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Vision, Enabling Technologies, and Scenarios for a 6G-Enabled Internet of Verticals (6G-IoV)

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Abstract: 5G is the critical mobile infrastructure required to both enable and accelerate the full digital transformation of vertical sectors. While the 5G for vertical sectors is aiming at connectivity requirements of specific verticals, such as manufacturing, automotive and energy, we envisage that in the longer term the expansion of wide area cellular connectivity to these sectors will pave the way for a transformation to a new Internet of Verticals (IoV) in the 6G era, which we call 6G-IoV. In this paper, we describe our vision of 6G-IoV and examine its emerging and future architectural and networking enablers. We then illustrate our vision by describing a number of future scenarios of the 6G-IoV, namely the Internet of Cloud Manufacturing accounting for around 25% of digital services and products, the Internet of Robotics to cater the challenges of the growing number of robotics and expected 7% increase in usage over the coming years and the Internet of Smart Energy Grids for net-zero energy balance and shifting to 100% dependence on the renewables of energy generation.

Keywords: 5G; 6G; IP communication; determinism networking; reliability; semantic communications; non-terrestrial networks; artificial intelligence; internet of verticals; cloud manufacturing; robotics; smart energy grids; semantic communications; internet of space

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1. Introduction

The 5G in conjunction with IoT, AI and Cloud technologies will drive a significant digital transformation to fulfill the requirements of the fully connected, digitalized carbon-neutral society and industries [1]. Unlike the previous generations, 5G is offering not only ultrafast (20 Gbps peak data-rates) but also ultra-reliable, ultra-low-latency (1 ms) and massive connectivity capabilities. In comparison with the previous generations, 5G also comes with significant architectural innovations including network slicing, private networks, and edge computing/edge-AI [1]. The 5G-enabled, AI-assisted IoT has the capability of connecting both digital and physical entities, giving rise to fruitful applications including smart cities, smart homes, industry 4.0 and society 5.0 [2]. Enabled by network slicing, in the 5G era, communication services are transitioning from mass connectivity provisioning to per service level and vertical customization. Edge solutions and private networks help to overcome network performance limits, e.g., in terms of latency and deterministic delivery. Local data processing enabled by 5G private networks help to achieve the stringent security and privacy requirements of vertical sectors.

Armed with the above features, 5G is proving successful as the first generation of mobile communication systems to achieve the long-anticipated expansion of operators' connectivity services into vertical sectors, enabling new types of usage and new Business-to-Business (B2B) opportunities and communities [3–5]. Prominent success story examples of 5G for verticals include smart manufacturing, industrial automation and smart grids. There is already a rapidly growing literature on requirements, challenges and solutions and achievements, both from a technology and business perspective, of 5G services expanding into vertical sectors.

5G indeed made a significant contribution towards developing low-latency networks by providing new frequency bands, such as the millimeter-wave (mmWave) spectrum, advanced spectrum usage and management in licensed and unlicensed bands and a complete redesign of the core network. However, the rapidly growing IoT networks require a data rate on the order of terabits per second, which may exceed even the capacities of the existing 5G systems. The 6G systems are being designed to meet the demands of a seamless connectivity and ubiquitous intelligence. The current research focuses on enabling communication technologies, network architectures and integrating intelligence into the 6G networks [6]. Table 1 lists the 5G and 6G research trends from 2018 to 2030, as defined in [7]. There has been very little research, however, on taking a more "transversal" view in terms of the longer-term implications in the 6G era, which will enable the transformation of multiple verticals into new services and businesses, and its impact on the vertical digital ecosystem as a whole.

Table 1. The 5G and 6G research trends from 2018 to 2030.

Year	Research Trends
2018	5G evolution
2020	6G structure and framing, 6G technology components, 6G requirements
2022	
2024	6G systemization of research
2026	
2028	6G technical standardisation
2030	6G evolution, 6G commercialisation

The purpose of this paper is to take the first step in filling this important gap. In particular, we envisage that in the longer term the convergence of 6G "networkization" of vertical sectors with their continued digitalization, and integration with AI and cloud/edge computing will pave the way for a new type of Internet, which virtualizes orchestrates and federates entire vertical entities and services, hence ushering in the era of the 6G "Internet of Verticals" (IoV). The main contributions of the paper are as follows:

1. We provide an overview of the key 5G and 6G architectural enablers that will underpin our vison of 6G IoV.
2. We describe a number of prominent IoV transformation scenarios, namely the Internet of Cloud Manufacturing, the Internet of Robotics and the Internet of Smart Energy Grids.

The rest of this paper is organized as follows. In Section 2, reviewing key architectural and networking innovations is required to support the IoV vision. We describe key IoV applications scenarios in Section 3, and conclude the paper in Section 4.

2. Technology Enablers for the Internet of Verticals

In this section, we review key technologies that undelay the architecture for our vision of the IoV. A number of these technologies are currently being developed under the umbrella of 3GPP's 5G standards, while others, with a focus on the wide area and IP networking, are in their early stages and are being made multiple standardization bodies, including 3GPP, IETF, ETSI and the ITU, as well as the research community.

2.1. Network Slicing

Network slicing [8,9] is an innovative architectural solution in 5G networks which, thanks to virtualization, allows an operator to provide multiple services with different performance characteristics. It is defined in the 3GPP Release 15 specifications. Further enhancements to network slicing are occurring in successive releases. Each network slice operates as an independent, virtualized version of the network designed to serve a defined business purpose or customer. Thus, each slice consists of all the network resources required to address the specific need. For a given application, the network slice is the only network that the application sees. The other slices, to which the application is not subscribed, are invisible and inaccessible. GSMA [9] has identified the following vertical sectors as ones that will benefit from network slicing: Augmented Reality and Virtual Reality, Automotive, Energy, Healthcare Manufacturing, Internet of Things, Public Safety, and Smart Cities.

The standardization for statically provisioned network slices has already been completed in 3GPP. However, more work is being carried out [8] to enable dynamically provisioned network slices in an SDN-type approach. A combination of specialized applications plus 5G Network Slicing and Virtual Private Network (VPN)/Virtual Routing and Forwarding (VRF) technologies could be deployed to create large extranets that would connect and federate multiple vertical slices, hence paving the way for the IoV.

Towards the 6G era, the parallel streams of Open RAN (O-RAN) and Centralized RAN (C-RAN) will be fully realized, as well as the Cell Free architecture, hence allowing RAN resources to also be fully virtualized and software-controlled. Consequently, in the 6G era, we will see full (core, transport, and RAN) slicing of mobile networks, hence enabling end-to-end slicing of the network per (vertical) service. There is a need for orchestration solutions for the networking resources associated to each slice, so they can be dynamically coordinated to meet the performance requirements of services. Several AI approaches, including Deep Reinforcement Learning (DRL), are used for automated resource orchestration. Moreover, federated learning-based DRL solutions for 6G RAN slice orchestration are proposed in the literature [10]. Network slicing is also expected to complement digital twins-based 6G systems along with other enabling technologies, such as blockchain [11].

2.2. Private (Non-Public) Networks

In the shorter term, 5G private networks can fulfil many of the requirements of Network Slicing for verticals, as well as offering additional security that cannot be provided by public networks. Private 5G networks comprise Radio Access Networks (RAN) and core elements. The 5G base station (gNB) can scale from low to high capacity and power output according to needs. They connect to private core networks (in contract to operator's public core) that provides security, authentication, session management and QoS-control. The private 5G core network could be deployed on edge compute nodes, installed locally on premises to ensure high reliability, enable low-latency, ultra-security, and privacy, or be virtualized and reside on cloud servers. In the longer term, 5G private networks may coexist with Network Slicing or they may be entirely overtaken by slicing. Global companies are quickly recognizing the potential afforded in private 5G networks, and the additional revenue streams it offers. Deloitte expects more than 200 mobile network operators investing in 5G standalone networks in 2023, which is at least double from 2022 [12]. Early adopters for private 5G networks will be large seaports, airports and other logistical hubs. The 5G Private networks are very likely to spawn the first wave of IoV with multiple private networks belonging to different verticals, and/or enterprises are linked and orchestrated together thanks to ultra-reliable, ultra-secure, and deterministic wide area networks.

2.3. Edge Computing/Edge AI

ETSI is standardizing Multi-access Edge Computing (MEC) [13], previously known as Mobile-Edge Computing, a technology that empowers a programmable application environment at the edge of the network, within the RAN. The benefits are reduced latency, more efficient network operation for certain applications, and an improved user experience.

For many vertical applications, latency will determine how close the edge servers need to be to user devices. The 5G networks are striving for 1 msec latency (round-trip time) within the network. Light travels 300 km per millisecond, so designers will need to plan their applications accordingly. Latency is critical in vehicular edge applications, specifically [14]. Moreover, a robotic controller can tolerate around four milliseconds latency (round trip) and therefore, allowing for fluctuations and processing time, MEC need to be placed as close as possible to the controller. The other consideration is the amount of data that needs transportation to MEC. For example, a factory performing AI-based video analytics of its assembly line operation may wish to conduct such calculations on a MEC at the factories' location rather than backhauling a huge amount of data to a more central operator location. The 5G standalone network architecture provides access to user data in a local environment via a distributed User Plane Function (UPF), thus enabling local data breakout and facilitating edge computing applications.

Variations of distributed AI, such as federated learning, are expected to be evolved in the future [15,16]. In the 6G era, we will see MEC integrating increasingly more secure, low-latency AI and data analytics services at the edge of the network to a host of verticals.

2.4. Wide Area Deterministic Networks

When a network can provide end-to-end ultra-reliable packet transmission with bounded small values of latency/jitter, it is said to be a deterministic network. This concept is illustrated in Figure 1. In some industry applications, the deterministic networks are also required to provide precise end-to-end time synchronization. One of the most important features of 5G is Ultra Reliable Ultra Low Latency (URLLC) communications, e.g., for smart and fully automated manufacturing. As an example, consider mobile robots such as Automatic Guided Vehicles (AGVs), which have numerous applications in the future factories. They are usually monitored and controlled by a guidance control system. The mobile network is the most promising communication technology due to the large-scale mobility of the vehicles. The communication in some mobile robot applications may require the transmission latency to be between 1 to 10 msec and jitter to be less than 50% of latency. Furthermore, the reliability is required to be above six nines (99, 9999%). Another yet more stringent example in industry is the motion control, which is responsible for controlling the moving and/or rotating parts of the machines in a critical manner.

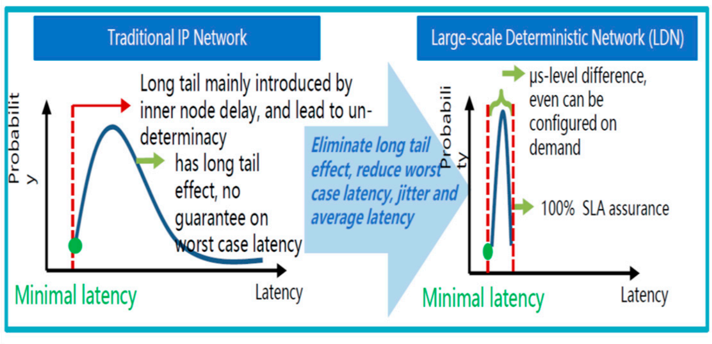

Figure 1. Latency performance of the traditional IP networks (**left**) is contrasted with the performance of future wide area/large-scale deterministic networks (**right**).

With respect to the 5G mobile networks operating on top of the TCP/IP suit of protocols, the application scenarios described above can only be realized for localized networks. The queuing in forwarding nodes may introduce large latency and jitter. The theoretical reliability of a single device is usually below six nines, which, even without packet loss, cannot meet the required reliability of the end-to-end path. For URLLC local area networking (e.g., inside a single factory plant) the Time Sensitive Networking standardized in IEEE 802.1 [17] and industrial Ethernet technologies can be used. Furthermore, staring with the Release 16, the 3GPP is progressing a new study on the NR Industrial Internet of things (IIoT), targeting the integration of the 5G and TSN networks.

However, the wide area deterministic networking for evolved vertical applications, including the distributed cloud manufacturing and wide-area smart grids, would require expanding the capabilities of TCP/IP [18,19]. The ITU-T Focus Group Technologies for Network 2030 (FG NET-2030) [18] and The ETSI Industry Specification Group on the Non-IP Networking (NIN) [19] have identified key technical issues with the current TCP/IP-based networking, which prevent it from delivering the required levels of deterministic services in a wide area and mobile networks, and are currently developing the approaches of TCP/IP evolution to address these.

2.5. Non-Terrestial Networks

From 3GPP Release 17 onwards, the 5G network architecture includes the Non-Terrestrial Networks (NTN), which include GEO, LEO and HAPS. The focus is currently on non-transparent architecture where satellites or HAPS act as “dumb” relays in the space/sky for 5G, but from Release 19 (2025) onwards, we can expect a full integration, where a satellite or HAPS will have a full gNB on board. In the 6G era, this will bring a massive change to the architecture of mobile networks with new “mobile infrastructure in the space” carried by satellites and HAPS. This will open up the extension of mobile Internet to space in the 6G era, built on a multi-tier network infrastructure architecture in the space reminiscent of Macro (GEO), Small (LEO, Femto (HAPS) networks. Besides providing ubiquitous coverage for a host of vertical applications, e.g., in areas such as transportation, supply-chain and logistics, 6G NTN will enable new “Internet of Space” applications, such as the remote command and control of spacecrafts, space robots and the Internet of Space Things, e.g., for assets in space, health and security monitoring in space and space engineering.

2.6. Semantic Communications

Semantic communication, widely regarded as a potential breakthrough in the 6G era beyond the Shannon paradigm, aims at the successful transmission of semantic information conveyed by the source rather than the accurate reception of each single symbol or bit regardless of its meaning. In contrast to the Shannon paradigm, semantic communications only transmit necessary information relevant to the specific task at the receiver. This can empower a truly intelligent and autonomous system with significant reduction in data traffic. For many vertical applications in the age of 6G empowered by artificial intelligence (AI), the agent, such as smart terminals, robot, and smart surveillance, is able to understand the scene and executes the instruction automatically using semantic communication. Hence, the technology will be widely used in the Industrial Internet, connected and autonomous driving and vehicles, and, as we describe further, for robotic communications.

3. Future Scenarios for the Internet of Verticals

3.1. The Internet of Cloud Manufactoring

Cloud manufacturing (CMfg) is an emerging manufacturing paradigm developed from existing advanced manufacturing models and enterprise information technologies with the support of cloud computing, service-oriented technologies, and advanced computing technologies. It transforms manufacturing resources and manufacturing capabilities into manufacturing services, which can be managed and operated in an intelligent and unified way to enable the full sharing and re-use of manufacturing resources and manufacturing capabilities. CMfg can provide safe and reliable, high quality, cheap and on-demand manufacturing as services. The growing use of CMfg can be realized from the fact that cloud as a digital service accounts for around 25% of the total involvements that go into complete manufactured products [20]. In the CMfg system [21], various manufacturing resources and abilities can be intelligently sensed and connected through wide area networks, and automatically managed and controlled using IoT and AI technologies. Subsequently, as is shown in Figure 2, the manufacturing resources and abilities are virtualized and encapsulated into different manufacturing cloud services that can be accessed, invoked, and deployed based on knowledge by using virtualization technologies, service-oriented technologies, and cloud computing technologies. End- users can search and invoke the qualified Manufacturing Cloud Services (MCSs) from the related manufacturing cloud according to their needs and assemble them to be a virtual manufacturing environment or solution to complete their manufacturing task involved in the whole life cycle of manufacturing processes. This means replacing high capital expenditures with pay-as-you-go manufacturing services and through-life support, which radically transforms the economics of the new product information, volume manufacturing, and lifecycle management.

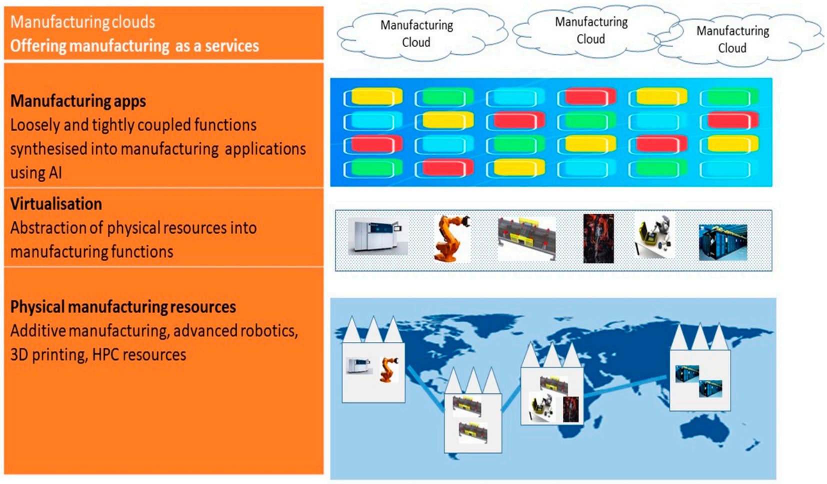

Figure 2. The transformation from CMfg to an Internet of Manufacturing enabled by 5G Wide Area Deterministic Networks.

We envisage that 5G and beyond-5G wide area networking will enable the distributed network architecture for CMfg and new Over The Top (OTT) players in the manufacturing sector (Mf-OTT). This model builds in analogy with the how the internet together with cloud computing has enabled the emergence of OTTs such as Uber for the transport sector. As shown in Figure 2, it introduces three layers: manufacturing service providers, Mf-OTTs and end-users. A layer of manufacturing service providers consists of manufacturing, computational, and AI clouds. Manufacturing clouds are formed by 5G/beyond-5G interconnected manufacturing service providers. The Mf-OTTs use intelligent search mechanism analogous to Internet search engines endowed with new AI capabilities for dynamic manufacturing service composition based on end-user requirements, and the search mechanism propagates manufacturing service inquiries through the decentralized network. Software and AI tools supporting the search process are accessible to Mf-OTTs providers in computation and AI clouds.

3.2. The Internet of Robotics

Robotics is a rapidly growing general-purpose technology with many new applications appearing in the market every day. Furthermore, with rapid advances in AI and Cloud technologies, we are seeing a rise of intelligent and cloud-based robotics in many industry sectors. A robot is a complex intelligent machine composed of mechanical, electronics, computing, embedded intelligence, sensors and connectivity technologies. Major economies in the world have the development of this technology as one of the key pillars of their national strategy. According to a recent report from the International Federation of Robots (IFR), robot installations hit new record level in 2021 with a 31% increase, and an average of 7% increase is predicted until 2025 [22]. The largest projected market for robotics currently is in the manufacturing sector, with the highest level of development being in automotive and electronic industries [23].

Robots endowed with Artificial Intelligence, rich sensorial capabilities and mobility will require communicating in a variety of scenarios, with a variety of other "actors" and for a range of reasons. Furthermore, while Human–Robot Communications will be limited by the sensory and processing capabilities of humans (which is a limiting factor in both in the nature and the rate of communications), entirely new sensory and much richer ways of communication may emerge among intelligent robots. For example, robots may use various forms of multi-sensory/multi-modal communications, which could include 3D images and videos, sound and ultra-sound, temperature and haptics to share situational information with other robots. Or they may develop new forms of speech or multi-layer vision perception for their communications, which are unrecognizable by humans. For example, a robot could layer together an image of its environment which may contain not only visible light reflection data but also infrared, radio frequency and ultrasound data all fused together. Cloud robotics are a paradigm that leverages the powerful computation, storage and resources of modern data centers combined with high speed and low-latency communication to enhance the capabilities of robots. Cloud robots are controlled by a "brain" in the cloud that may constitute a data center, a shared knowledge base, artificial intelligence and deep learning algorithms, information processing, task planners, environment models, etc. Cloud Robotics open up the possibility of *robot virtualization*, where all or the majority of Robotic intelligence as well as low-level control functions are virtualized and run on cloud or edge cloud servers. Table 2 summarizes key robotic communication scenarios together with their projected data-rates. Semantic communications will be essential in order to both drastically reduce data requirements for future robotic communications but also allow for the emergence of new ways for robots to communicate among themselves, which will go far beyond the capabilities of human-centric communications.

Table 2. Future scenarios and communication requirements of robotic networks.

Scenario	Purpose	Expected Communication Rate
Robot-environment Communications Robot–Things Communications	Control of and adaption to environment /exchange of sensory data with environment	Mbps/Gbps
Robot–Human Communications	Control, cooperation/coordination, information and context sharing, problem solving	Up to Gbps
Robot–Robot Communications (voice, video, data, VR/AR, Holographic, Multi-modal/Multi-sensory l)	Control, cooperation/coordination, information and context, sharing, problem solving	Up to Tbps

Besides the above communications scenarios, with the advancement of robot intelligence, new forms of communication scenarios can emerge [24], which will be mediated with a next generation-wide area network capable of supporting the "Internet of Robotics" (IoR), through which robots can share sensory and situational data, information and knowledge to collaborate and orchestrate their activities, collectively solve problems, learn from each other and even create their own social networks. As illustrated in Figure 3, the IoR combined with robotic visualization will pave the way for the transformation of robotic technology from specialized verticals to horizontal and virtualized robotic service platforms, and the emergence of robotic apps.

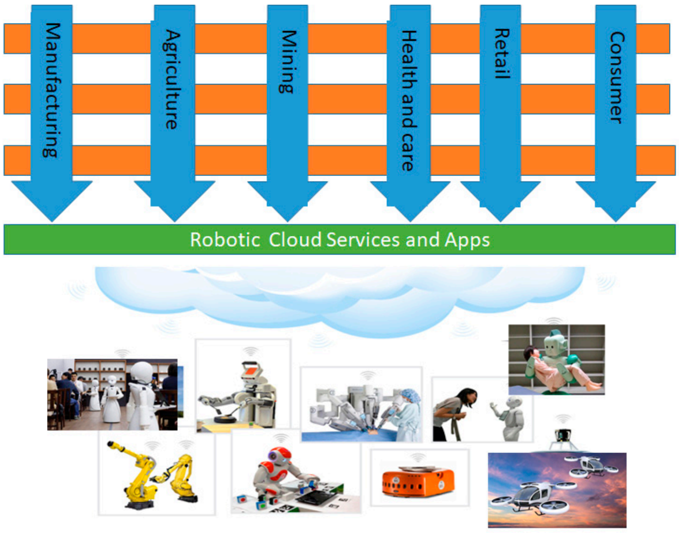

Figure 3. Transformation of robotics from specialized verticals to horizontal and virtualised robotic service platforms enabled by the IOR, and the emergence of a robotic apps ecosystem.

3.3. The Internet of Smart Energy Grids

The United Nations progress report on Sustainable Development Goals (SDGs) states that since 2012, the growth of renewables (has) outpaced the growth of total energy consumption [25], and this trend has been accelerated during the COVID-19 pandemic, i.e., we can find further evidence in relation to COVID-19. While there was a 3.8% decrease in energy demand during the first quarter of 2020 due to the lockdown, renewables were the only energy sources that posted a growth in demand, driven by larger installed capacity and priority dispatch. Hence, society as a whole is moving towards the use of renewable and sustainable energy sources. Consequently, the increase in energy demand will not be manageable unless the traditional electricity grid evolves. The convergence of the ICT infrastructure with the electricity domain, the Smart Grid (SG), has enabled new services and business opportunities, including customer-side generation and real-time energy consumption, which are guiding a significant revolution in the energy landscape.

The SG is also underpinning the emergences of new actors and entities in the energy ecosystem. In particular, the future energy user does not only consume energy but performs a crucial role as an energy Prosumer (energy producers and energy consumers) as well as providing distributed platform for renewables' energy storage, e.g., electric vehicles. These new actors are going to play a crucial role in the transition of the energy sector towards 100% renewables as well as a disruption of the entire energy value chain, resulting in the emergence of new aggregator/retailer in addition to Energy Services Companies (ESCOs), Virtual Power Plants (VPPs), Microgrids (MGs) and Prosumer Consumer Group (PCGs), which are also new components in the energy market value chain [26]. The growth in end-use consumption results in electricity generation increasing 79% between 2018 and 2050. Electricity use grows in the residential sector as rising population and standards of living in non-OECD countries increase the demand for appliances and personal equipment. Electricity use also increases in the industry and business sectors as well as demonstrating a steep rise in transportation sector as plug-in electric vehicles (EVs) enter the fleet and electricity use for the rail expands. Consequently, besides the residential sector, industry and enterprise verticals can be expected to become a key component of energy prosumer by 2050, while EVs are expected to play a major role in both prosumer and energy storage for future smart grids. Due to their energy intensity, industrial prosumers are important players in the energy transition.

Distributed Energy Resources (DERs) onsite (e.g., renewables, storage) can further help their business case. In recent years, there has been an exponential growth in offshore wind power turbines as a key renewable energy technology towards achieving carbon neutrality by 2050, and there is great interest recently in floating wind power turbines, as they can be reconfigured based on wind speed, water depth and distance to shore. Finally, the Vehicle to Grid technology (V2G) enables energy stored in Electric Vehicles to be fed back into the electricity network (grid) to help supply energy at times of peak demand and is considered a key component of future smart grids.

In order to provide monitoring and control in real time and integrate these emerging energy and storage system into the smart grid, a unified, high stability and ultra-reliable wireless communication infrastructure is required, which also support high-bandwidth, low-latency and mobility requirements. Network slicing also seems to be a promising and optimal solution for the diverse performance requirements of smart grids. It can offer virtualized and scalable communication architecture for a customized communication service expected by future smart distribution grids [27]. Consequently, the above evolving landscape in smart grids necessitate the availability of the 6G network infrastructure supporting the often-stringent requirements (in terms of latency, reliability and security) for both wide area connectivity and mobility for management of an Internet of Smart Energy Grids (IoSG).

4. Conclusions and Outlook

In this paper, we reviewed key architecture, networking and technology components, which are underpinning the successful expansion of 5G connectivity services and platforms into vertical sectors in the 6G era, as well as providing an overview of the worldwide progress by the public, and while 5G for verticals is aiming at the 5G native connectivity for specific verticals sectors in the longer term, these anticipate the emergence of entirely new horizontal entities and services across enabled by wide area 5G connectivity, which will the pave the way for a 6G-enabled Internet of Verticals (6G-IoV). Prominent use cases of 6G-IoV include distributed and over-the-top cloud manufacturing and manufacturing as a service, and the Internet of Robotics (IoR) and the Internet of Smart Energy Grids were described. In terms of timelines, we expect that by 2027 we will see 5G-native connectivity to be fully deployed in key verticals such as manufacturing automotive electricity grids, after which we will witness the initial instances of 6G-IoVs with the worldwide Internet of Verticals fully emerging in the mature era of 6G, i.e., beyond 2035.

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