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Information Technology Vision 2035

by VDE ITG

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Content

Executive Summary

Today the world stands at a critical juncture. The risks from global fragmentation, economic and social imbalances as well as increasing environmental degradation are real. Europe, and Germany in particular, has the potential to leverage its leading capabilities in research, technological innovation as well as its social market economy to address these challenges. We can push towards a world that reflects our values of economic and environmental sustainability as well as social participation and digital inclusion. We need to respect security, privacy and trust and employ "green by design" principles. To achieve this vision in a digitalized and interconnected world, Information Technology will play a critical role.

This VDE ITG Impulse Paper will explore how Information Technology innovation can help to achieve and drive economic, societal and environmental sustainability [1] for the next decade anchored in the purpose of helping the world to collaborate. Awareness of Information Technology evolutionary and revolutionary options to address opportunities of the future will help to foster digital inclusion and social participation to achieve this vision in a joint effort of citizens, government, and industry. Information Technology has become general purpose with enabling impact across all sectors of the economy, it is one of the fundamental pillars of our daily life and a key driver of economic growth. The objective of this Impulse Paper is to describe the Information Technology evolution and innovation, the resulting opportunities and threats while assessing and describing the associated ecosystem economic value impact which correlates with positive impact for the society in the dimensions of energy efficiency, sustainability, security and trust, social participation as well as digital inclusion.

To build an Information Technology Vision, we develop, describe and discuss a taxonomy of the Information Technology Foundational Technology Enablers, Systems as well as Services and Applications, mapping them against the Ecosystem Value. Herewith, we associate both expected future market opportunities as well as the broader sustainability impact driven by the respective ecosystem. Note that some of the top Information Technology companies are positioned at the intersection of taxonomy building blocks such as the enabling intersection of microelectronics and AI/cognition. Foundational technology enablers include data transmission, data processing, data memory and storage, Input/Output (I/O) devices, quantum technologies, Operating System (OS), drivers and firmware as well as semiconductors/microelectronics. We define "Systems" to comprise the integration of Hardware (HW) and Software (SW) technologies, device-cloud-edge-continuum, system software as well as capability exposure of networks, Information Technology infrastructure and devices. Services and Applications are meant to include autonomous operations and application software. Digital twinning as well as an open Application Programming Interface (API) regime will apply across the taxonomy stack to enhance performance and sustainability of a variety of use cases. Sustainability, Security as well as Cognition and Artificial Intelligence (AI) can be seen as comprehensive drivers for design and value.

Key prerequisites to live up to our Information Technology Vision 2035 will be awareness of the drivers and technology options by key stakeholders across sectors and in our society at large. This includes to find ways to enthuse, educate and recruit young talent within and outside Germany as well as appropriate vehicles of cooperation and public private partnerships. Public funding of research in key Information Technology domains continues to be a very important enabler in terms of both building a strong research foundation as well as training the next generation of Information Technology specialists. Standardization and openness will be an essential factor of success also in 2035 for reasons of economy of scale as well as interoperability. A fair, reasonable and non-discriminatory patent regime will be needed to allow the Information Technology industry and practicing entities to recapture some of their value and to respect the legitimate interests of both patent holders and implementers. Complex regulatory frameworks need to be simplified to foster growth, innovation and scalability for German and European companies and ecosystems.

Germany and Europe have a lead position in advanced connectivity and communication networks which needs to be leveraged also in the interest of technology sovereignty [2]. Our ambition needs to be to foster a vibrant Information Technology ecosystem including academia, service providers and industry (large corporates, SMEs and start-ups) to strengthen the full value chain from research to products and services. We need to build on our strengths and drive the accelerated build-out of Information Technology infrastructure in the next several years. This will be the steppingstone to maximize Information Technology's positive impact in the 2030s.

1 Introduction and Motivation

Our life is unconceivable without the widespread use of Information Technology. In all areas of our economy, society and personal environment we depend on its performant and reliable functioning, often without even noting that Information Technology is behind nearly everything we do. Examples include the use of computers of every kind, communication by smartphones, travel by car and navigation, transporting people and goods, medical diagnostics, industrial production, agriculture, the whole financial systems, public administration as well as safety and security systems. Also, the transformation of our society and economy towards sustainability and the needed levels of security and trust as well as digital inclusion i.e., equitable access to Information Technology will not succeed without targeted use of Information Technology. Indeed, innovation in Information Technology will help to achieve economic, societal and environmental sustainability and help the world to collaborate to solve these essential challenges.

Europe and Germany have played leading roles in developing and leveraging Information Technology since the very beginning, as just a few names illustrate: Werner von Siemens's first telegraphy lines in 1847, Guglielmo Marconi's inventions in the field of radio technology around the turn from the 19th to the 20th century, or Konrad Zuse's first computers in 1941. The strong academic tradition, the research environment in Germany and the close collaboration of academia and industry have been key factors of success, laying the conceptual groundwork and contributing successfully to the advances of Information Technology and their application. Growing complexity of technology and ecosystems has led to a high degree of cooperation on national and European levels as well as on a worldwide scale.

Initially, Information Technology systems were standalone solutions to specific problems such as the telephone networks for voice communication, or computer systems for scientific or economic calculations. Throughout the last five decades, Information Technology has gradually found its way into all technical systems we use today across all sectors. Thus, Information Technology has become a general purpose technology. It is one of the fundamental pillars of our daily life and a key driver of economic growth [3]. Understanding the current state of the art and the evolution of the related technologies is critical to the future competitiveness of our economy, the assurance of future sustainability, individuals' wellbeing and the advancement of human possibilities.

The "Informationstechnische Gesellschaft im VDE" (VDE ITG), founded in 1954, encompasses the various players in Germany's Information Technology ecosystem on scientific-academic, service provider and industrial level, including nearly 10,000 individual experts working in the field. Given the importance of Information Technology as described above, we at VDE ITG feel that the time has come to develop and share a vision for Information Technology 2035 based on latest research and to formulate key recommendations on how to get there and what the associated policy implications will be.

Key objectives are to

- Outline the Information Technology evolution and innovation,
- Make recommendations on how to capture value and seize potential opportunities as well as how to mitigate risks, and address aspects of policy and regulation,
- Assess and describe its value for the society and associated drivers such as energy efficiency, sustainability, security and trust, social participation, as well as digital inclusion.

The paper is primarily targeting stakeholders and decisions makers

- in the Information Technology domain and beyond, both public and private sector,
- in government, regulation, and policy making,
- in civil society and the public at large.

While the depth of the analysis is profound, the aim of the paper is to provide a comprehensive overview. Information Technology experts and others interested in further technical details are kindly referred to the references provided in this paper.

The document starts with a brief look at relevant macrotrends and key trends inside Information Technology research and industry in Section 2. These are further explored by looking more thoroughly at selected fields of technology, their state of the art, current trends and expected state by 2035 in Section 3. Based on this technology perspective, the paper outlines some fields of application with potential usage scenarios in Section 4 and considers key factors of success beyond technology in Section 5. In a synthesis of the technology and use case perspective, it derives in Section 6 our recommendations on how to make sure we exploit the opportunities and mitigate the risks which the Information Technology progress will hold.

2 General macrotrends and key trends in Information Technology

The challenges in today's world are manifold. Information Technology has helped to tackle many of these in the past, but more importantly there are numerous opportunities for Information Technology to address key challenges of the future in the dimensions of economic, environmental and societal sustainability. They build on key technological trends which shape the evolution of Information Technology, and which will enable value drivers of the 2030s such as "green by design", security, resilience and trust as well as digital inclusion. The following Figure 1 shows an integrated view of the drive towards trustworthy sustainability and trends in Information Technology on our path to the next decade that will be discussed and introduced in this section. Information Technology pull effects are generated from macro-trends and their associated challenges and opportunities in an increasingly challenging geopolitical context. At the same time the same time we can expect a continued push from Information Technology research and innovation in key domains including Artificial Intelligence/ Machine Learning (AI/ML) and data processing, novel software technologies, system and network, transport and access, microelectronics as well as security technology.

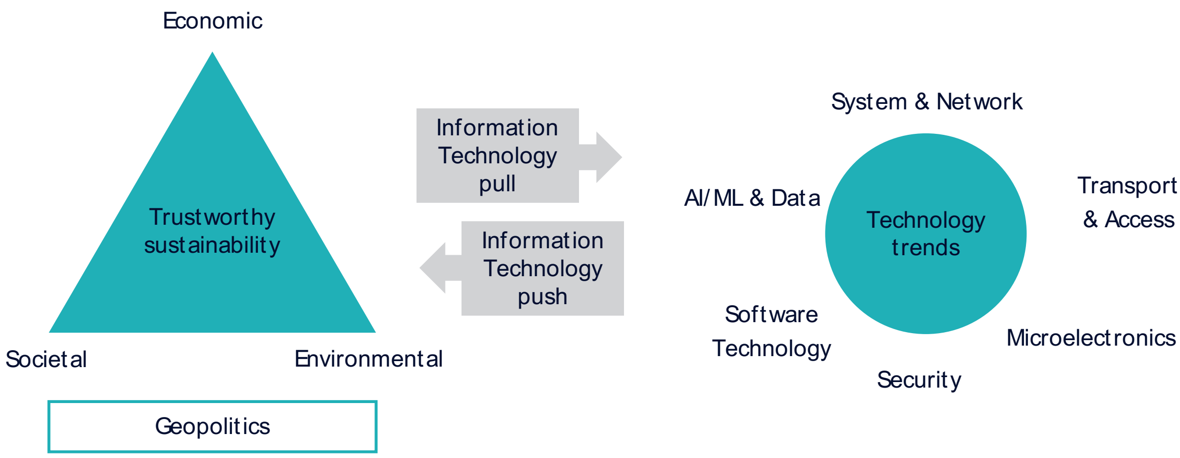

Figure 1 Information Technology pull and push effects between the three dimensions of Sustainability in the geopolitical context and top six Technology trend domains

2.1 General macrotrends and challenges

Environmental sustainability is one of the biggest challenges our planet is facing today and in the foreseeable future. Information Technology will be able to contribute to transformational handprint (i.e., positive impact) within Information Technology and in the various sectors pervasively served. Undoubtedly, there is a need to actively manage Information Technology environmental footprint (i.e., negative impact) by reducing overall power consumption and transforming to circular re-use of materials and products. However, Information Technology is the base for a countless number of solutions which help to cope with the environmental challenges. It can help to deal with the intricacies of renewable energies in modern power grids. Information Technology also enables clean manufacturing and supply chains, energy-efficient transportation of people and goods, and many other applications. It can also empower advanced space borne systems to provide continuous monitoring of the state of the planet by means of remote sensing [4].

Germany, like many other industrialized countries, faces an **ageing society**. The resulting shortage of skilled technical experts will pose a major challenge to the whole Information Technology ecosystem including the sector itself and all sectors which make use of Information Technology. At the same time, Information Technology helps to mitigate problems arising from the ageing society by enabling advances in medical and elderly care, or by enabling the wide-spread use of Artificial Intelligence to automate work, thus helping institutions to mitigate the risks of a shrinking talent base and workforce. Information Technology will be able to offer innovative and cost-effective solutions for **digital inclusion** of the elderly as well as to connect the unconnected by means of non-terrestrial Information Technology to complement terrestrial technology and networks.

The ubiquitous use of Information Technology fosters **societal value** creation, but it also brings **societal changes** we must cope with. On the one hand, Information Technology-based applications such as messengers and social media have allowed for instantaneous worldwide multimedia communication and sharing for the good. On the other hand, they also have led to filter bubbles on the Internet which reinforce non-factual or even extremist opinions and are being exploited by multiple forms of cybercrime. Information Technology advances such as the current rapid progress of AI will offer attractive new solutions, but undoubtedly bring along new challenges as well, and the highest ethical standards need to be assured. Information Technology offers a variety of innovative solutions for the future to assure **security, privacy and trust** [5]. In the upcoming era of extended reality and digital twins, privacy as intrinsic part of Information Technology solutions deserves dedicated attention: Quantum safe cryptographic schemes and advanced schemes of encryption such as homomorphic encryption, shared and federated processing of data across edge clouds as well as trusted execution environments (TEEs) will be some of the related technology building blocks. Beyond these aspects, autonomous systems such as autonomous vehicles heavily relying on deep neural networks in their environment perception require new ways to deal with system validation and the overall goal of safety.

Given the global importance of Information Technology, we must also consider the geopolitical situation. Amid heightened geopolitical uncertainties, we need to collaborate and address current and future relevant challenges. These, for example, range from cyberattacks to disinformation campaigns, from unauthorized or malicious exploitation of data to direct espionage, and from limitations in access to materials and components to restrictions in access to relevant knowledge. A sufficient degree of **technological sovereignty** [6] is key for both the government and the private sectors to cope with the risks and remain capable of making use of Information Technology as needed [2]; technological sovereignty appears to be of special relevance in conjunction with chipset availability and design capabilities [7]. There is value in **global standards** from both economy of scale and interoperability perspective, fragmentation needs to be avoided. Also, a fair, reasonable and non-discriminatory patent regime will continue to be a key factor of success also in the 2030s. Policy making, and regulation need to foster innovation and growth while providing reasonable and simple competitive frameworks as well as guardrails to maximize the positive impact of Information Technology on the society and the economy.

2.2 Key trends in Information Technology

Within the field of Information Technology, one of the most essential trends is the continuing **progress, innovation and relevance of microelectronics**. Moore's law has been shaping this evolution for decades. However, with the end of the Moore paradigm now approaching, there are other parameters as well which are key to modern Information Technology, such as novel compute architectures and in-memory compute, chiplets, cost of storage, electronic and optical interconnect capacities, pixel density in cameras and screens, novel chip level architectures, the use of new materials, or the integration of microelectronics and micromechanical systems. Finally, Artificial Intelligence is a driver for massive parallelization e.g., by means of graphical processing units (GPUs). These trends build the essential hardware base for Information Technology. Power consumption and energy efficiency have emerged as key issues to be addressed. In mobile network systems, for instance, the uptake of very high frequency bands for specialized local use cases will imply full focus on energy efficiency while spectral efficiency is no longer as critical due to bandwidth availability. Koomey's law states that the energy efficiency of computing doubles approximately every 18 months, meaning that for a given amount of computational power, the energy required decreases significantly over time. However, recent studies indicate that this trend has slowed, reflecting the diminishing returns in energy-saving advancements and optimization in the computing industry. Also, novel technologies such as quantum sensing, quantum computing and quantum communications may have a major impact for selected applications and on the future development of Information Technology. The biggest impact we see in the mid-term is the AI infrastructure race. In a competition to build the largest GenAI models for training, hyper-scalers have set out to build a new generation of AI data centers with AI/GPU clusters with up to a million processors consuming more than a Gigawatt of power.

Continuous progress is observed in the **transport of data**, either via **radio** "over the air" (whereby "air" also may include the outer space), or via (mainly infrared) light through **optical** fibers and in some cases also through air or space. Special semiconductor materials and high integration densities of analogue and digital electronics combined with sophisticated system architectures and the usage of high frequency bands drive design for always higher data rates, low latencies, and low power consumption. They form the base for new systems like 5G/6G mobile communication networks [8], ultra-dense optical access (to address a large number of customers in the most cost-effective way) and high-capacity packet-optical transport networks (to maximize the capacity between a low number of end-points (mostly data centers and central offices)), low power wide area networks for the Internet of Things (IoT), and non-terrestrial networks (NTNs) which use satellites to provide communication services [9].

Enabled by the progress in microelectronics as well as optimized network capability such as 5G Reduced Capability ("RedCap"), which allows for devices with reduced capabilities and low power wide area networks for mobile and mission critical scenarios, **ever growing amounts of data** are being generated by all kinds of sensors such as multiple Ultra High Definition (UHD) cameras or a multitude of IoT-devices. Of special relevance are advanced radar sensor systems including novel cognitive Radar, Multiple In Multiple Out (MIMO)-Radar as well as multi-static approaches with sophisticated processing including Synthetic Aperture Radar (SAR) based concepts [10] [11]. A promising concept for the 2030s is to design systems and networks to do Joint Communication and Sensing (JCAS) [12] [13]. Beyond the pure handling by Information Technology transport, storage, and processing functions, sensor data form the base for countless novel applications and various scenarios of digital twinning as well as the training and use of AI based applications.

Data processing poses opportunity for innovation across the distributed cloud architecture [14]. Edge-based solutions range from medical solutions such as (very low-powered) hearing aids and cochlea implants over smartphones to powerful environment perception for autonomous vehicles, the latter requiring fusion techniques to support the various types of sensors being deployed. Cloud-based data processing solutions are not insensitive to power consumption - millions of service users can quickly impose heavy energy usage and efficiency constraints on cloud services.

AI and Machine Learning are essential data processing technologies. Currently they are developing at a very fast pace enabled by suitable processors, large amounts of data, and novel algorithms; at the same time, trustworthiness including explainability of AI/ML has become a prominent theme [15]. In 2012, the renaissance year of AI, and the subsequent years, many have spoken of an AI hype. As we know 12 years later the fast pace of AI was not just technology-driven, but with the vast innovative business opportunities ("technology pull") of AI in the last several years, AI is the fastest growing branch of Information Technology with immense impact on society and the economy. Most recently, and at the forefront of this, the generative AI (GenAI) general market take up has been extremely fast. Language technology will play an increasing role, as large language models (LLMs) or vision-language models have just started to transform societies on global scale due to their immense power to support efficient training of AI, innovative workflows and inclusion. At the same time, it is expected that numerous purpose-designed AI solutions will emerge, which will perform specific tasks and - deployed in a well-designed end-to-end manner - will allow to drive and optimize the functioning of highly complex technical systems.

Software technology also develops at a fast pace. Programming takes place on always higher abstraction layers, so that rather than writing code, programmers often implement business logics using powerful SW toolsets provided by communication network and infrastructure vendors ("no code" and "low code"), service providers and the hyper-scalers whose cloud platforms are being used. At the same time, resource efficient programming remains essential when strict real time performance is needed, or when electrical energy, computing power or memory is limited such as in many IoT devices. This can be seen in the automotive industry, where mastering complex SW technology and architecture will play a core role in going forward.

On higher levels, the progress in HW and SW technologies is used to build highly **differentiated computer systems and networks**. Of relevance are various cloud topologies including edge cloud / edge computing and powerful data centers but also embedded systems where Information Technology functions are deeply "buried" within all kinds of products. Alongside with these developments, a blurring of the distinction between communication and computing is observed i.e., we see the convergence of communication and information technologies, exemplified by the slogan "the network is the computer", and in the various "as a service" applications. The paradigm of integrated network and compute in conjunction with the device-edge-cloud continuum will open new possibilities in the years to come; seamless and dynamic orchestration will be needed [16].

The **increasing complexity and widespread usage** of Information Technology systems and networks, the multitude of stakeholders involved, and billions of connected devices, vehicles and machines will bring along **security and safety challenges**, which in turn require regular SW upgrades in the field. Beyond security and safety, privacy, data sovereignty, resilience and high availability are further topics which evolve in the Information Technology landscape.

Both the technical evolution of Information Technology and its affordability have led to a **ubiquitous availability of computation and communications** functions including IoT, embedded in many appliances in daily use by professionals and individuals alike.

Bringing the mentioned technology fields together, Information Technology has become a key **enabler for innovation** and has essential attributes of general-purpose technology, essential for our daily lives and all industrialized countries' competitiveness and economic growth, while focus is needed on value creation in dimensions of environmental sustainability, security and trust, safety as well as digital sovereignty.

3 Technology Base for the Information Technology Vision 2035

3.1 Approach – Foundational Technology Enablers, Systems and Services & Applications

Beyond a simple listing of relevant technologies, building a technology vision requires an understanding of the relevance and impact of Technology Enablers, Systems in the sense of system-level solutions, Services & Applications and the associated Ecosystem Value. Hence, this paper proposes a taxonomy as shown in Figure 2 for description and analysis of Information Technology Vision 2035. The taxonomy shows the vertical stack of Foundational Technology Enablers, Systems and Services & Applications mapped against Ecosystem Value as shown on the horizontal axis, whereby positive value impact increases from left to right. Note that the key value impact that we indicatively associate with the respective building blocks across the three layers of the stack includes not only the overall size and dynamic of the respective markets but also dimensions of societal value such as trustworthiness and environmental sustainability. Security, Sustainability and Cognition are meant to be aggregates of the associated Information Technology building blocks (the aggregate nature is visualized by the arrow symbols).

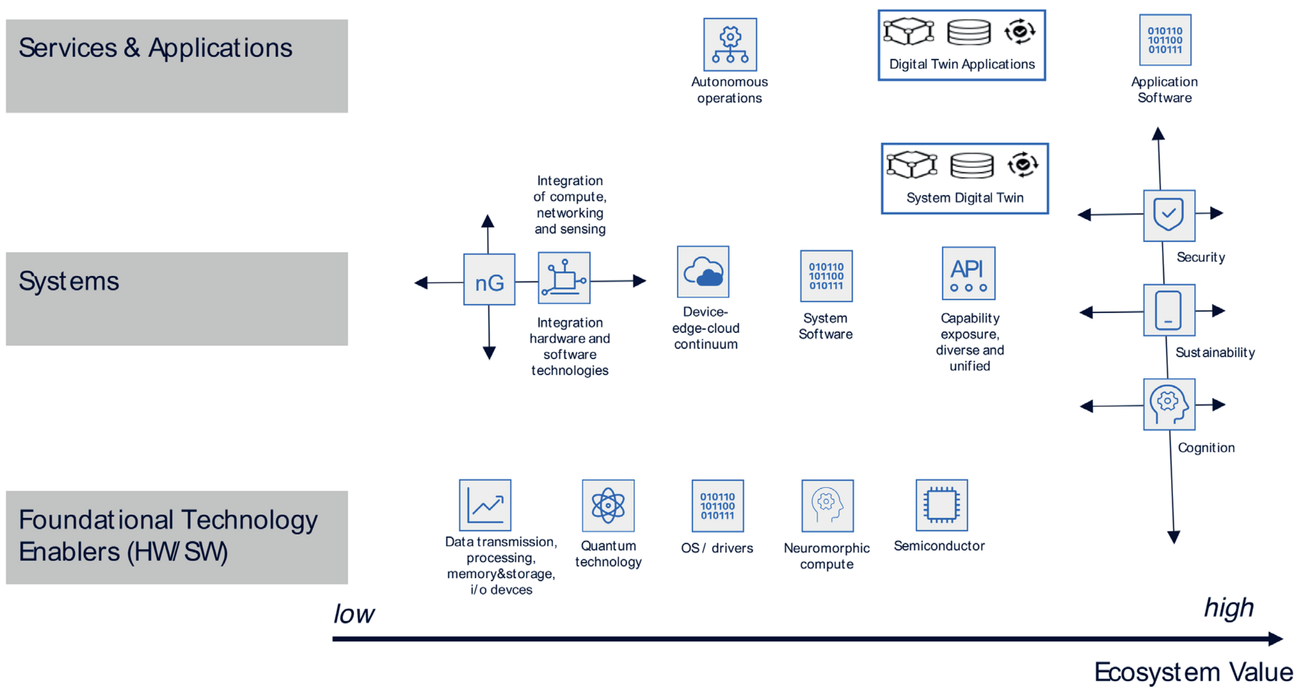

Figure 2 Foundational Technology Enablers, Systems and Services & Applications mapped versus Ecosystem Value

Generally, processes, desired outcomes with their associated KPIs and their underlying problems such as e.g., sustainability, security, or cognition do not change over time, unlike the technologies used to realize them. For example, on the layer of foundational technology enablers, the process of "transmission of information" has been realized by different technologies during the past decades, such as the different generations of cellular radio and fiber technologies. Similar observations can be made for "data processing", "data storage", and further core functionalities of Information Technology systems. However, disruptive innovation is driven by novel combinations of technology enablers and building blocks. For example, the use cases we broadly associate with metaverse and digital twinning (DT) are enabled by holistic orchestration and exposure, Quality of Service/Quality of Experience (QoS/ QoE), analytics and data, AI/ML, sensor and actuation technology, security, and privacy as well as by compute performance across the device-edge-cloud continuum.

In the following, this section will start by analyzing key technologies expected to be commercially available by 2035, applying a distinction into hardware-centric technology enablers on the one hand and software-centric technology enablers on the other hand. The subsequent sub-section will then provide a synthesis by elaborating how selected technologies are integrated to realize specific end-to-end Information Technology systems that can be used in different Services & Application areas (final subsection) and across industry sectors (see Section 4).

3.2 Trends in hardware-centric Foundational Technology Enablers

This subsection analyzes technology trends in hardware-centric Information Technology enablers. The continuous improvements in microelectronics and semiconductor technology will shape future Information Technology hardware and its applications. Until 2035, performance, energy efficiency, feature size, and densification are expected to reach new levels. For example, Gate-All-Around (GAA) and Complementary Field Effect Transistors (FETs) architectures are expected to enable feature sizes below 1nm. We discuss which trends may impact the future hardware in four major areas of Information Technology – data transmission, data processing, data storage, and data Input/Output (I/O) devices.

3.2.1 Data transmission

One emerging and two established technologies are expected to be essential to the communication systems landscape of the 2030s. First, starting with the established technologies, **broadband wireless communication** systems will provide data transmission over the air, addressing communication requirements in mobile scenarios [17]. By 2035, the sixth generation of mobile networks (6G) will be deployed at a significant scale. While **6G radio** is expected to be an evolution of 5G New Radio (NR), it will also exhibit several new innovative features. It will expand into new frequency bands, including Frequency Range FR3 (7-24 GHz) and sub-Terahertz bands (90-300 GHz), thus allowing for an at least 10-fold increase of available spectrum. Hardware architectures realizing sub-array-based radio frequency (RF) transceivers with analog beam steering per antenna subarray and digital precoding over multiple RF chains could enable scalable use of beamforming to effectively leverage sub-THz bands. For lower mmWave bands, the transition from analog to hybrid/digital beamforming will continue. Semiconductor technology advancements will also enable cost- and energy-efficient realization of massive (multi-user) Multiple Input / Multiple Output (MIMO) systems, allowing for larger antenna arrays to be deployed. In terms of radio waveform, refined Orthogonal Frequency Division Multiplex (OFDM) schemes, such as Discrete Fourier Transform-Spread-Orthogonal Frequency Division Multiplexing (DFT-S-OFDM) or Single Carrier (SC) schemes, will address shortcomings of 4G LTE and 5G NR such as improved peak-to-average power ratio. Overall, these developments will result in better network coverage, increased spectral efficiency, higher capacity, and more efficient power consumption. At the same time, latency and reliability of wireless data transmission will be enhanced. Beyond cellular radio, we will also see performance improvements in radio technologies operating in unlicensed bands, like Wireless Local Area Networks (WLAN), Bluetooth, or long-distance radios.

Second, data transmission via **high-capacity fiber-optic networks** will provide the means to cope with the ever-increasing data volume in “Tier 1” (Internet exchange or transit Internet Service Providers (ISPs) backbone network), “Tier 2” (intra-ISP network or enterprise Wide Area Networks (WAN)), and “Tier 3” (Mobile or Fixed Broadband Packet Core) networks [18]. Besides an evolution towards a less hierarchical infrastructure topology, where an “Interconnect Core” will dynamically create high-speed and low latency connections between networks within and across tiers and the associated data centers, there will also be further hardware-centric technology innovations. Passive Optical Networks (PON) [19] i.e., optical networks without active components like switches or multiplexers, are the dominant type of fiber-optical networks. With the typical PON generation cycle, we can expect the beyond 50 Gbit/s (“50G”) era to start in the early 2030s. For symmetrical data rates of 100Gbit/s and beyond, digital coherent technology will be required. Advanced digital signal processors, electro-photonic integration, and modifications of optical transmitter and receivers, new generation of lasers and optical amplifiers, and the development of increasingly linear circuits will push maximum data rates in PONs to these new levels. Scaling up the capacity in packet-optical transport networks in aggregation, metro, long-haul and subsea domain in an economically and environmentally sustainable way is an equally formidable challenge. Coherent transmission technology for per port data rates of 1600 Gbit/s and beyond, an exploration of time, wavelength and space domain to make best use of the available fiber infrastructure. Novel fibers such as hollow-core fiber which offer lower latency, lower dispersion, negligible non-linearity and broader bandwidth with potentially lower transmission losses could be the enabler for a new generation of packet-optical transport systems in the next decade. Growing bandwidth demands in hyper-scale compute and AI clusters will require massive interconnect capacities which present new opportunities for optical technologies and increased electro-photonic integration.

Third, quantum technologies may play an important role in the long term. Transition from the Quantum Key Distribution (QKD) systems that are commercially available today to the **Quantum Communication Infrastructures** (QCI) with trusted nodes that are currently tested in field trials; eventually the future Quantum Internet, for which the technological building blocks (such as quantum memories and entanglement swapping required in quantum repeaters) still require research for their possible future commercialization. Note also that, while QKD is the primary application of QCI, Quantum Internet will enable other quantum applications such as distributed / delegated quantum computing, quantum consensus / Byzantine agreement and quantum sensing networks.

3.2.2 Data processing

Next-generation computing will leverage three major technologies – well-established, yet continuously evolving **digital computing** on the one hand, and the two more disruptive technologies of **quantum computing** and **neuromorphic computing** on the other. As a common enabler to all three computing paradigms, AI will play an important role in automating, accelerating, and optimizing data processing procedures.

In **digital computing**, further advances of microprocessors need to optimize (and potentially resolve) the trade-off between cost, flexibility, energy efficiency, and processing power (as measured by e.g., transistor count/density, clock rate, instructions per clock). Domain Specific Architectures (DSA), such as Graphics Processing Units (GPUs) or Tensor Processing Units (TPUs) are limited to a narrow range of computing tasks but can achieve high energy efficiency and processing power. General-purpose microprocessors (as used in e.g., CPUs) can cope with a broad variety of computing tasks, but they are less energy-efficient and do not achieve the computing performance of specialized processors. In between these extremes, architectures such as field-programmable gate arrays (FPGAs) can realize good flexibility at a reasonable decrease of energy efficiency and computing performance. By 2035, we can expect continuous improvements in digital processors, including further advancements in highly parallelized computing, but the basic trade-off between flexibility vs. performance and energy efficiency will remain.

Quantum computers leverage the unique characteristics of quantum physics, such as superposition and entanglement. The concept of quantum supremacy denotes the expectation that quantum computers will prospectively become superior to classical digital computers in solving selected computational problems. Promising technologies for implementing quantum states include photonics, superconductors, semiconductor electron spin, neutral atoms, trapped ions, electrons on solid neon, or electrons over superfluid helium. Given further progress, they have the potential to overcome specific challenges like quantum decoherence and achieve high fidelity on a large scale. Another emerging technology comprises Majorana fermions. For each technology, highly specialized, cost-intensive materials and hardware systems are required to control and manipulate quantum states ("qubits") reliably. Examples include lasers, photonic and microwave components, superconducting circuits, semiconducting materials, or diamonds. Significant research and development breakthroughs are required by 2035 and presumably beyond, until any of these technologies can be mastered economically and at large scale.

Neuromorphic computers try to mimic the human brain – they comprise connected artificial neurons, thus building a neural network. Unlike conventional digital computers, neuromorphic systems integrate memory and processing elements within the same hardware and overcome limitations due to data shuffling between memory and the processor. Recent research and development efforts propose memristors, an electronic component exploiting the functional relationship between magnetic flux linkage and the amount of electric charge that has flowed, for interconnecting the artificial neurons of a neuromorphic computer [20]. A memristor can store and transmit a range of values (not only 0 or 1), thus mimicking the magnitude of a spike impulse exchanged between two neurons. These characteristics can be leveraged to build a spiking neural network, a processor architecture presumably much better suited for probabilistic AI computing tasks. Resulting characteristics of such neuromorphic computers are high energy efficiency and extreme adaptability to cope with heterogeneous computing tasks. For large-scale application, several challenges still need to be overcome, but the technology has the potential to disrupt the way IT industry builds computer systems.

3.2.3 Data memory and storage

Next-generation data storage and memory technologies need to be ready to cope with the ever-increasing amount of data of a fully digitized society in the 2030s. On a global scale, new mass storage (secondary memory) technologies need to reliably store zettabytes of data, while primary memory hardware must allow for quick and efficient retrieval by the processor. For both areas, semiconductor-based hardware is expected to be the dominant technology.

In the domain of mass storage, further performance and capacity enhancements of flash-based Solid-State Drives (SSD) are expected. Leveraging further densification and layering of "NOT-AND" (NAND) gate chips, SSDs beyond 1 petabyte seem realistic by the early 2030s and thus increasingly replace Hard Disk Drives (HDD). Additionally, research initiatives investigate more disruptive technologies for high-density data storage, among them holographic storage and DNA-based storage. While the former uses interfering laser beams to encode data to physical or chemical changes of a medium (e.g., polymers), the latter encodes data into synthesized DNA strands.

Similar double-tracked developments can be expected in the domain of primary data memory technologies. Within the next decade, well-established volatile memory technologies, including static random-access memory (SRAM), dynamic RAM (DRAM), and synchronous DRAM (SDRAM), will continuously enhance performance, energy efficiency, and overall cost. However, academia and industry have started exploring non-volatile memory (NVM) technologies, which originally have been exclusively targeted at data storage, for application as primary, on chip memory as well. Examples include resistive RAM (RRAM) variants (e.g., conductive-bridging RAM), magneto-resistive RAM (MRAM), or ferroelectric RAM (FRAM). These technologies excel in one or more of the following aspects: simple metal-insulator-metal structure, low fabrication cost, long endurance, low power consumption, multi-level cell (MLC) operation, or good scaling at low-nm technology nodes.

Another line of research investigates microelectronics that more tightly (or even inherently) integrate computing and storage functionality, like memristors as already described in Sec. 3.2.2.

3.2.4 Data input and output devices

The landscape of devices for data input and output develops at an ever-increasing pace. In the past, the introduction of the personal computer or the launch of smartphones, particularly Apple's iPhone, have marked major milestones in the way humans communicate. The use of novel technologies for input and output of data, media, and other contents comprises one reason for their tremendous success and impact. While these established devices will be further optimized and equipped with novel sensing and actuating technologies, we can in parallel expect the emergence of novel, more disruptive I/O technologies. These technologies will revolutionize consumer applications by enabling new device categories. Examples include ergonomic and affordable XR devices or devices that will increasingly support seamless multi-modality such as video and voice communication augmented with real-time haptic feedback. Holography will allow for live 3D reproductions of persons and objects in remote locations. In audio technology domain, silicon microphones and silicon earphones are the recent trend with long-term commercialization potential. These innovations will also bear effect in professional business environments by enabling new and more efficient forms of collaboration between humans as well as humans and machines. Finally, one of the ultimate I/O technologies under research is the brain-computer interface that may realize seamless exchange of data between humans and computers. While it is completely open if there will be any major breakthroughs until the 2030s, the technology has potentially groundbreaking impact on any area of personal or professional life, and the society at large.

3.3 Trends in software-centric Foundational Technology Enablers

This subsection analyzes technology trends in software-centric Information Technology fields in the time horizon of 2035. Very broadly, computer software can be categorized into two types.

Application Software comprises all software that is targeted to execute tasks beyond supporting the operation of the computer itself. Application software supports specified tasks from numerous application domains. This may range from software with very broad application areas, like word processing or spreadsheet applications, web browsers, data bases, all the way to highly customized software for application in very specific areas of industry, education, government, or entertainment. **System Software** denotes software that is required to execute tasks required for the operation of any type of computer. Particularly, this comprises Operating systems, including kernel, device drivers, and firmware. Operating systems are highly customized to the system they need to run, ranging from consumer electronics (personal computers, smartphones, TVs) to highly complex, large-scale IT systems. Utility software such as anti-virus software is considered as system software as well.

Another dimension comprises the s**oftware copyright status**. Very broadly, we can distinguish free software (e.g., opensource software) and proprietary software (e.g., most of the commercial software). While copyright status of software has high impact on several economic and societal factors, this paper will not further explore this dimension.

3.3.1 Innovations in application software

The evolution of application software will depend on the specific area. Nonetheless, we can identify a few commonalities independent of whether the applications will address industrial manufacturing, entertainment, or education services.

The establishment of so-called low code / no code (LCNC) software development platforms will transform software engineering. Such platforms largely rely on model-guided design and introduce visual approaches to programming such as "drag & drop" tools. The use of AI based programming will have strong impact and change the role of humans in software development. Such tools e.g., business process management software, can be used also by technically less versatile users to visually represent workflows. The resulting models are used by LCNC platforms for automatic code generation. LCNC will become more sophisticated and incorporate AI-guided software development methods ("Software 2.0"). Another general trend comprises the evolution from DevOps to DevSecOps, i.e., the usage of processes and toolchains that systematically integrate software development (Dev) and IT Operations (Ops) with state-of-the-art security procedures (Sec). This is complemented with further automation in Continuous Integration and Continuous Delivery/Deployment (CI/CD) methods in software engineering. Besides improving software equality and speed of delivery, these trends will also have profound impact on the competence profile of future software developers and programmers.

Within the next decade, several enabling software technologies will fuel distributed application and software development and deployment, overcoming centralized, hierarchical approaches dominated by a few companies. Microservice-based implementation and container-based deployment approaches will split application functionality into comparatively fine-grained units, improve modularity, and facilitate sustainable growth. This enables flexible, container-based deployments across private and public cloud resources and functionality bundling adapted to the user context. Transaction integrity for such distributed environments assured by distributed ledger/Blockchain technology. This transformation will yield additional benefits, it enhances both privacy – critical data only needs to be stored locally – and reduces the strain on networks since the need to transfer high data volumes will reduce significantly.

As a result of this technology evolution, the full user experience can only be leveraged by an accelerated shift to web-based application software, where a user has secure and reliable Internet-based access to the full software functionality from any location at any time. Moreover, usability and accessibility will improve by means of enhanced human-to-machine interfaces. Application software will be ready for delivery on new devices, allowing immersive mixed reality experience, haptic interaction even across remote locations, and real-time holographic communications.

3.3.2 Innovations in system software

As networking and computing systems are expected to undergo substantial transformation during the next decade, so are the respective OSs. "Traditional" OSs dominating the ecosystem today e.g., Unix/Linux, Windows, Windows Server, MacOS, Android, iOS, will continuously improve on all relevant dimensions, among them performance, usability, accessibility, and deployment flexibility. Moreover, the projected exponential growth of Industrial Internet of Things (IIoT) devices will demand for tailored OS and firmware solutions that are characterized by low power consumption, high scalability, and low-cost development and operation. While initially there will be very heterogeneous IIoT OS landscape, cost pressure will drive continuous consolidation towards very few competitive OS and system firmware solutions.

Beyond such device-centric OSs, the continuous trend towards distributed computing will require a new kind of "networked cloud OS". Using microservice-based implementation, application workloads are increasingly deployed across private, on-premises as well public-domain cloud platforms. Cross-platform, umbrella OSs control the underlying execution processes. Examples that already today implement a subset of these capabilities include e.g., Microsoft's Windows 365, Amazon's EC2, or Google's Chrome OS Flex. During the next years, such OSs will incorporate more sophisticated cloud and network orchestration functionality, allowing to schedule tasks on cloudified compute and network resources across multiple nodes in an integrated manner. Enhanced resource virtualization technologies such as the evolution of containerized cloud architecture will continue to serve as major enabler for these networked cloud OSs. Depending on the application area, they will also exhibit additional functionality such as cloud-network digital twin capability for optimization of scheduling decisions or preventive identification of cybersecurity threats. Due to the distributed, multi-domain nature of networked cloud OSs and architecture, they will incorporate Zero-Trust Architecture design principles (see Sec. 3.4.4).

Operating systems for quantum computers will face totally different challenges. New OS, driver, and firmware concepts need to be able to reliably cope with the unique features of quantum computing hardware. Novel abstractions such as the concept of qubits, and architectures, compared to those of classical compute systems, will have to be introduced. This affects resource scheduling algorithms, that, for instance, can exploit superposition of qubits for performing large-scale parallelized compute operations while at the same time controlling the impact of probabilistic qubit behavior (e.g., quantum errors, noise) with appropriate error correction and fault tolerance techniques. Currently, we expect the development of OSs to remain one of the research challenges in quantum computing. However, if successfully resolved within the next decade, it will have profound impact on all aspects of human life.

3.4 Integration to Information Technology Systems

This subsection elaborates on selected system-level Information Technology solutions expected to be relevant in the time horizon of 2035. The overall development will be characterized by five dominating trends: (1) optimization of the integration level of software and hardware, (2) the accelerated integration of computing and networking systems, (3) joint communications, computing, and sensing (JCCAS), (4) the embedding of Artificial Intelligence and Machine Learning to build AI-native Information Technology systems, and (5) the need for compliance with demanding security, resilience, and sustainability requirements.

3.4.1 Integration of hardware and software technologies

High-performance, reliable, and economic Information Technology components built on the appropriate level of integration of hardware and software components largely depend on the application scenario and the associated requirements in terms of performance, cost, flexibility, and versatility. On one end of the scale, a complete decoupling of (application-level) software and hardware can leverage the strengths (e.g., economies of scale) of general-purpose computing hardware (e.g., x86 system architecture). It allows to build massive computing capacity in central locations with access to power supply from renewable sources. On the other end, many Information Technology components call for a rather tight integration of hardware and software, thus leveraging the benefits of highly specialized microprocessors and the associated software architectures to generate high computational performance for a local, very specific application field (e.g., DSPs). In modern Information Technology systems, System on Chip (SoC) solutions, which integrate various microprocessors and microcontrollers on a single chip, are expected to gain further market share. Towards 2035, SoC technology will evolve along the trends of miniaturization, further integration, improved portability, higher power efficiency, as well as higher versatility by selectively integrating novel components for computing (potentially quantum processors) and storage (e.g., memristors to support neuromorphic computing).

3.4.2 Hyperconnected Information Technology infrastructure and the device-edge-cloud continuum

The transformation of Information Technology systems involves new paradigms in building and integrating networking and computing infrastructure. Cloud computing has become the foundation for enabling digital transformation and service delivery, including “everything as a service” (XaaS) solutions, across all industry sectors. Moreover, public compute infrastructures and more recently also public (mobile) networks have increasingly become cloud-native i.e., fully able to leverage the benefits of a distributed, multi-cloud architecture, enabling optimized service experience and resource utilization for both computing and networking. For example, edge computing comprises an effort to bring computing capabilities closer to the access network. At the same time, serverless computing allows developers to focus solely on writing and deploying code as the cloud provider manages the infrastructure automatically. In the private domain, industrial and enterprise Information Technology systems including the so-called Internet of Things (IoT), increasingly embrace the benefits of hybrid clouds with multi-tenancy usage models and federated data spaces. These trends will accelerate towards 2035, evolving into a fully networked device-edge-cloud continuum comprising general as well as highly specialized computing nodes deployed anywhere between the device, the edge, and the core of the network infrastructure and hosted in all domains – public, hybrid, and private. Fixed (wireless) access and extreme (mobile) broadband connectivity combined with lower latency and enhanced reliability, leveraging heterogenous communications solutions including NTN, will enable ubiquitous and robust service access and dynamic distribution of computing workloads across the continuum. This will improve the experience of real-time video communications, XR applications, holographic experiences, or even digital twin models updated in real-time. Ultra-Reliable Low-Latency Communication (URLLC) services will cater to extreme connectivity requirements, including sub-millisecond latency as required by industrial automation use cases.

The key players in this space i.e., Communication Service Providers (CSPs), Internet Service Providers (ISPs), cloud infrastructure providers, and web-/hyper-scalers need to ensure that networking and computing functions that they run over multiple cloud environments can be deployed, managed, and automated with uniform levels of service. All stakeholders will increasingly use different cloud resources for different purposes. Some of their applications and Information Technology functions will be run in private cloud e.g., in the enterprise premises, and some of them in the public cloud. In addition, the CSPs may use edge cloud resources provided by e.g., radio tower companies. In addition, the service providers may change cloud providers and therefore, seamlessly move softwarized Information Technology functions from one platform to another. To ensure seamless interoperability in such complex environment, a mix of proprietary solutions, standardized functionality, and cloud-related open-source frameworks has emerged and will continue to mature.

3.4.3 Joint Communications, Computation, and Sensing

Joint Communication, Computation, and Sensing (JCCAS) is a paradigm of system co-design that integrates the functionalities of (wireless) communications, cloud computing, and mobile sensing into a single system [21]. This approach involves using shared spectral and hardware resources for efficient data transmission, edge and cloud computing for real-time processing, and sensors for accurate environmental data collection and fusion. However, JCCAS requires high-performance, high-speed networks to transport the data, whereby the processing of the data must take place closer to the source or within the networks to act quickly enough and almost in real time e.g., through edge computing. The simultaneous use of communication, compute and sensor functions in an integrated communication-compute-sensor system enables optimized and efficient use of resources and data, as sensors capture the required information and simultaneously enable communication to transmit this information to the relevant locations. Applications of JCCAS range from gaming and everyday assistants to care robots, delivery drones, real-time digital twins, as well as autonomous vehicles in coordinated traffic. In connected vehicles, sensors are used to capture environmental data such as traffic conditions and distance monitoring. At the same time, these vehicles communicate with each other via wireless networks to exchange data and increase road safety. Mobile robots and XR devices will need to capture their surroundings in 3D using radar, spectroscopy, and localization technologies while maintaining communication over mobile networks. However, current radar systems must evolve to handle the future density and demands of mobile robots, including drones and autonomous cars, especially for 3D radar and spectroscopy.

A further Information Technology system evolutionary step comprises the systematic and unified exposure of system capabilities to various users and ecosystem partners across the value chain. API-driven exposure can assure programmatic, machine-consumable service re-usability, not only across Information Technology subsystems, but also in the domain of services and applications to compose industry-specific value-added services.

3.4.4 Artificial intelligence, machine learning, and ubiquitous data

The availability of abundant data already transforms the 2020s. By 2035, Information Technology infrastructures will not only fully embrace the opportunities of ubiquitous data for their own development and operation, but also comprise the single most important enabler for leveraging data-driven insights in all industries. We envision that the Information Technology infrastructure of 2035 will integrate a richness of AI and ML functionalities, with all components becoming progressively AI-native by design – enabling the networked cloud to act autonomously in real time, adapting to service needs and events. Novel, holistic data architectures will ensure secure, reliable, and scalable data creation, collection, storage, processing, transmission, and distribution.

The deployment of AI within the Information Technology landscape has become integral to the evolution of network and cloud systems. For example, new releases of communication and IT functionalities are explicitly designed with native AI support as a key step towards full automation and programmability. AI-native Information Technology functions promise built-in cognitive capabilities that enable intelligent decision making and overall intelligent operations [22]. AI-native interfaces promise dynamic adaptation, mutual model sharing, split inferencing (e.g., between end devices and network nodes), and coordination of intelligent Information Technology functions across multi-vendor interfaces. A wealth of AI/ML functions and related capabilities can transform the functionality of any Information Technology system component such as the intelligent edge [23]. In the networking domain, new air interface technologies will apply AI to real-time signal processing tasks in the transmitter and receiver, enabling a self-optimizing 6G air interface that is perfectly adapted to any channel, hardware, and application sitting on top of it [24]. In the computing domain, new processor architectures will leverage the advantages of neuromorphic computing to apply different flavors of AI to solve complex computational problems.

3.4.5 Security and sustainability of future Information Technology systems

Technology evolution and an environment with multiple stakeholders in society, industry, as well as government and administration bring along a large variety of threat vectors. Ensuring security and privacy will critically depend on a comprehensive set of technology enablers. For example, threats resulting from architectural disaggregation or open interfaces can be mitigated by Zero-Trust Architecture concept. AI/ML will be pervasive and of key relevance across the security technology stack and architecture. However, while AI will help to secure Information Technology systems effectively, it may also impose security threats. Ensuring trustworthiness and explainability of embedded AI for instance by means of zero-knowledge proof methods will therefore play a key role. Moreover, many of today's cryptographic algorithms will need to be replaced with quantum-safe concepts [25]. Enhanced privacy-preserving technologies including homomorphic encryption and differential privacy will help to protect sensitive data. Confidential computing technologies like Trusted Execution Environments will attest data and system integrity as well as provide proof of data ownership anchored in silicon and hardware. Web 3.0 technologies enable the next major evolution in the world-wide web. It paves the way towards a more decentralized, user-centric online ecosystem where technologies such as distributed ledger technology (DLT) enable actors within a value chain to offer services and resources and conduct peer-to-peer negotiations between buyers and sellers, without going through preestablished, centralized gatekeepers. At the same time, these technologies provide the means to maintain a high level of confidentiality, integrity, and privacy. Application examples of DLT include self-sovereign identities or Blockchain technology used for e.g., transaction management, smart contracts, non-fungible tokens (NFTs), or crypto currencies.

The intricate interplay between hardware and software, the nature of new applications that are physically exposed to their users and therefore potential attackers, the globalization of the supply-chains, and the advent of nanoelectronics technologies lead to new types of security threats [26]. These include leakage of information such as cryptographic keys but also artificial intelligence models, through side-channels; malicious manipulations of systems during operations, or "hardware Trojan" functionality introduced by untrustworthy manufacturers, tool vendors or intellectual property providers. An ability to securely operate in a world where such vulnerabilities exist is essential for the European industry that still largely follows "fabless" or "fablight" business models.

Another aspect that was traditionally considered a European strength is design of systems that are robust and resilient – both against malicious attacks and against natural failures. This encompasses physical damage due to natural disasters or kinetic impacts, cyberthreats, but also failures due to unreliable electronics, as exemplified by the ongoing "silent-data corruption" debate about high-performance processor chips used in data centers [27]. Safety-critical applications such as automotive, medical, transportation, energy-distribution and industry-automation systems require fault-tolerant electronics, functional safety ecosystems, and advanced test methods. Moreover, sustainability requirements as reflected in United Nations' 17 sustainable development goals, will result in additional requirements for Information Technology systems. Today's networks and computers have a non-negligible CO_2 footprint, which may grow due to the power needs of AI data centers. The ambition for future Information Technology infrastructures is "net zero" design, manufacturing, deployment, and operation. This will be addressed by an approach comprising three major pillars: (1) advances in networking and computing hardware aiming at reduced power consumption and cooling requirements of semiconductor components, (2) AI-supported operations i.e., leveraging energy savings by optimizing workload distribution according to energy consumption criteria, and (3) efforts to exploit date center waste heat and cover remaining energy demands from 100% renewable sources. Finally, the Vision 2035 also foresees Information Technology to improve the handprint of users, enable more inclusive and trustworthy access to services and technologies, respond to the needs of different social groups and communities, drive the economic viability for operators and vertical sectors, while supporting their transformation towards reducing energy consumption, Greenhouse Gas (GHG) emissions, or water and material usage.

3.5 Services and Applications

This final subsection of Section 3 describes novel paradigms of autonomous services and applications, including domain-specific in addition to selected aspects of Application Software as covered in subsection 3.3. In the 2030s, a multi-resource approach in conjunction with additional expectations concerning adaptability, flexibility, and reliability will become the norm for communication services and solutions. Vertical industries will need seamless integration of their turnkey solutions, as well as flexible combinations of physical and digital items, actors, and services in the metaverse. Many of the new requirements are automation related: Automated operations will require intent-based autonomy, distributed, flexible service instantiation, and industry-specific optimization [16].

The autonomous services concept requires a general framework for run-time service composition as well as the facilitation of the use of different types of automation paradigms, supported by enablers such as GenAI. As a particular use case, the composition architecture allows for creation of digital twins tailored for a specific use case, including application digital twins. An autonomous service provides a set of capabilities via a service interface while exhibiting autonomic behavior and awareness of its environment. An autonomous service may be stand-alone or consist of various services, which in turn may be discrete or composite. An autonomous service instance has an intent/insight interface, where insight is a return channel to intent. Intent negotiation and insight generation are supported by contextualization functionality, which on the system level builds on a tailored scope of the function. Autonomy is implemented by means of analytics-driven self-management, typically involving closed loop automation.

4 Use cases of Information Technology in 2035 and beyond

The progress of Information Technology will have a significant impact on many sectors of our society, economy, environment, and personal lives. Examples include telemedicine and healthcare services, industrial automation and cooperating autonomous robots, connected vehicles in the dimensions land, air, and sea, smart cities, and critical infrastructures such as distributed energy networks. All of these use case families will leverage the metaverses i.e., eXtended Reality (XR), Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR) and, often in conjunction with AI.

Without pretending to be able to predict the 2035 future, the following subsections outline a vision how future Information Technology capabilities as described in Section 3 may play a major role in the evolution of four key sectors of the economy, namely Energy, Automotive, Manufacturing and Health-care.

4.1 Energy

In the next ten years the opportunity is all about the global net-zero transition by renewable energy providers, retail aggregators, enterprise customers and eco-conscious consumers and prosumers. In the electricity grids, this means the transition from a synchronous generator-dominated to a converter-dominated network alongside a massive decentralization which in turn requires a high degree of digitalization. Energy industries will leverage information technology to tackle the opportunities and challenges in conjunction with this “green transition” - from autonomous operations in remote locations, to much more distributed generation and storage of electricity, including the possibility to run parts of the grid in island mode and to run power grids reliably despite the volatile nature of most renewable power sources. There will be a need for decentralized scalable energy-management and optimization software platforms for a future-proof energy information and control network with distributed intelligence. Additionally, solutions must be developed addressing fast-charging infrastructure for Battery Electric Vehicles (BEVs) and considering the additional needs of widely deployed heat pumps as well as widespread energy storage in its various forms (electrical batteries, hydrogen, mechanical energy, and others). This implies the need for

- distributed energy management systems for orchestration, dynamic matching of demand and production, production forecast, load flexibility and energy-storage control in a market-oriented and grid-supportive manner due to the increasingly decentralized nature of energy generation and storage requiring constant optimization, thus satisfying also the needs of the emerging Renewable Energy Communities (RECs),

- reliable communication links to numerous endpoints in the distribution grids for scaling up decentralized power generation, vehicle electrification through fast-charging infrastructure, the widespread use of heat pumps, and supporting the need for always-connected increasingly efficient and sustainable energy-storage solutions,

- establishing cross-sectional energy management to address the needs and exploit opportunities of electricity, heat, and gas networks to increase the overall flexibility potential and to provide seasonal storage facilities,

- hardening the Information Technology of the grid to achieve the needed resilience against technical outages, cyber-attacks, and other risks which could endanger the digital infrastructure needed to operate the future power grid [28].

In the 2030s, consumers will prioritize sustainable practices and renewable energy solutions with no compromise to the availability of electricity as needed. Revolutionary new technology approaches such as solar power beams from space may help tackle the challenge of increasing energy demand [29].

4.2 Manufacturing

Critical AI native communications and cloud network foundation will be needed to fuel the digital transformation journey offering advanced data communication and networking solutions that support critical operations of manufacturing. With a modernized Information Technology base, one can increase productivity, agility, and flexibility, and improve supply chain resilience and visibility throughout the operation. With intelligent automation, data center optimization and physical-digital fusion in operations, new efficiencies can be achieved while not compromising on sustainability targets.

Manufacturing in the 2030s will include the following information technology building blocks:

- reliable and secure connectivity of robots, sensors, tracking systems, smart tools and AGVs,
- video analytics, automated vehicle navigation and immediate robot response enabled by high-performance and ultra-low latency distributed cloud and both fiber as well as wireless connectivity,
- digital twinning and augmented reality, on-floor video, and security systems in conjunction with increased network capacity and pervasive AI,
- efficiency and productivity boost from using insights about assets, processes, the environment and workers.

4.3 Automotive and Intelligent Transport

The automotive sector is transforming at a rapid pace – Information Technology will drive the road transport ecosystem and infrastructure to full digitalization. Networks sensing and sensor fusion will feed into real time digital twins with the role of digital road infrastructure being enhanced. Vehicles can act as sensors and vehicle probe data can feed into real time digital twins. Terrestrial connectivity will be complemented by non-terrestrial connectivity for automotive. Sophisticated AI based traffic and mobility management algorithms will allow smooth traffic optimization. Vehicle connectivity will be provided with predictive Quality of Service. In general, the transition to e-mobility is well under way, and inductive power transfer can be leveraged for road mobility [30]. Due to government incentives, emission standards and objectives of sustainability, the automotive industry is also undergoing a transformation in its operating model. Manufacturing operations and retail business models need to be smart, agile and efficient, which requires suitable Information Technology.

On rail transportation, the Future Railway Mobile Communication System (FRMCS) for resilient railway communications is an integral part of the way forward. Digitalization of the train control system will progress with the step-by-step implementation of the European Train Control System (ETCS) and digital control centers, which are meant to allow for carrying more traffic on the rail infrastructure and improve the reliability of train operation.

The transportation sector's contribution towards a net-zero energy consumption will also depend on the extended use of intermodal transportation systems. Seamless transfer of freight and passengers between e.g., rail and road transportation are not conceivable without the use of Information Technology.

4.4 Healthcare

The future of healthcare will – amongst others – be enabled by intelligent Information Technology and infrastructure to reduce costs, enhance accessibility and support better, more targeted patient care. Solutions for the 2030s will build on fully automated processes, intent based orchestration and sharing of medical data as well as the provision of advanced connectivity to transform health monitoring, automated workflows and innovative new patient treatments and care models. Subject to the broad availability of the needed data sets, the intelligent and connected healthcare model of the future will leverage

- AI / ML and real-time analytics to improve operational performance, diagnostics, and decision-making,
- distributed, low-latency edge cloud platforms to support remote and robot-assisted surgery,

- low-latency private cloud capabilities for data,
- efficient data models and processing capability scalable for sensor data to large 2D and 3D medical imaging files,
- collaboration across the value chain i.e., innovation with hospitals, clinics and partners with the highest security and reliability,
- intent based operational systems, analytics and device management for healthcare applications,
- joint sensing and communication for advanced solutions in patient monitoring and hospital@home approaches,
- integrated robotic and automation solutions for treatment and support processes in hospitals.

4.5 Other sectors

Beyond the sectors outlined above, Information Technology will continue to play its essential role in finance, media and gaming, commerce and retail, safety and security, government, national defense, and other areas of importance to Germany and to Europe. Beside industrial and enterprise related use cases, mass market consumer applications will be transformed by immersive experience and XR, telepresence and holographic communications and Artificial Intelligence while advanced smart home solutions as well as smart city ecosystems will become reality.

5 Factors of success beyond technology

A favorable industry and standardization environment will be a key factor of success to assure successful execution of ITG Information Technology Vision 2035. In the following, we describe the key factors of success and associated current state.

Standardization, openness, and collaborative advantage:
ETSI –> ETSI and SDO: The European Standardization organization ETSI plays a strong role in Europe and globally. ETSI is the independent, non-profit, standardization organization operating in the field of information and communications. ETSI supports the development and testing of global technical standards for Information Technology-enabled systems, applications, and services. European market leaders are key contributors to important Standard Defining Organizations (SDOs). Cutting edge research is being transformed into collaborative advantage by means of Public-Private Partnership (PPP) vehicles such as EUREKA Celtic-next and SNS-JU.

- *5G and 6G:* 6G progress is on track for mass market deployments in 2030, with a single global 6G standard to be produced in 3GPP, in line with the ambition of a global ecosystem, despite the geo-political tensions. In 2024, industry is preparing the transition from the phase dominated by regulation (ITU, WRC) and innovation/research (collaborative projects) to the phase of technical standardization, which will start in 2025. ITU-R sets the timeline, vision and performance targets, WRC allocates new spectrum, and 3GPP will define the actual technical standard. Standardization enabling e.g., x-border use of advanced services should be particularly fostered to help overcome the fragmentation of European markets. Collaborative research on 6G technologies is currently successfully moving forward. In Europe, 63 projects from the Smart Network and Services 6G research program (SNS-JU) are already contracted, including the 6G flagship project Hexa-X-II [8]. The SNS-JU will invest at least €1.8 billion in 6G research over the next seven years. The German National 6G BMBF Platform [32] and associated 6G Hubs [33][34] are off to a great start thanks to continued funding and engagement of the German Ministry of Education and Research (BMBF)

- *Wi-Fi:* The SDO for Wi-Fi standards is the IEEE. Wi-Fi Alliance (WFA) has launched a certification program for Wi-Fi 7. The second release of Wi-Fi 7 certification is expected to be launched by end of 2025. The development of specification and test plans for the 6 GHz Automated Frequency Coordination (AFC) system has been completed, including requirements for FCC approval. WiFi 8 work has started, targeting ultra-high reliability with 25% increase in throughput and reducing latency and data loss by 25% over Wi-Fi 7. Multi-Access-Point coordination is going to be one of the key features of Wi-Fi 8. A study group has started to investigate extending Wi-Fi 6/7 into the 60 GHz band.

- *Metaverse and XR:* Novel XR/VR/MR applications impose a variety of information technology infrastructure and network requirements to support consumer and industrial Metaverse, including e.g., innovations related to Volumetric Video Codecs as standards for immersive video. The Metaverse Standards Forum (MSF), aims to foster interoperability standards for the Metaverse, as does the ITU-T Metaverse Group.

- *Internet:* Continuous innovation in packet routing and switching and telemetry protocols (e.g., TWAMP) work is ongoing in IEEE and IETF. Chinese initiatives on Compute-aware Networking (CAN) to route packets according to both network and compute metrics exist. Corresponding work in CCSA under the name of Compute First Networking/Computing-Networking Convergence (CFN/CNC) is attracting interest in the Chinese ecosystem, and related work is taking place in ITU-T SG13. Globally, we see an increased interest for the QUIC protocol for Web and Media traffic and then MASQUE as protocol to tunnel any protocol over QUIC. The Ultra Ethernet Consortium (UEC), created in the Linux Foundation by cloud players, aims to optimize communications for Artificial Intelligence clusters. Given an ever-increasing complexity of protocol stacks, an exploration of new avenues for simplification is desirable.

- *Packet-optical transport and fixed access:* In transport and fixed access networks, one of the ecosystem's key topics is the definition of the next generation of Passive Optical Network (PON) beyond 50 Gbit/s. Also, the evolution of Optical Transport Networking (OTN) as well as packet-optical networking towards 1600 Gbit/s and beyond per interface is gaining traction in standardization bodies such as ITU-T, IEEE, and OIF. The integration of telemetry and fiber sensing promises a better supervision of the fiber infrastructure as well as the surrounding environment. Boundaries between optical and IP networks blur and solutions are debated which provide hardware integration and functional demarcation to facilitate end-to-end management in the optical and packet domain.

- *Open-source Software:* Open-source projects will drive CSP network primitives (i.e., building blocks anchored in the containerized cloud architecture such as Kubernetes for creating and operating an application on the platform) through the associated Automation frameworks. Another key initiative for open Information Technology is CAMARA providing Network APIs, cf. bullet above on monetization. The CAMARA project was recently established as a Linux Foundation directed fund.

Intellectual property and patent framework:
In the Spring of 2023, the European Commission has proposed a new regulatory framework on Standard Essential Patents (SEP). The new regulation includes a register for SEPs, mandatory checks and process steps.

Regulation:
Generally speaking, current regulatory frameworks are too complex. Growth, innovation and scalability for German and European companies and ecosystems are at risk. Existing guard-rails do not consistently support the entrepreneurial momentum and investment level is insufficient.

Spectrum:
The outcome of World Radio Conference (WRC-23) is a solid basis to accommodate further growth of mobile data traffic. WRC-23 allocated and harmonized the upper part of the 6GHz band (6,425-7,125MHz) for mobile use for Europe, Middle East and Africa (EMEA), and for selected countries in Asia and Latin America (Mexico, Brazil). The agreed harmonized regulatory conditions (power) would allow deployment of full-power macro base stations while reusing the 3.5 GHz site grid. In Europe, discussions on potential sharing between licensed (5G) and unlicensed (Wi-Fi) use of the upper 6GHz band are ongoing. However, mission critical use cases do need dedicated licensed spectrum and sharing should be minimized. China has decided to allocate the upper 6GHz band for IMT prior to WRC-23. Also, sharing and compatibility studies are ongoing for 4.4..4.8GHz and 14.8..15.35GHz bands.

Economic sustainability and monetization:
- *Vertical Industry Initiatives:* There are several organizations where industries are joining forces to drive adoption of Information Technology such as wireless 5G on the path to 6G: 5GAA for automotive with active discussions on Cellular-Vehicle-2-X (C-V2X) and NTN; Future Railway Mobile Communication System (FRMCS) for resilient railway communications of the future [31]; 5G-ACIA for manufacturing with slower adoption than initially projected. NATO has created a group to make use of commercial 3GPP 5G standard and products for Defense. The 5G Media Action Group (5G-MAG) addresses aspects of media/broadcast and mobile industry convergence.

- *Open APIs:* GSM Association is a non-profit industry organization that represents the interests of mobile network operators worldwide. The recently launched Open Gateway Initiative will help developing network-provided application programming interfaces (APIs) towards application developers to leverage network capabilities to foster monetization. Rich Communications Services (RCS) have had a renaissance. They are now supported by both Google/Android and Apple phones.

- *Artificial Intelligence:* Fueled by breakthroughs in natural language processing (NLP) and generative AI (GenAI), 2023 was marked by an unprecedented surge in AI adoption across various industries. The AI Act of the European Union is the world's first AI law aiming to regulate AI to comply with ethical and social norms.

Security, privacy and trust:
Information Technology systems are increasingly secure and resilient by design. This encompasses their hardware and software components and their interactions and must consider malicious and intentional failures and Europe's role in a globalized world with only partially trustworthy and reliable supply chains. Security and resilience need to move to the center of the provision of public and private network-based services. As regards security, the aim is to develop and use quantum-resistant cryptographic techniques that are secure even in the presence of powerful quantum computers. ETSI has established a working group on Quantum Safe Cryptography (QSC) and has developed a Quantum Safe Cryptography migration document that will be the basis for 3GPP studies. More broadly speak-

ing, the evolution of Information Technology will contribute to a vector of threat in multiple dimensions, for instance through open interfaces and architectural disaggregation, the integration of open-source and multivendor software, and multi-stakeholder supply chains. Moreover, in the 2030s we are likely to see many AI-initiated attacks as well as attacks directed against the vulnerabilities of AI/ML-based mechanisms in our networks and IT systems in general.

Sustainability:
Environmental sustainability remains a key driver for Information Technology evolution. ITU-T standards will be relevant in the areas related to environmental impact, climate change and circularity. Academia, research institutions and industry are jointly engaged to assure “green by design” and circularity transformation. Societal sustainability is anchored in the understanding of why and how Information Technology can help tackle relevant opportunities and problems in the 2030s.

Talent and Education:
There is a shortage of talent. The availability and motivation of talent is a key factor of success to evolve and execute on Information Technology Vision in Germany and worldwide. Global competition is on to both train and - as importantly - attract and retain qualified Information Technology talent from the outside. Education related to Information Technology for local talent from kindergarten onwards appears insufficient at this time. An education reform is needed to strengthen the skill-base for both usage and creation of Information Technology and its broad application. Besides rebuilding silicon manufacturing in Europe, Computer Engineering (CE) curricula and design skills for integrated circuits as being taught to CE students are not fully adequate at this time. There is a shortage of electrical engineers.

Technological Sovereignty and Resilience:
German dependency on other countries outside Germany and Europe in almost all key domains of Information Technology is high. However, in the last years, silicon providers have made sizable investment decisions for Germany (e.g., AMD, TSMC). This trend needs further support to reduce the dependency in this key technology on countries in the Far East. Positive expected impact from foreign direct investment in Germany will not only be funding, but also expanding the local staff and knowledge base.

Digital Inclusion:
Besides the promotion of young talent with a focus on the future Information Technology related developments, it appears that the public needs additional support and awareness as regards the upcoming opportunities of digital change and transformation. Current software and user interfaces are often too complex for parts of the public and there is a lack of easy-to-use interaction such as speech or gestures as will be enhanced by AI.

6 Conclusion and Recommendations

This paper provides a comprehensive overview of the Information Technology Vision 2035 of VDE ITG. The Vision is framed by macro-trends in the three dimensions of sustainability (economic, environmental and societal) in a fast-changing geopolitical context as well as by the emerging trends in Information Technology on the path to the 2030s.

- The analysis of the emerging technology base has been broadly clustered into a taxonomy stack of Foundational Enablers, Systems and Services & Applications.

- In the domain of data transmission, we will see technology innovation in both wireless and optical transmission space; The 3GPP foundational release for 6G will be broadly defined in a year or so, and electro-photonic integration, new high-capacity fibers and related transmission systems as well as evolving PON solutions define the way forward for optical transmission. The relevance of data will steadily increase – indeed, the expected data growth to be transmitted is a key driver for both wireless and fixed network evolution.

- Data and sensor fusion in a broader sense (including remote sensing of the earth by means of advanced radar solutions or joint communications and sensing in terrestrial environments) will seamlessly link into AI as key transformational force of software and systems in the 2030s.

- On the processing side, novel concepts such as quantum and neuromorphic computing will play an important role for specific applications. Also to be mentioned is the upcoming paradigm on integrated compute and networking with a comparatively high Level of Technology Readiness (TRL) already today.

- Finally, the taxonomy stack of the Technology Vision can indicatively be mapped to Ecosystem Value – aspects of environmental sustainability and security, for instance, not only are of highest relevance to the society but also correlate with significant market size and momentum of market growth.

The future impact of key technology components as per our taxonomy in the Information Technology Vision 2035 can be explained from the fact that Information Technology is a general purpose technology enabling and transforming all sectors of the economy and society at large. This has been illustrated with key use cases in energy, manufacturing, automotive and transport as well as healthcare.

However, key factors of success to make Technology Vision 2035 happen go beyond technology. We have highlighted the relevance of standardization and openness, a fair, reasonable, and non-discriminatory patent framework, an appropriate regulatory environment, economic sustainability and monetization and key aspects of sustainability as well as the importance of talent acquisition and retention.

Key recommendations

Building on our analysis of key factors of success beyond technology, the VDE ITG Information Technology Vision 2035 is to provide a long-term perspective and guide governments, regulators and private sector. In the following, key recommendations are summarized to execute on the Information Technology Vision 2035 and its associated opportunities of value expansion in dimensions of economic, environmental, and societal impact.

- Standardization and openness:
  Contributors to ETSI need to keep up effort and commitment to avoid fragmentation of standards. While standardization needs to be industry-led, public support for coordination and funding for this will be appropriate. This also applies for the Wi-Fi ecosystem. The objective is to assure economy of scale as well as interoperability from global standards. Standards are needed for the Metaverse to foster interoperability. We need to continuously innovate in Data Center routing and telemetry protocols (e.g., TWAMP) work in IETF. In transport and fixed access networks, the ecosystem's priority topic in ITU-T, IEEE and OIF needs to be the definition of the next generation of PON and packet-optical transport system. European and German Information Technology ecosystem players

should consider contributing to open-source projects that have the potential to be directly used in their products.

- Collaborative advantage and research leverage:
  Vehicles of cooperation and Public Private Partnership (PPP) should be fostered such as Horizon Europe [6] and EUREKA Celtic-next as well as, BMBF 6G Platform on German national level [32] [33] [34] Transfer of research into industrial context (with higher TRL) needs dedicated attention, important Projects of Common European Interest (IPCEIs) such as Microelectronics-Communications Technology (ME-CT) need to continue. Cultural change is needed with regard to the entrepreneurial mindset and risk taking (cf. also bullet on societal sustainability below). In the interest of technology sovereignty, Europe needs to catch up in many of the key enabling domains of Information Technology [2]. By means of PPP and public funding, a vibrant Information Technology ecosystem including academia, service providers and industry (large corporates, SMEs and start-ups) needs to be fostered and the full value chain from research to product and services needs to be strengthened.

- Intellectual property and patent framework:
  A fair, reasonable, and non-discriminatory licensing environment remains a key success factor for the German and European Information Technology industry. European mobile network vendors and practicing entities depend on this instrument to capture some return of their investment.

- Legal framework and regulation:
  The legal environment needs to be simplified to foster growth and innovation. At the same time, it must be transformed beyond regulation for novel use cases and their unfolding implications for individuals and the society. For instance, cyberattacks can lead to physical damage and physical damage may impact the digital sphere. Digital rights and tax regimes for virtual assets need to be tackled.

- Spectrum:
  It will be crucial to provide dedicated and licensed radio spectrum in timely fashion to maximize the mission-critical potential and provide the needed basis for future traffic growth.

- Economic sustainability and monetization:
  We need to leverage the performance and value potential of Information Technology and the resulting performance enhancements across all sectors of the economy; industry verticals will have a value catalyst role. An Open API regime and the API economy should be fostered by public and private stakeholders alike. We need to actively drive AI as part of the Information Technology system design to achieve objectives in performance, automation, total cost of ownership reduction, and energy saving.

- Security, privacy, and trust:
  Security and cyber-resilience need to move to the center of Information Technology system design. Internationally agreed cybersecurity certification schemes can be leveraged to enhance the trustworthiness of Information Technology products, services and processes. Cooperation between governments, industry and research will be key by means of knowledge sharing, capability building and awareness raising. What we need is a comprehensive set of security technology enablers, enhanced and supported by AI/ML and new principles of cyber-resilience. We require a new paradigm for the way we create software: Software automation tools will include static and dynamic bug detection, code optimization and automated code testing. Fault injection for validation purposes will likely become the norm, assuring cyber-resilience in the 2030s.

- Sustainability:
  Academia, research institutions and industry need to keep up the joint engagement of driving “green by design” and circularity transformation. We need to tackle the biodiversity impact assessment standardization, actively contributing to the Sustainable AI standards in ISO/IEC and CEN/CLC that will be pivotal for all organizations using and developing sustainable AI systems in Germany, the EU market, and globally. Reach out to the wider public on why and how Information Technology can help tackle relevant opportunities and problems in the 2030s is a must - societal sustainability is anchored in the understanding of beneficial impact of use cases and value.

- Talent and Education:
  Recruitment of young talent within and outside Germany needs to be strengthened. We need to build awareness of the opportunities and options as per the ITG Information Technology Vision

2035 as well as the associated value drivers across sectors and in our society at large. Besides talent acquisition from abroad, local talents need a strong support by proper education, starting in the kindergarten time accompanying our youth until they enter the job market. STEM (Science, Technology, Engineering and Mathematics)/MINT (Mathematics, Informatics, Natural sciences, Technics) initiatives, promotions and support thus needs to cover kindergartens, schools and high schools. Engineering needs to be made "cool" again in the society and especially for our youth.

- Technological sovereignty and resiliency:
  Considering the indispensable role of Information Technology as "general purpose" today and even more in the 2030s, a sufficient level of technological sovereignty in the provision of Information Technology components and the operation of such systems must be secured. This applies to the whole value chain, from state-of-the art knowledge over chipsets and systems supply and access to software and platforms to the reliable operation of information technology infrastructure. Likewise, resiliency of the information and communication infrastructures and systems against technical failures, cyber-attacks, sabotage and kinetic impact as well as power outages are of utmost importance. Having in mind the complexity and multi stakeholder interdependencies in the creation and operation of information technology systems and services, resiliency needs to be thought and implemented along the whole value chain.

- Digital Inclusion:
  Appropriate means to deal with the upcoming challenges as described in Section 5 should be considered. Increased utilization of AI - for example to support basic configuration, programming, and fault detection in combination with educative means (explainable AI, XAI) can implicitly and explicitly teach the users about the possibilities, limitations, threats of AI technology. Changes in user and software interfaces, modalities, robustness and safety: given the different characteristics of the target groups the interaction needs must be adapted. Experts are typically familiar with form-based dialogues and programming interfaces. Interfaces for the public should support different modalities such as speech or gestures (and e.g., enhanced by large language models (LLM)). The public can be assumed to be more familiar with speech and gestures from human-to-human interaction. An important aspect is error prevention and correction as well as privacy protection to increase the level of trust and acceptance of Information Technology driven novel applications.

Glossary

100G	100 Gbit/s
3GPP	3rd Generation Partnership Project
50G	50 Gbit/s
5G NR	5G New Radio
5G AA	5G Automotive Association
5G-ACIA	5G Alliance for Connected Industries and Automation
5G-MAG	5G Media Action Group
5G RedCap	5G Reduced Capability, also called 5G NR-Light
6G	6th Generation of Mobile Networks
AFC	Automated Frequency Coordination
AGF CUPS	Access Gateway Function Control Plane and User Plane Separation (protocol)
AI/ML	Artificial Intelligence and Machine Learning
API	Application Programming Interface
ASICs	Application-Specific Integrated Circuit
BBF	Broadband Forum
BMBF 6G Platform	Funding Association of the 6G platform
BMTIA	Burst-Mode Transimpedance Amplifier
CAN	Compute-Aware Networking
CCSA	China Communications Standards Association
CEN	European Committee for Standardization
CFN	Compute First Networking
CI/CD	Continuous Integration and Continuous Delivery/Deployment
CLC	European Committee for Electrotechnical Standardization
CNC	Computing-Networking Convergence
CPU	Central Processing Unit
CSPs	Cloud Service Providers
C-V2X	Cellular Vehicle-to-Everything
DevOps	Software Development and IT Operations
DevSecOps	Development, Security, and IT Operations
DLT	Distributed Ledger Technology
DNA	Deoxyribonucleic Acid
DRAM	Dynamic RAM
DSP	Digital Signal Processor
DT	Digital Twin(ning)
EMEA	Europe, Middle East, and Africa
ETSI	European Telecommunications Standards Institute
EU	European Union
FCC	Federal Communications Commission
FET	Field-Effect Transistor
FPGAs	Field-Programmable Gate Arrays
FRAM	Ferroelectric RAM
FRMCS	Future Railway Mobile Communication System
GAA	Gate-All-Around
GenAI	Generative AI
GPU	Graphical Processing Unit
GSM	Global System for Mobile Communications
HDD	Hard Disk Drive
HW	Hardware
I/O	Input/Output (devices)
IoT	Internet of Things
IT	Information Technology
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IETF	Internet Engineering Task Force
IIoT	Industrial Internet of Things

IMT	International Mobile Telecommunications
IoT	Internet of Things
IPCEI	Important Project of Common European Interest
ISO	International Organization for Standardization
ISP	Internet Service Provider
IT	Information Technology
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
JCAS	Joint Communication and Sensing
JCCAS	Joint Communications, Computation, and Sensing
LCNC	Low Code / No Code (software development platforms)
LLM	Large Language Model
LTE	Long-Term Evolution
MASQUE	Multiplexed Application Substrate over QUIC Encryption
ME-CT	Microelectronics and Communication Technologies
MIMO	Multiple Input/Multiple Output
MLC	Multi-Level Cell
MR	Mixed Reality
MRAM	Magneto-Resistive RAM
MSF	Metaverse Standards Forum
NATO	North Atlantic Treaty Organization
NFT	Non-Fungible Token
NLP	Natural Language Processing
NTN	Non-Terrestrial Networks
NVM	Non-Volatile Memory
OFDM	Orthogonal Frequency Division Multiplexing
OS	Operating System
OTN	Optical Transport Networking
PAM-4	4-Level Pulse Amplitude Modulation
PON	Passive Optical Networks
PPP	Public Private Partnership
QCI	Quantum Communication Infrastructure
QKD	Quantum Key Distribution
QoE	Quality of Experience
QoS	Quality of Service
QSC	Quantum Safe Cryptography
QSN	Quantum-Safe Network
QUIC	Quick UDP Internet Connections
RCS	Rich Communications Services
RF	Radio Frequency
RRAM	Resistive RAM
SAR	Synthetic Aperture Radar
SC	Single Carrier
SDG	Sustainable Development Goal
SDO	Standard Defining Organization
SDRAM	Synchronous DRAM
SEP	Standard Essential Patent
SNS-JU	Smart Networks and Services Joint Undertaking
SoC	System on Chip
SRAM	Static Random-Access Memory
SSD	Solid State Drive
SW	Software
TEE	Trusted Execution Environment
TF	Task Force
TPU	Tensor Processing Unit
TRL	Technology Readiness Level
TWAMP	Two-Way Active Measurement Protocol
UDP	User Datagram Protocol

UEC	Ultra Ethernet Consortium
URLLC	Ultra-Reliable Low-Latency Communication
vBNG	Virtual Broadband Network Gateway
VDE ITG	Informationstechnische Gesellschaft im VDE
VR	Virtual Reality
WAN	Wide Area Network
WFA	Wi-Fi Alliance
Wi-Fi	Wireless Fidelity
WRC	World Radiocommunication Conference
XaaS	Everything as a Service
XR	Extended Reality

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For more information, visit www.vde.com/itg

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