combining each component to form interconnected event-based narratives.
- **Avatars and interactions**: Models for avatar reactions, backgrounds, behaviors, and relationships.
- **Recognition, generation and rendering:** Techniques for scene, object (face, pose, gesture, gaze), and speech recognition and rendering. Object recognition involves sensing, recording, and tracking, achieved via remote and proximity stimulation.
- **Virtual goods and services:** Offered via blockchains, NFTs, distribution and synchronization.

**Infrastructure & Third-parties Services**

- **Communication and networking infrastructures**: Efficient IMT 2000 and beyond, other mobile platforms and fixed network access and transport are essential due to rising data generation and consumption trends, particularly for user-end metaverse applications.
- **Computational infrastructures:** Cloud services, third-party services, and data centers require intent-driven orchestration emphasizing energy efficiency. These

orchestrations span across IoT, edge, and cloud resources. Integrating IoT, edge, and cloud tech is vital for a smooth transition to metaverse-centric systems.

- **Devices**: sensors & actuators (HMDs, etc.). They include:
  - *Head-mounted devices (HMDs):* Track head movements, offering varied perspectives in the virtual world. Types include non-see-through, optical-see-through, and video-see-through HMDs. Typically, they're bulky, pricey, and have limited battery duration.
  - *Hand-based and non-hand-based devices*: Ranging from eye/head tracking to voice input.
  - *Motion input devices:* Utilize physical space or gravity senses, body tracking, and treadmills for precise motion capture.

# 8 Definition and key concepts

This section describes the sustainable design approach, defines a sustainable metaverse ecosystem and key concepts for designing sustainable systems that build on the ***tech-responsible design approach*** proposed in [b-Tulone].

## 8.1 Comprehensive sustainability approach

To advance SDGs metaverse ecosystems are required to incorporate environmental, social, and economic sustainability considerations from early design stages~~,~~ when defining system assumptions, requirements, architecture (e.g., HMDs, equipment, and third-party services), as well as AI models and algorithms.

Integrating multi-dimensional sustainability needs into design doesn't mean solving all issues at once, but it involves a tech-responsible approach [b-Tulone] that aligns with human values, ethical and responsible design principles and that evaluates potential sustainability impacts over the short-, medium- and long-term sustainability needs and impacts.

As emphasized in [b-Tulone Samuel], focusing solely on technical enhancements, business growth, or energy efficiency in a single-path design approach is no longer acceptable, given the urgency of climate change. The UN Special Report on SDGs progress in May 2023 reveals that only 12% of sustainability targets for 2030 are on track [b-UN_GAES].

## 8.2 Definition of sustainable metaverse ecosystem

There is a lack of a widely agreed-upon definition of sustainability in the digital community, often limited to its environmental aspects, particularly energy efficiency and CO2 emissions. Moreover, while there's some research on AI system sustainability, as seen in [b-Tulone], a clear definition of system sustainability, especially in the metaverse context, is notably absent. Without a precise definition, it's challenging to uphold sustainability commitments and implement sustainable development plans. Establishing a clear definition for a sustainable metaverse ecosystem is the initial step toward aligning metaverse development with SDGs. Below is presented the first definition of a sustainable metaverse ecosystem.

Definition[2]: *A* ***sustainable metaverse ecosystem is a metaverse ecosystem which is designed and operated:***

a) *to address* ***present environmental and societal needs*** *without compromising the ability of* ***future generations*** *to meet their own needs, and*

[2] The definition contained in this document may be revised if the FG-MV will develop and approve a definition of metaverse.

b) *to harness s***ystem benefits for the environment, people and stakeholders** *while preventing* ***any type of harm*** *to them and mitigating* ***unintended sustainable impacts.***

Basically, a sustainable metaverse ecosystem is one that is designed and operated to leverage its potential benefits in terms of environmental, social, and economic sustainability while avoiding harmful effects on humans, the environment, and society.

This definition has several implications:

1. The conception and design of a sustainable metaverse ecosystem is required to proactively tackle **environmental** and **societal challenges** while enhancing the system's positive impact on users, stakeholders, communities, and the environment.
2. A sustainable metaverse ecosystem is required to build on **green technologies** and sustainable best practices to reduce energy and resource consumption, carbon footprint, and e-waste through the reuse of hardware, software, and data.
3. A metaverse ecosystem is required to **avoid harm** and unintended consequences on users, stakeholders, and the environment, even if unlikely. Inherent biases associated with the designer's specific culture, experiences, and social context shall be **mitigated, managed** and **communicated** to users.
4. A metaverse ecosystem is recommended to augment **human capabilities** and foster **individual growth** and **collaborations** while leveraging human uniqueness, intuition and creativity. As a result, it is required to ensure user self-determination.
5. Environmental, social and economic sustainability considerations are required to be integrated into the system model and drive technical design decisions.
6. A sustainable metaverse ecosystem is required to ensure **fairness, trustworthiness, transparency** and **inclusiveness** and evenly distribute benefits and costs (e.g., countries, communities, age). Moreover, it is required to guarantee **system robustness**, **security**, **privacy**, and **interoperability**.
7. The above conditions are recommended to hold not only **at the present time** but also in the **medium- and long-term** to safeguard the needs of future generations.

## 9 Design criteria for sustainable metaverse ecosystems

This section defines design criteria that are recommended to drive practitioners when conceiving and designing metaverse ecosystems. They build on the *tech-responsible design approach* [b-Tulone]. It is worth noting that the overlaps of these criteria provide practitioners with useful insights on sustainability inter-linkages. A detailed explanation of the different criteria is provided in the following subsections.

### 9.1 Problem selection and system impact

As discussed in the previous section, a sustainable metaverse ecosystem needs to be aligned with environmental and societal goals outlined in the UN SDGs. System sustainability benefits are required to exceed its inherent sustainability costs and risks, such as resource consumption, high carbon footprint, financial investments, and potential disruptions to businesses.

The choice of the problem to address or the service to offer is crucial step in designing a sustainable metaverse ecosystem that effectively contribute to the implementation of UN SDGs. This aspect merits increased attention from both the technical and business communities. Problem selection should result from a thorough multi-dimensional analysis, considering strengths, limitations, opportunities, and threats, much like the System Sustainability SWOT Analysis proposed in [b-Tulone].

## 9.2 System alignment with AI ethics principles

A sustainable metaverse ecosystem is required to align with ethics principles of human values, and responsible design according to the *tech-responsible design approach*. Table 2 summarizes criteria from Responsible Design and Table 3 from AI Ethics, as discussed in [b-Tulone 2023] and [b-AI HLEG 2019].

**Table 2: Criteria from responsible design**

| **Criteria from Responsible Design** | |
|---|---|
| **Anticipative & Reflective** | Envisioning system impacts and analyzing its underlying assumptions and key values help anticipate or mitigate possible future pitfalls and increase system value. |
| **Resilient & Adaptive to Change** | Embedding dynamic trade-offs into algorithms enhances system resiliency in the face of failures, low-quality data, malicious at- tacks, and evolving conditions. |
| **Diversity & inclusiveness** | Engaging stakeholders and domain experts is essential to set up realistic assumptions, and evaluate multi-dimensional sustainability impacts. |
| **Open & transparent** | Designing transparent systems calls for a deep understanding of users' expectations and perception of system benefits and risks. |
| **Accountability & Governance** | Design governance tools are key to ensuring accountability, sharing responsibility among stakeholders, and mitigating side effects. |

**Table 3: Criteria from AI Ethics [b-AI HLEG 2019]**

| **Criteria from AI Ethics** | |
|---|---|
| **Respect for human autonomy** | Users are required to keep self-determination and not be coerced or manipulated by a system. On the positive side, systems should be designed to empower user capabilities and reflect multiple viewpoints. |
| **Prevention of harm** | It entails the protection of people's privacy, human dignity (i.e., mental and physical integrity), vulnerable people, affected communities and ecosystems. System accuracy, safety, and security are required. |
| **Fairness** | Algorithms and models should ensure equal access to benefits and costs without favouritisms, discrimination, and stigmatization. |
| **Explicability & Transparency** | System transparency and user perception of system benefits and limitations are crucial to meeting user needs and correcting misconceptions. |

## 9.3 Resource efficiency, recyclability and proportionality

The concept of resource efficiency and proportionality is at the core of technological sustainability. It emphasizes that the tools, techniques, and resources used by the system should directly match the system's functions and benefits. A key challenge is aligning technical and business requirements with sustainability needs. With the world's emphasis on significant CO2 reduction and responsible resource use, designers and developers it is required to prioritize decisions that reflect this imperative.

Efforts to maximize recycling and reuse of material and product it is recommended to drive design decisions pertaining to hardware, software, datasets, networking, and infrastructure, as elaborated below:

- **Hardware**: Devices like HMDs, sensors, and related equipment are recommended to be designed with their **end-of-life** in consideration. This means selecting materials for their recyclability and prioritizing modularity for the replacement of faulty components rather than the entire device. Metaverse devices and equipment it is recommended to be designed and used to prevent landfill disposal. Reducing e-waste not only conserves critical resources like rare metals but also mitigates the release of harmful chemicals into the environment, safeguarding biodiversity.
- **Software and Data**: In the world of rapid software iterations, practitioners are recommended to prioritize building on existing solutions wherever feasible, enforcing **software recyclability**. Similarly, **data reusability** is required to be encouraged. Collected datasets should be repurposed for new models and applications and made available, thus limiting the need for fresh data collection and reducing its associated carbon footprint.
- **Networking and Infrastructure Growth**: Because of the explosion in networking capabilities, computational infrastructure, and renewable plants, care is recommended to be taken not only to ensure reusability and recyclability but also to prevent harmful consequences for the biodiversity of occupied lands, such as disruption of natural habitats.

## 9.4 Energy-efficiency

This section proposes design criteria for energy savings following the functional metaverse building blocks outlined in Section 7.

### 9.4.1 Datasets & Data representation

Datasets underpin the metaverse's development, driving ML models and applications that animate avatars, forge virtual worlds, and generate digital assets. Yet, the performance gains plateau as dataset size and model complexity increase [b-Schwaartz]. Thus, it's pivotal to **balance model performance with resource allocation**. Below are the design criteria:

- ***Data collection***: only **essential data** is recommended to be collected, reducing data volume that needs to be processed and stored. In addition, data collection has to comply with regional **privacy laws**, such as the *EU General Data Protection Regulation* (GDPR) [b-Voigt]. Moreover, harnessing **open-source data** reduces carbon footprint and foster cross-sector collaborations.
- ***Data compression and encoding***: advanced compression techniques and efficient encoding formats are recommended to reduce the energy needed for data processing and decoding.
- ***Data aggregation and maintenance***: Eliminating replicated or irrelevant data to **reduce** the overall dataset size, on-demand processing data over different network layers on demand is essential to optimize energy usage and processing time.
- ***Data center location and infrastructure***: Data is recommended to be stored in nearby, renewable energy-powered centers, cutting down transmission distances and associated energy consumption.

### 9.4.2 Virtual environment generation

Digital twins play a key role in creating virtual worlds, which encompass data collected by IoT devices and transmitted by high-speed broadband networks and data processed in the cloud. Different techniques have been developed to reduce energy consumption in the process of virtual environment generation, such as approximate sensing, semantic communication, device-to-device communication and beamforming for radio access network, server consolidation, job scheduling, and cooling system optimization for data centers. Below, design criteria for generating energy-efficient virtual environments:

- ***Lightweight assets***: Develop 3D models, textures, and animations with lower polygon counts and optimized file sizes to reduce rendering and loading energy.
- ***Dynamic level of detail***: Develop innovative techniques to automatically adjust the level of details based on the viewer's distance from objects, optimizing rendering efficiency.
- ***Optimize occlusion***: Use occlusion culling techniques to render only what is visible, minimizing unnecessary rendering processes and conserving energy.
- ***Efficient lighting and shading***: Employ efficient lighting models and global illumination techniques to achieve realistic lighting while minimizing computational demands; use optimized shaders that balance visual quality and energy efficiency.
- ***On-demand and prioritized streaming***: Stream assets in real-time as needed, reducing the initial load time and minimizing energy used for asset loading; load essential assets first and progressively load secondary assets, enhancing user experience while conserving energy during rendering.
- ***Virtual user-interaction management***: Design virtual environments to react dynamically to user interactions, reducing the need for constant calculations and energy-intensive processes. Implement techniques to distribute users evenly across servers to prevent overcrowding in specific areas, reducing energy demands.

### 9.4.3 Avatar generation and interaction

Optimization in avatars' creation and rendering processes is pivotal for minimizing energy consumption. Below, design criteria to conserve energy:

- ***AI-Driven Techniques:*** Utilizing AI, particularly neural networks for image generation and compression, minimizes the computational workload necessary for generating rich avatar visuals. This not only improves performance but also cuts energy costs.
- ***Adaptive Rendering:*** Central to energy savings, this technique adjusts the rendering quality depending on user proximity and attention. Objects central to a user's focus are rendered in high definition, while peripheral or distant items are rendered with lower details. Moreover, server-side rendering can step in when user devices may not be able to handle the high computational needs of rendering, processing the complex visuals and delivering ready-to-view images to the user.
- ***User Customization for Sustainability:*** By offering users choices favouring minimalistic and recyclable designs for avatar outfits and accessories, a culture of digital sustainability and reuse can be nurtured.
- ***Blockchain's Carbon Footprint:*** Blockchain’s significant carbon footprint [b-Pagone], used in some virtual goods transactions, highlights the need for energy-efficient digital currencies. Decisions and interactions should be managed through energy-efficient algorithms, and green hosting platforms reduce carbon footprint.

### 9.4.4 Communication & Computational Infrastructure & Devices

The communication infrastructure that supports the metaverse, responsible for seamlessly connecting users worldwide, it is required to manage **high bandwidth** and **low latency** requirements [b-Zhang], which triggers an expansive network of routers, relay stations, and possibly even satellite networks, all contributing to energy consumption and environmental impact. Below, energy-efficient design criteria:

- ***Energy-efficient of metaverse IoT components****:* Implement energy-efficient procedures (hardware and software) for IoT devices to reduce energy consumption and carbon emission of existing applications and services, as well as IoT devices. Employ when convenient energy harvesting technologies to reduce devices’ carbon footprint. Energy harvesting is a technology that collects (i.e., harvest) small amount of energy from various unconventional sources such as light, heat, vibrations, and radio waves occurred in the immediate surroundings of the device.

- ***Energy-efficient of metaverse cloud computing:*** Use cloud computing services empowered by **renewable energy** sources and utilize low-carbon technologies to reduce the greenhouse gas emissions and ecological footprint of the metaverse.
- ***Energy-efficient of metaverse communication protocols:*** Design and implement communication protocols that are optimized in size, format, compression, and transmission to reduce the **energy consumption** and **bandwidth** requirements of the metaverse. That will also contribute to make systems operational in developing countries and rural areas.
- ***Energy-efficient design of metaverse HMDs:*** As the human fovea has a higher visual acuity than the rest of retina, foveated rendering technique renders the gazed area of the image at a higher resolution and the peripheral area at a lower resolution, which can achieve **3 times speedup and 70% pixel reduction** [b-Zhang]. Moreover, by smoothly decreasing the brightness level of the screen, a significant amount of energy can be saved while keeping the same brightness perception.

### 9.4.5 Human-centred design

Sustainable systems are recommended to adhere to human values and the principles outlined in Tables 2 and 3 of Section 9.2. Its design needs to address a multitude of potential opportunities and risks for users, minorities, communities, and businesses, some of which can be harmful.

As emphasized by initial design criteria, the design of a metaverse ecosystem should take a **positive and proactive stance** on sustainability, fostering the empowerment of human capabilities, uniqueness, and creativity. The design of metaverse ecosystems should not merely focus on harm containment but should actively promote individual and community growth.

In the initial stages of design, it's recommended for practitioners to invest time and effort in discovering ways to maximize the system's positive impact on users and communities, collaborating with domain experts and key stakeholders. This effort aims to identify opportunities within the system to:

- Empower user capabilities, uniqueness, and creativity.
- Foster diversity and inclusion.
- Strengthen relationships and collaborations.

This proactive approach complements the identification, mitigation, and management of potential adverse impacts on users and communities. It is imperative to **avoid any potential harm** on individuals, communities, and their activities and address possible misuse by users, exploitations of user vulnerabilities, as well as inherent biases.

Harmful biases can manifest in seemingly innocuous design elements, such as **avatar appearances**. For example, when users choose avatars unrelated to their physical bodies, it can amplify societal stereotypes (e.g., skin colour, body size), potentially impacting an individual’s **self-esteem** [b-Henz 2022]. Regularly using avatars different from one’s physical self and interacting with the virtual environment can even lead to a shift in self-perception. Positive feedback to avatars representing suppressed attitudes and preferences can empower individuals to reinterpret themselves and modify their behaviours in the physical world [b-Henz]. To ensure this is a positive experience, it is imperative that the metaverse not only upholds human rights but actively fosters the creation of a diverse and inclusive virtual reality.

Avatar actions can have severe consequences, encouraging behaviours that is illegal or deviates from social norms, ranging from cheating and bullying to kidnapping and even killing. While these actions are subject to **prosecution in the real world**, they may be considered acceptable and harmless in the virtual realm, despite their real emotional and mental impacts on individuals.

Practitioners bear the responsibility of regulating avatar actions, interactions, and appearances that could incite bullying, manipulation, or reinforce stereotypes, illegal activities, or deception, such as theft of material or intellectual property. These actions can lead to mental health issues, including disconnection from reality, relationship problems, isolation, diminished self-esteem, and difficulty distinguishing between the real and virtual worlds. During the design phase, it's crucial to prohibit harmful avatar behaviours by establishing rules that align with legal and societal norms. Harmful actions in the virtual world should be subject to legal enforcement, as their consequences are real and, in some cases, have resulted in tragic events reported by the media.

Practitioners are required not to accept compromises with harmful consequences only because they affect a small group of individuals or occur in specific scenarios. While small probabilities might be deemed insignificant from a technical standpoint, they cannot be ignored from an ethical and social perspective, as real people are affected by these probabilities [b-Henz].

In addition to identify and avoid potential sources of harm, it is necessary to identify and manage apparently **harmless biases**. Biases are inherent in design decisions, stemming from choices related to datasets, AI models, virtual environment definitions, and avatar characteristics, attitudes, and interactions. They often reflect the perspectives, backgrounds, experiences, values, and cultural and socioeconomic contexts of the designers. Practitioners it is required to be aware of the inherent system's biases. While achieving bias-free virtual environments, avatar characterizations, and interactions is unrealistic, it is required for practitioners to 1) avoid design choices that could potentially harm users, especially young people and minorities, and 2) mitigate potential harmless side effects.

Below are summarized design guidelines for practitioners:

- Verify system alignment with human values and ethical principles (e.g., system assumptions, requirements, data, underlying AI models and algorithms);
- Actively engage stakeholders and domain experts to define realistic assumptions, user requirements, and constraints, identify and classify biases associated with datasets, particularly non-curated datasets, models and algorithms;
- Collaborate with domain experts and stakeholders to oversee avatar actions, interactions, and appearances, ensuring that actions with potential adverse emotional and mental effects on individuals are avoided;
- Design transparent and explainable systems, leveraging AI trustworthiness results;
- Apply existing legal frameworks within the virtual world to prohibit actions that are morally unacceptable in society.
- Scrutinize design decisions to prevent the following potential harm to users:
  - Manipulation;
  - Stigmatization;
  - Disinformation and asymmetry of influence;
  - Lower user self-esteem and self-determination;
  - Harmful users' dependence on the system;
  - User disconnection from reality;
  - Relationship issues and a propensity for user isolation;
  - User misuse;
  - Hidden exploitations of user vulnerabilities.
- Openly communicate inherent system limitations and biases to users.

## 9.6 System trustworthiness

As mentioned in Section 8, a sustainable metaverse ecosystem it is required to be trustworthy, which means, for instance, to be secure, fair, available, robust, privacy-preserving, and efficient.

## 9.7 Medium- and long-term perspective

As pointed out in Section 8.2, a sustainable system is required to ensure its sustainability also in the medium and long-term to ensure that future generations will be able to meet their own needs. As a result, system sustainability is required to embrace the entire **life-cycle** of the system from manufacturing to disposal [b-ITU-T L.1410]. Moreover, practitioners should ensure the sustainability of system resources as users and system functionalities grow, as addressed by [b-Tulone].

## 9.8 Inclusions and interoperability

Metaverse ecosystems are required to be designed and function not only in tech-advanced regions with high-quality networking and computational infrastructures. Current and future system legacy are required to be guaranteed. The current development of metaverse can deepen gaps between countries, rural areas and cities, even within a metropolitan area, but also between corporates and SMEs, wealthy and poor. To mitigate this gap, metaverse ecosystems are required to provide a "lightweight system version" offering basic functionalities to allow users to access the system via limited quality infrastructure and interact with the system without being locked out.

# 10 Technical requirements for a sustainable design

The following tables 3, 5, 6, 7, and 8 summarize the general requirements for the design of sustainable metaverse ecosystems. They follow the functional building blocks described in section of Section 7.

**Table 3: Data design & management requirements**

| Data Design & Management | Requirement types | | |
|---|---|---|---|
| | **Is required** | **Is recommended** | **Optional** |
| **Energy-efficiency & environmental aspects** | | | |
| Collect only essential data, minimize data volume for intended use | | x | |
| Balance model performance and resource allocation. | | x | |
| Use advanced compression techniques and employ efficient encoding formats | | x | |
| Combine similar data points and regularly review/remove outdated data. | x | | |
| Distribute data processing tasks optimally and load data based on demand. | x | | |
| Store data closer to access points and opt for data centers powered by renewable energy | x | | |
| **Human-centric design** | | | |
| Include datasets from all parts of society for a robust and more realistic representations of virtual environments and avatars. | | x | |
| Regularly review datasets to ensure that all groups are adequately represented. | x | | |
| Identify datasets biases and limitations together with domain experts. | x | | |
| Protect user data from unauthorized access, modification, or deletion in the metaverse. | x | | |
| **Community & economic growth** | | | |
| Ensure backward compatibility so that datasets can make use of data collected through legacy systems with limited accuracy. | | x | |
| Allow users to create value from their data and improve their experiences in the metaverse. | | x | |

| | | | |
|---|---|---|---|
| Allow users to control their data and exercise their rights and responsibilities in the metaverse. | **x** | | |

**Table 4: Virtual environment generation requirements**

| Virtual Environment Generation | Requirement types | | |
|---|---|---|---|
| | **Is required** | **Is recommended** | **Optional** |
| **Energy-efficiency & environmental aspects** | | | |
| Use low-polygon 3D models and optimized file sizes. | | **x** | |
| Adjust detail based on the viewer's proximity to objects. | | **x** | |
| Implement occlusion culling to render only visible components. | | **x** | |
| Adopt efficient lighting models and global illumination techniques, and use optimized shaders for balance between visual quality and energy efficiency. | | **x** | |
| Stream assets in real-time as needed; prioritize loading of essential assets. | **x** | | |
| Use protocols optimized in size, format, and compression. | **x** | | |
| **Human-centric design** | | | |
| Available options should not be limited to physical reality, but also represent culture and art | | | **x** |
| Identify together with domain experts harmful and non-harmful biases associated with the environmental representation and mitigate/manage them. | **x** | | |
| Virtual environments should be customizable and personalized, allowing users to create and modify their own spaces according to their preferences and needs. | **x** | | |
| **Community & economic growth** | | | |

| | | | |
|---|---|---|---|
| Virtual environments should not be too complicated to be operated by low-end systems to facilitate inclusion and system operability in rural areas and developing countries. | | x | |
| Virtual environments should be realistic and diverse, reflecting physical and cultural diversity. | | x | |
| Virtual environments should facilitate collaborations among users, enabling them to work, socialize, learn, and co-design in the metaverse. | | x | |
| Virtual environments should offer different graphical options to be inclusive and meet the requirements of different platforms (e.g., mobile, laptop, low and high bandwidth). | x | | |

**Table 5: Avatar characterization & interaction requirements**

| Avatar Characterization & Interaction | Requirement types | | |
|---|---|---|---|
| | **Is required** | **Is recommended** | **Optional** |
| **Energy-efficiency & environmental aspects** | | | |
| Employ AI-based image generation and compression algorithms to decrease computational load. | | x | |
| Reduce energy consumption and bandwidth requirements for metaverse interactions. | x | | |
| Implement LoD in avatar rendering and ensure avatars maintain visual quality with fewer resources at varying distances. | | x | |
| Encourage users towards minimalistic designs for avatar clothing and accessories | | x | |
| Ensure avatar responses/decisions are adapted for efficient communication over limited capability networks. | x | | |
| Improve energy efficiency of algorithms governing avatar behaviours and interactions. | x | | |
| Ensure avatar responses/decisions are adapted for efficient communication over limited capability networks. | x | | |
| **Human-centric design** | | | |

| | | | |
|---|---|---|---|
| | | | |
| Ensure user security and privacy to prevent harms such as fraud, defamation, identity theft, and crime. | **x** | | |
| Avatar options should represent the outer appearance and attitude of all individuals in society. | | **x** | |
| Review avatar options on a regular basis. | **x** | | |
| Allow users to customize and personalize their avatars according to their preferences, needs, and contexts. | | **x** | |
| **Community & economic growth** | | | |
| Ensure that avatars are compatible across different virtual worlds and platforms within the metaverse, promoting inclusivity and user engagement. | **x** | | |
| Allow users to choose from a range of realistic and diverse avatars that reflect their physical and cultural characteristics, as well as their moods, tastes, and styles. | | **x** | |

**Table 6: Object regeneration, recognition, and rendering requirements**

| **Object Regeneration, Recognition, and Rendering** | **Requirement types** | | |
|---|---|---|---|
| | **is required** | **Is recommended** | **optional** |
| **Energy-efficiency & environmental aspects** | | | |
| Adjust rendering quality based on user proximity and focus, and conserve computational resources by avoiding high-definition rendering for distant or peripheral objects. | **x** | | |
| Streamline rendering by not rendering objects obscured from the user's view. | | **x** | |
| Utilize a range of object complexities, show details only when significant, and opt for simpler representations otherwise. | | **x** | |
| Be aware of the varied computational capacities of user devices, use server-side rendering for devices with lower computational capabilities. | | **x** | |

| | | | |
|---|---|---|---|
| Adapt rendering outputs for unique capabilities of each device, from mobile interfaces to VR headsets. | **x** | | |
| **Human-centric design** | | | |
| Enable users to express their creativity and innovation through object regeneration, recognition, and rendering, adapt their appearance and behaviours to different situations and audiences in the metaverse. | | **x** | |
| Object regeneration, recognition, and rendering should reflect the physical and cultural diversity of the real world and allow users to create and interact with a range of realistic and diverse objects that suit their preferences and needs. | | **x** | |
| Ensure users' security and privacy in individual recognition, object regeneration and other related tasks. | **x** | | |
| **Community & economic growth** | | | |
| Ensure system operability in developing countries and unstable broadband networks, enabling lower quality rendering. | **x** | | |

**Table 7: Infrastructure & devices requirement**

| Infrastructure & Devices | Requirement types | | |
|---|---|---|---|
| | **is required** | **Is recommended** | **optional** |
| **Energy-efficiency & environmental aspects** | | | |
| Use energy-efficient platforms, cloud services and data centers powered by renewable sources, and fostering the reuse of devices. | **x** | | |
| Manage high bandwidth and low latency for seamless global connectivity. | **x** | | |
| Optimize network components for energy efficiency. | **x** | | |

| | | | |
|---|---|---|---|
| Design the system architecture to reduce operational energy usage and extend device's lifetime to reduce e-waste. | **x** | | |
| **Human centric design** | | | |
| Design devices for human safety using for instance warning labels and safety guards. | **x** | | |
| Select devices based on users' characteristics, behaviours, and expectations. | | **x** | |
| **Community & economic growth** | | | |
| Involve prospective users and stakeholders in the choice of devices. | | **x** | |
| Design modular and upgradable devices to allow reuse and refurbishment especially in disadvantaged communities. Devices with close physical contact to users or those carrying personal data it is required to have replaceable parts to enable owners' switching. | | **x** | |
| Users' devices it is required to be accessible regardless users' physical or cognitive abilities. | **x** | | |
| Design equipment to last for a long time and enhance its robustness to failures and unfavourable environmental conditions. | **x** | | |

## Appendix I
## Recommendations for future work

(This appendix does not form an integral part of this Technical Specification)

***Recommendation 1: Evaluation of system sustainability via metrics and indicators.*** Establish standardized sustainability metrics and indicators, along with methodologies, to assess a metaverse ecosystem's sustainability impact. This is essential to evaluate the system's impacts on the environment, individuals, communities, and businesses.

***Recommendation 2: Incentivize impact-driven metaverse design geared towards UN SDGs.*** Promote sustainable design practices for the Metaverse within the research and business communities by introducing incentives at the institutional, business, and research levels.

***Recommendation 3:*** *Define* ***Integrated guidelines for an ethical, socially responsible, and green system design.*** Define technical design guidelines to promote the use of green technologies and practices in the metaverse, such as low-carbon devices, renewable energy-powered data centers, energy-efficient AI models, and data/software reusability. These guidelines shall also ensure the system's alignment with human values ethical principles, and the promotion of human capabilities, individual uniqueness, diversity, and real-world collaborations. Additionally, they shall assist practitioners in identifying, mitigating, and managing various types of system biases while preventing harm.

***Recommendation 4: Rise awareness and support the transition to a sustainable system design approach.*** Advocate a transformative shift in the system design approach within technical research and business communities, akin to the tech-responsible design approach. It's vital for practitioners to recognize significant sustainability risks posed to individuals and the environment, including disconnection from reality, manipulation, user isolation, diminished self-esteem, misinformation, and influence polarization. Institutions shall actively promote awareness of system sustainability risks and opportunities. For example, they shall encourage universities to offer courses on metaverse sustainability, aligning system design with environmental, ethical, economic, legal, social, and psychological aspects while fostering fairness, diversity, and inclusion.

## Bibliography


| | |
|---|---|
| [b-ITU-T M.3080] | Recommendation ITU-T M.3080 (2021), *Framework of artificial intelligence enhanced telecom operation and management (AITOM).* |
| [b-ITU-T P.1320] | Recommendation ITU-T P.1320 (2022), *Quality of experience assessment of extended reality meetings*. |
| [b-ITU-T Y.4600] | Recommendation ITU-T Y.4600 (2022), *Requirements and capabilities of a digital twin system for smart cities*. |
| [b-ITU-T Y.4000] | Recommendation ITU-T Y.4000/Y.2060 (2012), *Overview of the Internet of things.* |
| [b-ITU-T Y.101] | Recommendation ITU-T Y.101 (2000), *Global information infrastructure terminology: Terms and definitions*. |
| [b-ITU-T L.1410] | Recommendation ITU-T l.1410 (2014), *Methodology for environmental life cycle assessments of information and communication technology goods, networks and services.* |
| [b-AI HLEG 2019] | HLEG, A. (2019). *Ethics guidelines for trustworthy artificial intelligence*. High-Level Expert Group on Artificial Intelligence (AI HLEG), 8. Available [viewed 2023-09-15] at: https://digital-strategy.ec.europa.eu/en/library/ethics-guidelines-trustworthy-ai |
| [b-Garcia-Betances] | García-Betances, R. I., Jiménez-Mixco, V., Arredondo, M. T., & Cabrera- Umpiérrez, M. F. (2015). *Using virtual reality for cognitive training of the elderly*. American Journal of Alzheimer's Disease & Other Dementias, 30(1). Available [viewed 2023-09-15] at: https://journals.sagepub.com/doi/full/10.1177/1533317514545866 |
| [b-Henz] | Henz, P. (2022). *The societal impact of the metaverse*. Discover Artificial Intelligence, 2(1), 19. Available [viewed 2023-09-15] at: https://link.springer.com/article/10.1007/s44163-022-00032-6 |
| [b-Henz 2022] | Henz, P. (2022). *The psychological impact of the metaverse*. Discover Psychology, 2(1), 47. Available [viewed 2023-09-15] at: https://link.springer.com/article/10.1007/s44202-022-00061-3 |
| [b-Hupont] | I. Hupont Torres, V. Charisi, et al. (2023). *Next generation virtual worlds: Societal, technological, economic and policy challenges for the EU* (No. JRC133757). Joint Research Centre (Seville site). Available [viewed 2023-09-15] at: https://ideas.repec.org/p/ipt/iptwpa/jrc133757.html |
| [b-Liu] | Liu, F., Pei, Q., Chen, S., Yuan, Y., Wang, L., & Muhlhauser, M. (2023). *When the metaverse meets carbon neutrality: Ongoing efforts and directions*. arXiv preprint arXiv:2301.10235. Available [viewed 2023-09-15] at: https://arxiv.org/abs/2301.10235 |
| [b-Logeswaran] | Logeswaran, A., Munsch, C., Chong, Y. J., Ralph, N., & McCrossnan, J. (2021). *The role of extended reality technology in healthcare education: Towards a learner-centred approach*. Future Healthcare Journal, 8(1), e79. Available [viewed 2023-09-15] at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8004346/ |
| [b-Ning] | Ning, H., et al. (2023). *A survey on the metaverse : The state-of-the-art, technologies, applications, and challenges*. IEEE Internet of |

Things Journal. Available [viewed 2023-09-15] at: https://ieeexplore.ieee.org/abstract/document/10130406

[b-Pagone] Pagone, E., Hart, A., & Salonitis, K. (2023). *Carbon footprint comparison of bitcoin and conventional currencies in a life cycle analysis perspective*. Procedia CIRP, 116, 468-473. Available [viewed 2023-09-15] at: https://www.sciencedirect.com/science/article/pii/S221282712300094X

[b-Schwaartz] Schwartz, R., Dodge, J., Smith, N. A., & Etzioni, O. (2020). *Green ai*. Communications of the ACM, 63(12), 54-63. Available [viewed 2023-09-15] at: https://dl.acm.org/doi/abs/10.1145/3381831

[b-Tulone] D. Tulone. *Tech-Responsible Design to Advance UN SDGs*. To appear in Proc. of IEEE Web Intelligence and Intelligent Agent Technology, October 2023.

[b-Tulone 2023] D. Tulone. *Leveraging sustainability benefits of ai systems while mitigating risks*. International Conference on Sustainable Development, Track Digital Era, 18-20 September 2023.

[b-Tulone Samuel] Sector, S. FG-AI4EE D. *WG1-08 Driving AI-IoT design towards the UN sustainable development goals (SDGs)*. Available [viewed 2023-09-15] at: https://openportal.isti.cnr.it/doc?id=people______::95952b836da8c8b620d4f823966df402

[b-UN_GAES] UN General Assembly Economic and Social Council. (2023). *Progress towards the Sustainable Development Goals: Towards a Rescue Plan for People and Planet*. Report of the Secretary-General (Special Edition). Available [viewed 2023-09-15] at: https://www.un.org/en/conferences/SDGSummit2023/documentation

[b-Voigt] Voigt, P., & Von dem Bussche, A. (2017). *The eu general data protection regulation (gdpr)*. A Practical Guide, 1st Ed., Cham: Springer International Publishing, 10(3152676), 10-5555. Available [viewed 2023-09-15] at: https://link.springer.com/book/10.1007/978-3-319-57959-7

[b-Xu] Xu, M., et al. (2022). *A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges*. IEEE Communications Surveys & Tutorials. Available [viewed 2023-09-15] at: https://ieeexplore.ieee.org/abstract/document/9944868

[b-Zhang] Zhang, S., Lim, W. Y. B., Ng, W. C., Xiong, Z., Niyato, D., Shen, X. S., & Miao, C. (2023). *Towards green metaverse networking : Technologies, advancements and future directions*. IEEE Network. Available [viewed 2023-09-15] at: https://ieeexplore.ieee.org/abstract/document/10012292