IoT AND EDGE COMPUTING: OPPORTUNITIES FOR EUROPE

TAKEAWAYS FROM THE NGIoT WORKSHOPS ON IOT AND EDGE COMPUTING

NEXT GENERATION INTERNET OF THINGS

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Next Generation Internet of Things

IoT and Edge Computing: opportunities for Europe

Takeaways from the NGIoT workshops on IoT and Edge computing towards the NGIoT IoT Research and Innovation roadmap, 2020/2021

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SUMMARY

IoT and Edge Computing: Opportunities for Europe

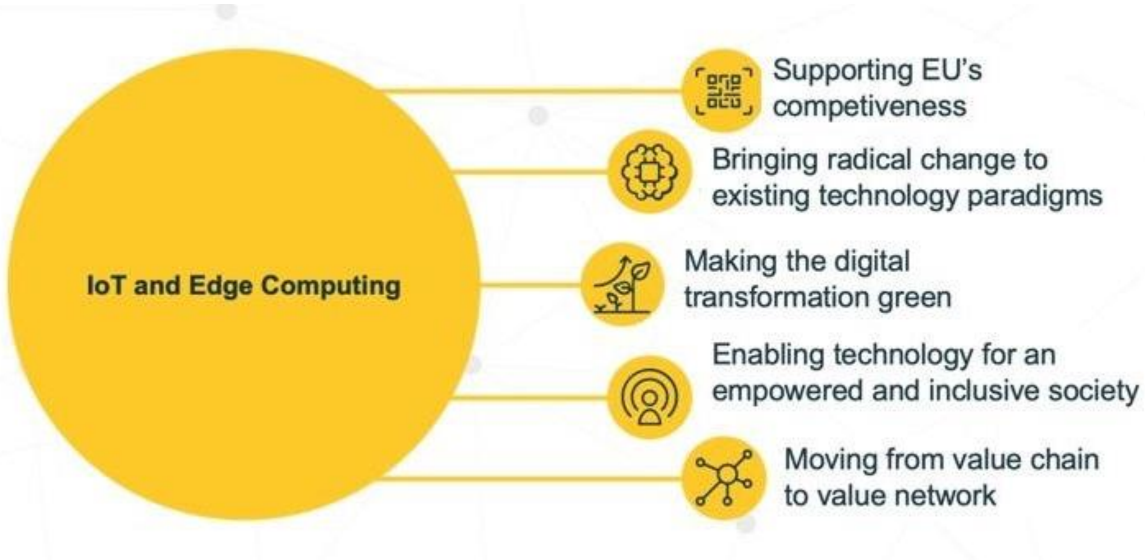

Fig. 1: Next Generation Internet of Things (NGIoT) policy impact targets when identifying opportunities for Europe in IoT and Edge Computing.

Economy impact: realising opportunities for Europe

Digital transformation of industry and the public sector is fundamental to accelerate economic recovery after COVID 19 and to exploit new opportunities: The Internet of Things (IoT), which is now a mature technology, is the backbone of digitalization with a potential market exceeding 3 trillion € and 30 billion devices expected to be connected in the 3-5 years from now[1]. It is broadly accepted that the current shift from cloud to edge is a substantial opportunity for Europe: it paves the way for new applications, new value propositions and sustainable growth, delivering on the European Green Deal.

Technology impact: interactive control and intelligence

We are witnessing a convergence of IoT with other technologies: The move from IoT to AIoT[2] and the IoT and edge computing convergence have the potential to bring radical changes to technology paradigms. Edge computing transforms IoT by making it near-real-time and decentralized. IoT thus moves from passive monitoring to interactive control and intelligence. Beyond that, the paradigm shift from cloud to edge computing also transforms hardware, as in the automotive industry.

1 Source: SRIA 2021, Electronic Components and Systems, Artemis, Aeneas, EpoSS

2 AIoT: Combination between Artificial Intelligence and Internet of Things

Sustainability impact: connecting the digital transformation with the green transformation of Europe

Sustainability is a key priority for Europe. IoT has a key role in enabling the green transition in multiple sectors. The move to the edge is promising in this respect, due to potential energy savings and the possibility to reduce network load. In addition, it is easier to power smaller devices from renewable sources. However, end-to-end energy consumption by application needs closer investigation, to be able to progress in making cloud-edge energy efficient.

Europe should take the advantage of turning the digital transformation into a green transformation, as envisioned in the strategies “A Europe Fit for the Digital Age[3]” and the “European Green Deal”.[4]

Societal impact

The current Covid 19 pandemic, that has accelerated the digitalisation of society at remarkable pace, shows the importance of approaching IoT and Edge computing from a human-centred perspective. IoT and Edge computing, together with Artificial Intelligence, will increasingly play a role in creating inclusive societies with a focus on citizens’ quality of life. The move to the Edge brings intelligence to devices and supports the development of personalised services and empowerment of citizens.

Ecosystem approach: Move from value chains to value networks

European leadership in IoT and Edge computing can only be achieved when European actors join forces. Key organisations in Europe should work on alignment of strategic research agendas and collaboration and ecosystems should be strengthened, moving from narrow and vulnerable value chains to broad and robust value networks. Collaboration between large industry, SMEs and innovators needs to be supported. Open source and open platforms are important in this respect, as they support newcomers and SMEs in accessing the market, unleash innovation potential, complement de jure standards and facilitate collaboration. Avoiding fragmentation is crucial.

3 https://aeneas-office.org/wp-content/uploads/2021/01/2021_ECS-SRIA-final_1501.pdf

4 https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age_en#latest

PART I

THE POTENTIAL FOR EUROPE

"Edge computing is the logical evolution of the dominant cloud computing model, avoiding the transfer of mission-critical data to the cloud, supporting resilience, real time operations, security, privacy and protection while at the same time reducing energy consumption and carbon footprint. In edge computing, the processing moves from a centralised point, closer to (or even into) the IoT device itself, the 'edge' or periphery of the network."

EC Fireside Chat Report, 2021

1. INTRODUCTION

With the proliferation of Internet of Things (IoT), the need to evolve Edge computing solutions is becoming urgent. By bringing sensing, computing and actuation to any part of the computing continuum, providing responsiveness and intelligence where needed, IoT devices accelerate the convergence of Information Technology (IT) and Operational Technology (OT) and fuel the digital transformation of areas, like energy, health and care, agri-food, mobility/automotive, manufacturing and smart cities & communities.

The shift from cloud to edge is a substantial opportunity for Europe: on the one side, the European industry is strongly positioned in edge technologies, covering key players in the value creation from sensors and systems, embedded computing, connectivity, software design to the development of complex products and services; on the other side, GAFAM (Google, Apple, Facebook, Amazon and Microsoft) do not yet have the capacity to provide edge resources in Europe, while a wide set of cloud and telco providers can already, today, provide edge and far edge access.

Embracing this opportunity may bring a key competitive advantage to Europe for the years to come, but European actors need to join forces and act with speed. It is necessary to take stock on where European industry and other players stand and what is needed in the short/medium and in the long term, in forms of investments in research, innovation and deployment instigated by the European Commission's new programming cycle, including Horizon Europe, the Digital Europe Programme, Connected European Facility, the Missions, and The Recovery and Resilience Facility. Furthermore, it is important to boost the growth of relevant strategic European projects like GAIA-X, which foster interoperability, data sovereignty and innovation development based on the interplay between cloud and edge computing. GAIA-X is already developing common requirements and specification for a European data infrastructure, and as such provides unique opportunities for sharing and exploiting IoT data at scale.

This paper on IoT and Edge Computing builds on our previous work[5] and on presentations and discussions during a series of webinars organised from August 2020 to June 2021 by the Horizon 2020 European IoT Roadmap Coordination and Support Action "Next Generation Internet of Things" (NGIoT) in collaboration with the European Commission DG Connect (IoT Unit, E4), AIoTI, Artemis, HIPEAC, Eclipse Foundation and the many speakers and attendants to the workshops. The contents of this paper will be further shaped through engagements and discussions with key stakeholders in the coming months and integrated into the upcoming "Roadmap for IoT Research, Innovation and Deployment in Europe", authored by the NGIoT CSA consortium and foreseen to be published in its final form in October 2021. Stakeholders and communities around IoT and Edge are invited to engage with the findings and to join the discussions through the NGIoT webinars and the NGIoT website.

5 https://www.ngiot.eu/deliverables/#1613463848204-4c123af5-2661

1.1. European Policies and strategies

A focus on IoT and Edge computing contributes to [the European Commission (EC) priorities for 2019-2024](), specifically "A Europe fit for the digital age" which has three key objectives:

- Technology that works for people;
- A fair and competitive economy; and
- An open, democratic and sustainable society.

These objectives are pushed by a number of key ongoing and future actions, summarized in Figure 2.

Fig. 2: EU's key digital strategies and policies

Several of the above strategies are strongly interlinked with IoT and Edge Computing:

- A European strategy for data[6] focuses on the **enablement of data spaces in the cloud-edge continuum;**
- A new Industrial Strategy for Europe[7] includes among the priorities the **digitalisation of EU industry;**
- An SME Strategy for a sustainable and digital Europe[8] promotes concrete actions to support SMEs (as the heart of EU industry) **toward a sustainable digital transition**;
- A White Paper on Artificial Intelligence[9] **promotes a human centric approach to AI**;

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6 EC. Communication: A European Strategy for Data. 2020

7 EC. A new Industrial Strategy for Europe. 2020

8 EC. An SME Strategy for a sustainable and digital Europe. 2020

9 EC. White Paper on Artificial Intelligence: a European approach to excellence and trust. 2020

- A set of policies[10] linked to the Green Deal target to "make data centres **and ICT infrastructures climate-neutral by 2030";**
- A new agenda for the European strategic autonomy[11] underlines the need for **Europe to support its capacity to act independently and defend its sovereignty in the Digital Age;**
- The Data Governance Act[12] fosters a **EU approach for data sharing to increase trust, neutrality and fairness.**

The strategies and policies are supported by the upcoming programmes: Horizon Europe with a € 95.5 billion budget, including € 15 billion for the 'Digital, Industry and Space' cluster, and the €7,5 billion Digital Europe Programme, focusing on building digital capacities and facilitating the wide deployment of digital technologies in Europe. A third programme: The Connecting Europe Facility (CEF) Digital is the follow-up of the current CEF programme, focusing on the creation of transnational digital infrastructures with a € 2 billion budget.

Beyond the above programmes, due to the pandemic, the European Commission, the European Parliament and EU leaders have agreed on a €750 billion recovery plan (Next Generation EU) that will help repair the economic and social damage caused by the coronavirus pandemic, and lead the way out of the crisis and lay the foundations for a modern and more sustainable digital Europe.

Reinforcing the previous strategies, on 9 March 2021, the Commission presented The European Digital Decade: a vision and avenues for Europe's digital transformation by 2030, including the deployment of 10,000 climate neutral highly secure edge nodes, and an adoption rate of 75% of advanced cloud services for European businesses. The edge nodes that will allow data processing at the edge of the network should be distributed in a way that guarantees access to data with low latency.

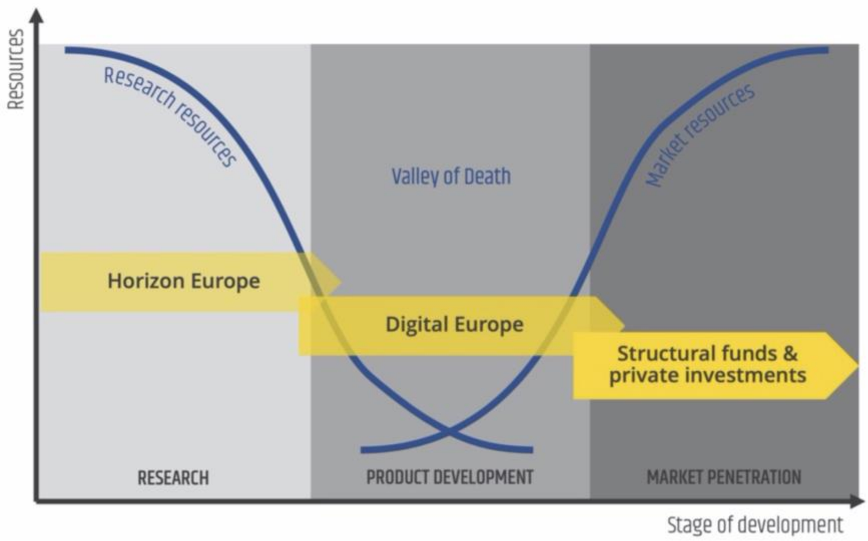

Fig. 3. The funding spectrum, exemplifying the relation between Horizon Europe and the Digital Europe Programme.

10 EC. Supporting the green transition. 2020

11 EC. Rethinking Strategic Autonomy in the Digital Age. 2019

12 EC. Data Governance Act. 2020

On 9 March 2021, the Commission presented a vision and avenues for Europe's digital transformation by 2030. This vision for the EU's digital decade evolves around four cardinal points:

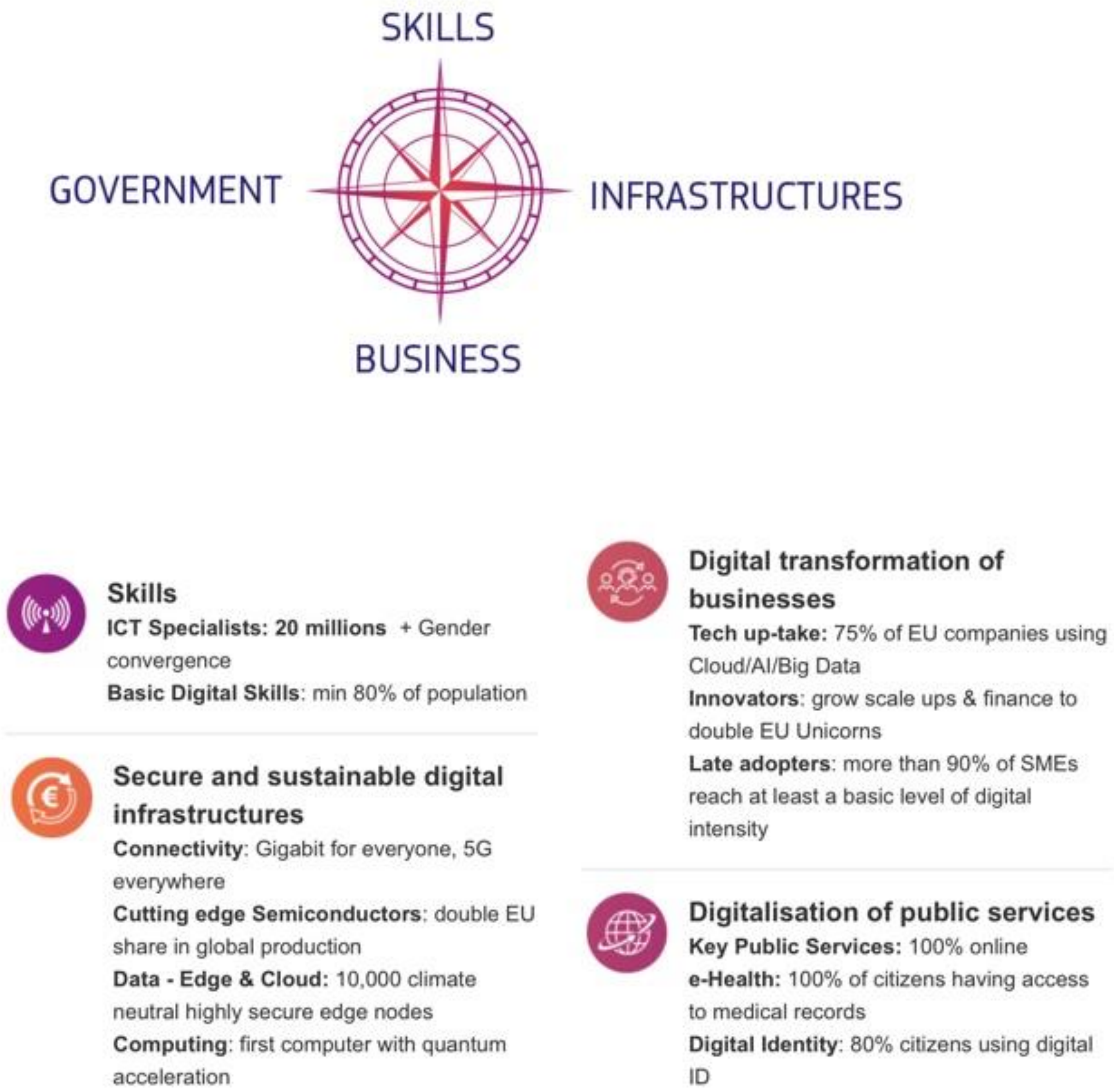

Fig. 4. The Digital Compass translates the EU's digital ambitions for the next decade into clear, concrete targets, setting out a European way for the digital decade.

2. IOT AND EDGE COMPUTING

2.1. Trends and drivers

As the number of IoT devices and sensors will increase dramatically in the coming years, maintaining such device infrastructures will become a very costly affair. In addition, the inherent latency of the cloud is not fully supporting the benefits of the digital transformation. Consequently, there is a trend of computation offloading towards the edge, extending the cloud to the edge of the network, close to end users, bringing ultra-low latency and high bandwidth. In the following section, we will look into the various trends that we see emerging with the paradigm shift from cloud to edge computing and from the convergence of IoT and edge computing.

2.1.1. IoT and Edge – Trends

- **IoT from static monitoring to dynamic intelligence.** With the increased concentration of data value at the edge, edge computing has become a vital component of the processing layer of the IoT architecture: advancing the real-time processing of large-scale IoT applications and deploying edge computing units with storage, computational, connectivity and intelligence capabilities to implement newly decentralised IoT solutions. IoT is thus transforming from static monitoring to active and intelligent device automation, based on real-time processing of data usage, edge processing, AI, mesh connectivity and end-to-end security.
- **From big data to relevant data.** While the last decade was about big data stored and analysed centrally, with edge computing we will see an increased focus on the processing of relevant data only in decentralised settings. With edge computing, connected devices are able to complete local data analysis, sending only necessary data to a central server or data centre or back to the intelligent device. This has of course also a positive impact on transforming IoT into a green technology.
- **Evolution to Everything as a Service.** XaaS—everything-as-a-service or anything-as-a-service—refers to products, tools, and capabilities that are delivered to users as services. Through edge computing, data collection and initial processing can move closer to the user and to the place where the data is produced and used so “intelligent edge” services as well as hybrid services that combine on-premise services and cloud can be delivered to end-users.
- **Strong cybersecurity everywhere.** There is a general concern that with the shift to the edge and decentralisation that follows along, cybersecurity threats will increase. This concern can slow down the push for edge supported services and solutions. To effectively protect the edge, organizations are now moving toward a layered defence-in-depth approach to secure their systems and networks[13]. Holistic cybersecurity approaches are required that address security vulnerabilities and threats from the device level up to the edge/cloud levels without essential gaps that can be exploited by adversaries.

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[13] An Overview of Cybersecurity Best Practices for Edge Computing. Whitepaper 12, Version 1. Daniel Paillet, CISSP, CCSK, CEH, 2021. Schneider Electric.

- **Privacy and data protection:** Along with cybersecurity, emerging IoT applications are expected to provide stronger data protection, especially for sensitive data (e.g., Intellectual Property in industry, personal data in healthcare). The move from cloud to edge reduces data exposure to adversarial threats and boost stronger data protection. This boosts compliance to mandatory regulations like GDPR, while fostering adherence to sector specific regulations about data privacy.
- **Towards sustainable IoT.** The expectation is that the move to the edge will help saving energy due to the reduction of the network load. The current environmental challenges require a move towards green, energy efficient and low carbon IoT technologies for distributed edge. Future IoT applications will have to ensure the power efficient operation of IoT devices. Moreover, they must contribute to more sustainable AI operations. Running AI on edge devices (e.g., embedded machine learning, edge AI, TinyML) can contribute substantially to a greener AIoT.

2.1.2. Drivers to the shift from cloud to the edge

The key drivers for the adoption of edge computing infrastructure are[14]:

- **Scaling with the increasing amount of data generated.** The number of Internet of Things (IoT) devices worldwide is forecast to almost triple from 8.74 billion in 2020 to more than 25.4 billion IoT devices in 2030[15]. Modern cars generate already 25GB of data per hour, and it is expected that autonomous vehicles will generate around 3 terabyte of data per hour. Moving such an amount of data to the cloud is not an option[16].
- **Supporting low-latency and real-time interaction.** In several IoT scenarios, real time decisions based on data are critical. Doing the processing in the cloud introduces, in the best case 100 milliseconds delay, which could be the difference between avoiding a collision or not in the autonomous vehicle scenario.
- **Increasing data sovereignty**. Storing data collected at the edge in a central cloud may imply moving data across different geographies and domains, thus reducing data owners' control.

2.1.3. Technology enablers

Nowadays IoT, in its wider notion, is not a technology per se, but rather a combination of existing technologies that evolved thanks to things-enabled applications' requirements. In the transition of IoT toward the edge, a number of technology enablers are key:

- **AI & ML architectures**: the recent evolutions in terms of AI software platforms and hardware platforms and the availability of massive data sets to test and apply AI combined with increasing computing capability made AI key in several IoT real-life scenarios. Still this evolution so far has been mostly at the core of the network, while current evolutions of AI

14 Industrial Internet Consortium. Introduction to Edge Computing in IIoT, 2018.

15 Statista. Number of Internet of Things (IoT) connected devices worldwide from 2019 to 2030, 2021

16 Statista. Big Data on Wheels. 2017

platforms and hardware are increasing support for AI at the edge, more has to be done to efficiently support AI at the edge in combination with low power computing devices. The latter approaches include far-edge solutions such as TinyML and embedded machine learning.

- **5G & 6G networks**: cheap, reliable and scalable internet connectivity is a key requirement for several IoT scenarios. This requirement is even more important with the increase of edge computing adoption that will contribute further to increase the load at the network edge. With the increase of edge network load, to avoid energy consumption increase of edge network apparatus, it is important that 6G technologies will even further reduce the energy footprint for GB of data transported. Beyond that, it is expected that the ongoing virtualisation of mobile infrastructure will fuse connectivity and edge computing infrastructures, thus opening up new ways to deliver and manage IoT infrastructures.
- **Cloud technologies**: while the increasing transition toward edge will reduce adoption of traditional cloud providers, the role of cloud technologies will be still key to enable scalable and autonomic IoT infrastructure spanning from cloud to edge (or across edges). Cloud-native approaches have been proved to work effectively also in distributed scenarios and to enable role out and automation of IoT services in the cloud-edge continuum. Evolutions of these technologies will be key to allow IoT to scale at the edge and across multiple infrastructure providers. Novel IoT applications are expected to leverage leading data-driven cloud innovations such as MLOPs and AIOps for infrastructure management.
- **Hardware & Sensors**: the role out of edge computing clearly depends on the evolution of hardware. Edge nodes are requested to run AI and machine learning tasks that so far were only possible in cloud infrastructures, while dealing with other constraints such as energy capacity. The latest developments in microprocessor architectures and ongoing research (e.g. neuromorphic computing) should provide novel computing capacities able to support AI tasks not possible today at a lower energy footprint than today. The increasing number of deployed sensors will also impact IoT sustainability, thus demanding for - not only more energy efficient sensors - but as well more bio-compatible ones.
- **Cybersecurity:** the move from a centralised infrastructure to a distributed and decentralised one, while clearly reducing the need to move data to third party infrastructures, it increases the complexity of security management and increases the potential surface of attack of the infrastructure. It is expected that security and privacy technologies will evolve to scale in a decentralised deployment and to increase their resiliency to novel mechanisms of attack that may compromise edges.
- **Tactile Internet – Augmented Reality (AR) / Mixed Reality (MR) / Extended Reality (XR):** Some of the above-listed advances (e.g., 5G networking) coupled with the reduction of the cost of the AR/MR devices (e.g., AR headsets) are acting as catalysts for the faster adoption of the tactile internet. IoT will be soon combined with AR/MR to enable novel applications and business models that completely break time and space boundaries. The COVID19 pandemic is another catalyst in this direction, as it has led to an explosion of market demand for services that involve remote monitoring and support.

2.2. Market potential

Various projections based on total IoT connections, among other parameters, estimate a global growth in IoT connections to reach from 25 to over 41 billion devices[17] [18] by 2025, with market value ranging from $1.1 Trillion to $1.5 Trillion[19] and a CAGR ranging from 25%[20] to 44%[21]. As for Edge computing specifically, Mckinsey positions the forecast to 2025 at a potential hardware value of $175B-$215B[22], while the Linux foundation calculates an approximate global CAPEX of $146B for 2028 at an average CAGR of 35%[23], with a faster growth on the device edge.

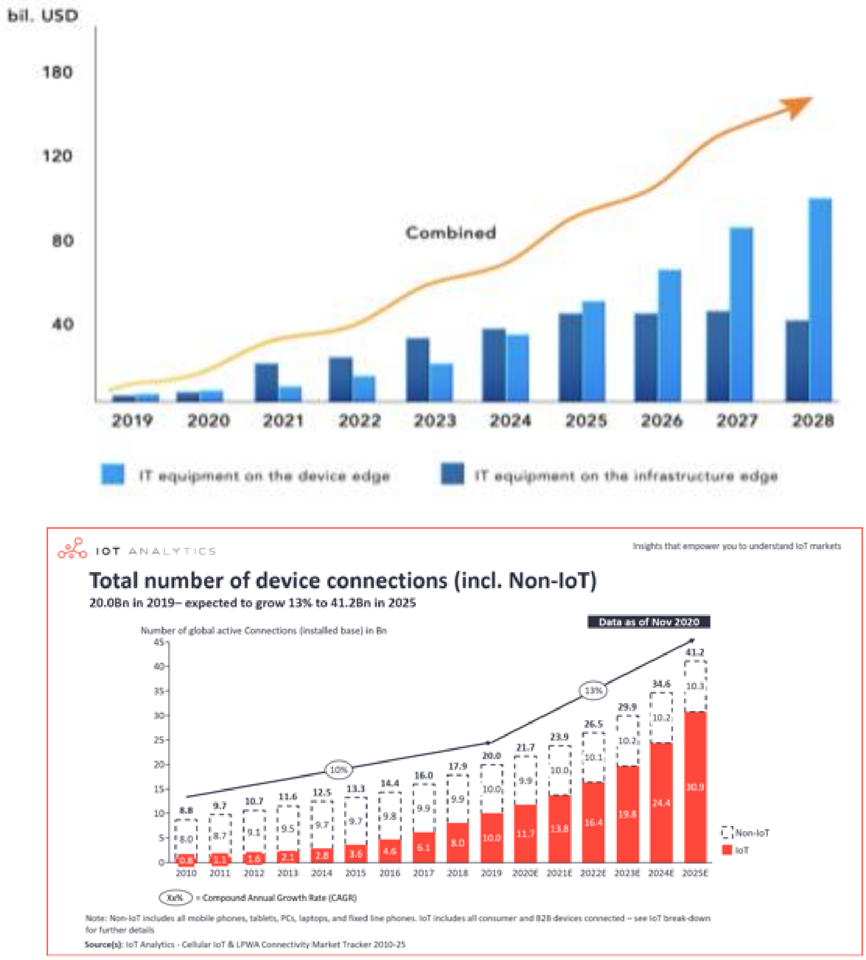


Figure 5. IoT [24] and Edge[25] global market estimations

17 https://www.idc.com/getdoc.jsp?containerId=prAP46737220

18 https://iot-analytics.com/state-of-the-iot-2020-12-billion-iot-connections-surpassing-non-iot-for-the-first-time/

19 http://ficci.in/spdocument/23092/Future-of-IoT.pdf

20 https://www.verifiedmarketresearch.com/product/global-internet-of-things-iot-market-size-and-forecast-to-2026/

21 https://www.statista.com/statistics/976313/global-iot-market-size/

22 https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/new-demand-new-markets-what-edge-computing-means-for-hardware-companies

23 https://www.lfedge.org/wp-content/uploads/2020/04/SOTE2020.pdf

24 https://iot-analytics.com/state-of-the-iot-2020-12-billion-iot-connections-surpassing-non-iot-for-the-first-time/

25 https://www.lfedge.org/wp-content/uploads/2020/04/SOTE2020.pdf

Projections position North America dominating the Edge Computing market due to its high adoption of technologies such as IoT and 5G[26] [27]. Europe shows the second highest edge infrastructure investment by 2028 just behind APAC, which is the region with the highest growth rate[28]. The largest customers are Western Europe multinational network operators leading network upgrade efforts.

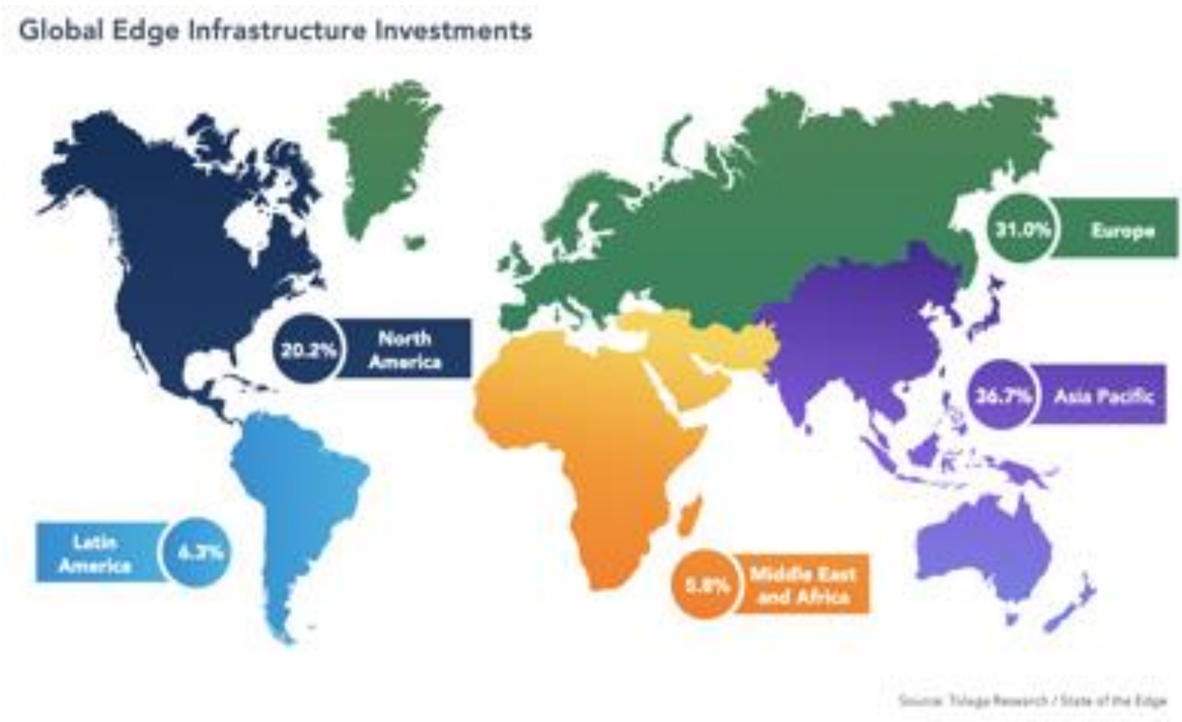


Fig. 6. Global Edge Infrastructure Investments

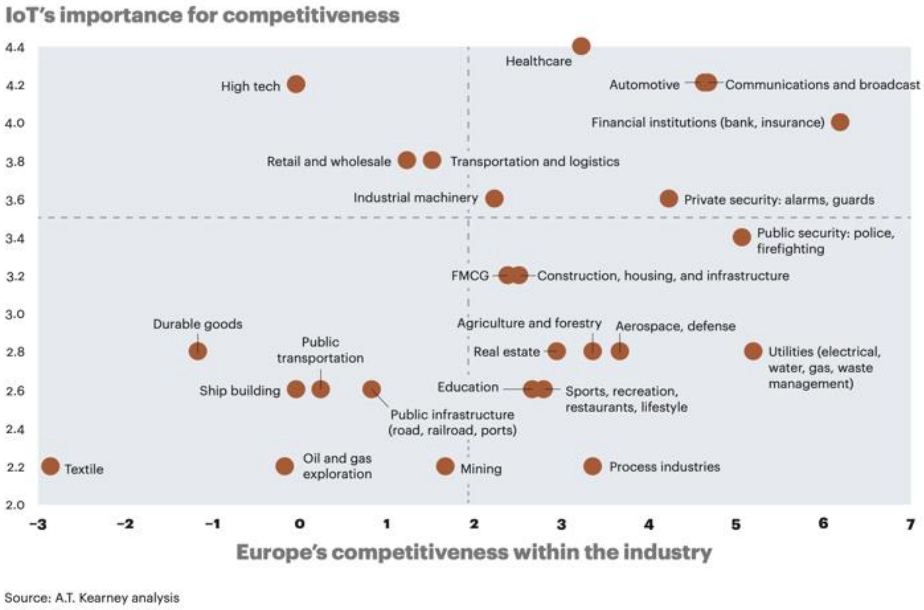
26 https://www.industryarc.com/Report/17939/edge-computing-market.html

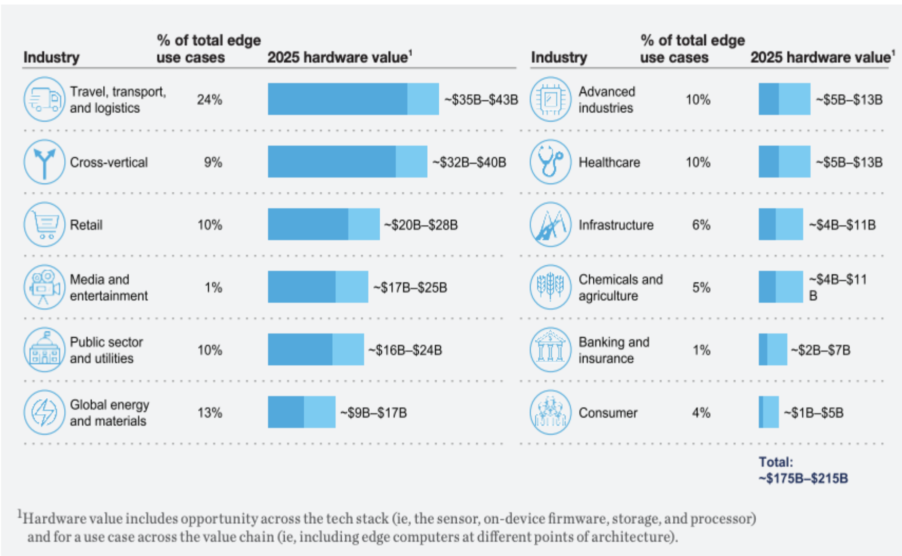
27 https://www.idc.com/getdoc.jsp?containerId=prUS46878020

28 https://www.industryarc.com/Report/17939/edge-computing-market.html

2.2.1. Verticals and transversals

The intersection of IoT and Edge Computing brings different potential opportunities across verticals. In order to prioritize the most promising verticals for Europe, this paper evaluates the estimated global impact according to present use cases, together with Europe's competitiveness and input from the community. From this analysis, the salient verticals where Edge and IoT have the most impact for Europe are Manufacturing, Automotive & Smart Mobility, Smart Cities and Communities, Smart Health, Smart Energy, and Agrifood & Smart Farming.





Industry	% of total edge use cases	2025 hardware value[1]	Industry	% of total edge use cases	2025 hardware value[1]
Travel, transport, and logistics	24%	~$35B–$43B	Advanced industries	10%	~$5B–$13B
Cross-vertical	9%	~$32B–$40B	Healthcare	10%	~$5B–$13B
Retail	10%	~$20B–$28B	Infrastructure	6%	~$4B–$11B
Media and entertainment	1%	~$17B–$25B	Chemicals and agriculture	5%	~$4B–$11 B
Public sector and utilities	10%	~$16B–$24B	Banking and insurance	1%	~$2B–$7B
Global energy and materials	13%	~$9B–$17B	Consumer	4%	~$1B–$5B
					Total: ~$175B–$215B

[1]Hardware value includes opportunity across the tech stack (ie, the sensor, on-device firmware, storage, and processor) and for a use case across the value chain (ie, including edge computers at different points of architecture).

Fig. 7. 2025 edge computing value estimations [29] and IoT importance by sector [30]

29 https://www.mckinsey.com/~/media/McKinsey/Industries/Technology%20Media%20and%20Telecommunications/High%20Tech/Our%20Insights/New%20demand%20new%20markets%20What%20edge%20computing%20means%20for%20hardware%20companies/New-demand-new-markets-What-edge-computing-means.pdf

30 https://www.kearney.com/digital-transformation/article?/a/the-internet-of-things-a-new-path-to-european-prosperity

3. LANDSCAPE

3.1. Vendor landscape

As the IoT market matures, the implementations across different sectors are starting to deliver the real value. According to a study conducted by Bain in 2019, IoT is integral to many businesses' operations, including floor automation, equipment inspection, maintenance, real-time tracking and crowd safety, among other applications[31]. In the case of Edge computing solutions, IDC points that over 60% of European companies are leveraging edge computing solutions in some way, driven by its potential benefits[32].

Networking vendors seek to offer end-to-end solutions, from datacenter to endpoints, while partnering up with manufacturers and operational technology companies to deliver complete Industry 4.0 solutions. However, vendors are currently at different stages and the reach and purpose of their offer varies with some having specialized edge solutions and others having solutions for other purposes but adaptable to edge[33]. As the market is still not mature and expected to pass from being a marginal part of the IoT spending to a more significant portion, NGIoT drew a first approach to a European vendor and stakeholder landscape shown in figure 5. It is important to note that the front-runners only include European companies, however, many multinationals from other regions offer services apart from the European ones.

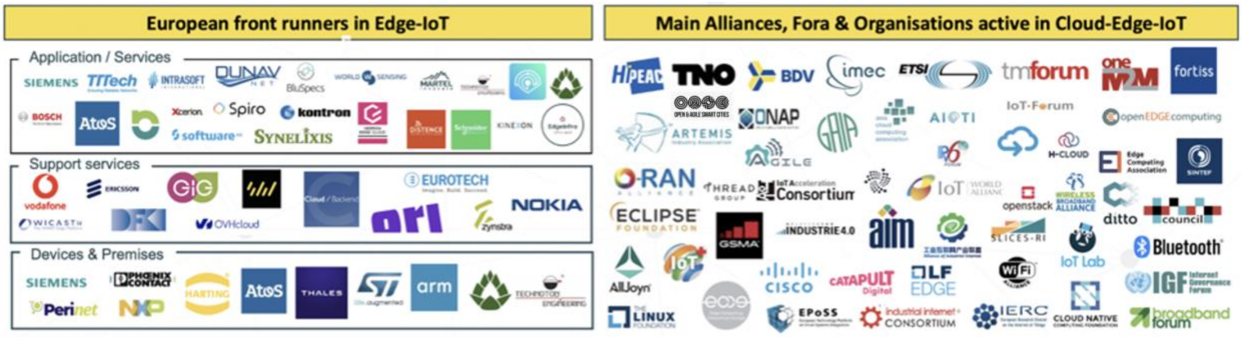


Fig. 8. IoT-Edge European frontrunners and organizations draft[34]

3.2. Public sector

While this paper primarily focuses on the industry perspective, the public sector, especially visible in the broad area of Smart Cities and Communities, has as catalyst and regulator (and not just as passive procurer) an important role in realizing the potential of IoT in Europe. In the field of digital cities and communities, we see the impact of new IoT developments and thus, the need for clear edge strategies. In addition to cloud, cities have a need for analytics on the edge for real-time data, high response time, as well as for relevant data.

31 https://www.bain.com/globalassets/noindex/2020/bain_report_technology-report-2020.pdf

32 https://www.uk.idc.com/research-uk/RESOURCES/ATTACHMENTS/EUR245277019.pdf

33 https://www.uk.idc.com/research-uk/RESOURCES/ATTACHMENTS/EUR245277019.pdf

34 NGIoT - IoT ecosystem building and vision report

In 2025, the expectation is that more than 500 urban digital twins will be deployed throughout Europe.[35] This means that a platform of platform approach is important, together with swarm computing and edge. Edge reduces latency and working with multiple networks and deploying microedge means that cities are able to develop more personalized services for their citizens and, thus, create inclusive cities. Using the edge as a service platform, cities can implement technology as part of the data economy. The shift to the edge also helps cities to avoid vendor lock-in, as it enables open collaboration and supports different services from various providers in the ecosystem.

In a smart cities and communities context, priorities in the short and medium term are well-defined open architecture of edge technology that can be deployed in cities and the multitenant use of the technology. Interoperability is still a barrier in an local context, where both under- and over-connectivity is an issue. The Minimal Interoperability Mechanisms (MIMs)[36] that the EU-based global network Open & Agile Smart Cities (OASC) has developed, backed by many cities and communities as well as industry and SMEs across the world, is an important step forward in creating the minimal but sufficient interoperability, e.g. when procuring local digital twins and other complex Edge IoT-related systems. The MIMs are governed in relation to EU policy through the Living-in.EU[37] joint initiative as "MIMs Plus"[38], referenced in the European Coordinated Plan on Artificial Intelligence.[39]

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35 Digital Twins in Smart Cities and Urban Modeling application analysis report, ABI research, 2019.

36 OASC MIMs: https://mims.oascities.org

37 Living-in.EU: The European way of digital transformation in cities and communities

38 MIMs Plus, current version: https://living-in.eu/groups/commitments/technical

39 Coordinated Plan on Artificial Intelligence 2021 Review, European Commission, April 2021: https://digital-strategy.ec.europa.eu/news-redirect/709091

PART II

MOVING FORWARD:

REALISING OPPORTUNITIES FOR EUROPE

1. TECHNOLOGY PRIORITIES

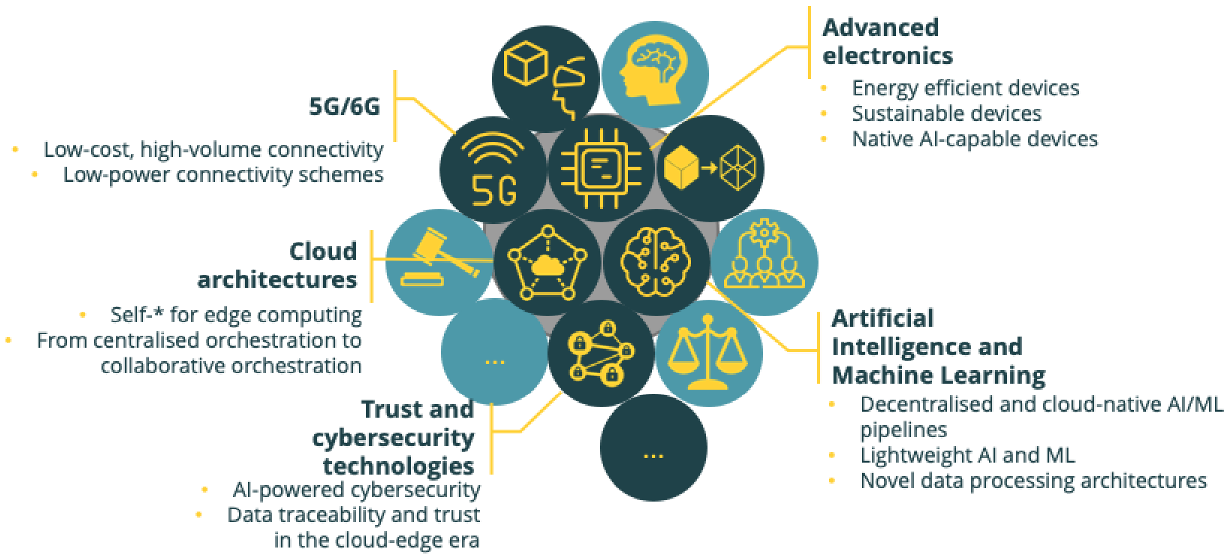

Fig. 9. Key enabling technologies

The transition towards edge computing of IoT technologies, and hence the wide deployment of IoT, requires the evolution of different technology enablers to tackle requirements posed by decentralised IoT systems. In the following, in relation to the key technologies identified in Section 2.1.3, we highlight key advancements needed to: 1) evolve IoT solutions from static monitoring to dynamic intelligence; 2) enable the shift from big data to relevant data; 3) support the IoT transition toward "Everything as a Service"; 4) empower trust in IoT solutions; and, 5) support the transition towards sustainable IoT.

Artificial Intelligence & Machine Learning

- **Decentralised and cloud-native AI/ML pipelines.** With the advent of edge computing, AI processing is moving from the cloud toward the edge, allowing for fast local decisions. To make this possible it is key to explore decentralised mechanisms to orchestrate AI pipelines, i.e. the process of collecting and adapting data for model computation, the model computation and their deployment. Such pipelines will need to have ways to define conditions to trigger model re-computation and ways to preserve data privacy in complex and distributed IoT ecosystems (e.g.by leveraging federated machine learning architectures). Such mechanisms will have a key role to increase data privacy.
- **Lightweight AI and ML**. While the "divide et impera" approach is essential to support distributed/decentralised computation, it may not be enough to support the training of algorithms and their deployment in low power devices at the edge. Approaches that have a small computational footprint both during the training phase and the inference phase are essential to enable intelligence in the case of low power devices. In this sense research approaches, like embedded machine learning and TinyML, provide interesting solutions that in combination with decentralised AI architectures may scale in the cloud-edge continuum.

- **Novel data processing architectures.** With the advent of edge computing, data processing is becoming more distributed and decentralised. Most of the data processing solutions in place today are cloud-native and assuming a centralised processing. While first steps are ongoing to deliver such architectures, these are evolutionary solutions, i.e. extension of existing technologies and approaches to incorporate edge processing. Research should explore novel mechanisms for data processing, looking beyond current consolidated solutions. A promising trend that could support such evolution is function-as-a-service that recently introduced support for edge-cloud orchestration and in memory-databases. Furthermore, the potential of decentralized architectures based on technologies like blockchain and decentralized ledger technologies (DLT) for data traceability and data certification could be leveraged.

5G & 6G networks

- **Low-cost, high-volume connectivity.** Research should explore radio transmission solutions that, while increasing bandwidth available for IoT data transport, would reduce the cost of deployment of the radio networks. In particular, interesting areas of investigations are: new frequency bands (e.g. unlicensed band > 200 GHz), new medium for signal propagation (e.g. single mode optical waveguide using laminated polymer platform). Light Fidelity communication technology and its convergence with 5G should be further explored as well.
- **Low-power connectivity schemes.** Hardware and software solutions should drastically reduce the energy consumed by IoT devices to collect and transmit information. Software solutions and communication protocols may optimize activation of communication and consumption during communication, while energy harvester and other bio-inspired solutions may increase the capacity of batteries and energy independence of devices.

Cloud architectures

- **Self-* for edge computing.** One of the key characteristics of determining the success of cloud services are their self-* (scaling, healing, …) capacities. These automation capacities are yet to be taken at the whole cloud-edge-device management continuum. Machine learning and artificial intelligence may provide essential instruments to achieve such automation, that is not yet embodied in any of the reference cloud-native orchestration solutions available in the market today. Additionally, such orchestration capacities should as well tackle more and more important aspects in infrastructure management such as energy impact. Initiatives (such as KubeEdge, microk8s, and k3s) around Kubernetes ecosystem are aiming at empowering its usage at the edge, still not all devices available at the edge may be able to host solutions like k8s, and research and development toward more holistic approaches are required.
- **From centralised orchestration to collaborative orchestration.** Due to the heterogeneous nature of IoT infrastructures, which include a variety of edge nodes with different resources, capabilities, mobility, ownership, etc. managing and operating IoT infrastructure at scale is more and more complex. More, IoT is introducing novel requirements to the cloud-edge continuum management, where in more and more scenarios, IoT solutions may become dynamic ecosystems, thus requiring dynamic orchestration and composition of edge resources

from multiple owners, and moving from current federated approaches (such as the one proposed by GAIA-X acting as a central authority) toward more peer-to-peer approaches (not requiring a central authority). Such orchestration and composition should occur preserving isolation of different users and privacy of data by the different stakeholders leveraging shared edges. In this respect, approaches like Swarm Computing clearly provide a promising direction.

Advanced electronics

- **Energy efficient devices**. Early studies indicate that the combination of micro-energy harvesting and micro-storage technologies may be the future for long lasting IoT devices. Improving their combined performance while downscaling their size can only be achieved through breakthroughs in materials performance and system architectures that allow for high density features and embedded energy options in integrated circuits (ICs) .
- **Sustainable devices.** While energy efficiency is key to reduce the impact of IoT on the carbon footprint, it is not the only aspect that influences IoT device "sustainability": the shift toward the edge is going to increase the number of devices, thus potentially increasing the linked "digital waste". Devices need to be designed in such a way that their lifecycle environmental impact is close to zero. Recent research showed the great potential for the improvement of the devices' design holding by nano- and biomaterials invented in the last decade. Research should advance toward minimally invasive electronic devices embedded directly into biological objects. Such hybrid systems may enable high-quality, low-cost sensors as an alternative to more expensive fully electronic devices. IoT applications will benefit from using hybrid bio-electronic sensors which rely on natural capabilities of bio objects (e.g., bacteria, plants, animals) and react to changing environments.
- **Native AI-capable devices.** To improve performance of IoT-related data processing and decision making, developing devices with novel processing capacities is key. In particular, advancements in AI specialised processors are required. Good progress has been made toward processing units capable of performing machine learning and deep learning tasks at the edge. Current research shows that AI specialised processors can achieve 10 times the performance of GPUs and FPGAs. Still this capacity may not be enough with the increasing volume of data that will be generated and new research developments such as neuromorphic computing should be investigated.

Trust and cybersecurity enabling technologies

- **AI-powered cybersecurity.** Research in cyber security explored supervised and unsupervised machine learning methods such as Random Forest (RF), SVM (Support vector machine), decision trees (DT), k-nearest neighbour (KNN), k-means, Principal component analysis (PCA) and association rule (AR) algorithms have been widely adopted in cyber security. Their ability anyhow to detect an attack is strictly related to the attack patterns identified in the past. More recently, initial attempts to leverage deep learning and reinforce deep learning provided interesting results in the identification of IP Spoofing and DDOS. Such methods seem promising since they have been able to recognize attacks that were not showing similarities with previous attack patterns. Research in this direction is key to increase resiliency of IoT platforms in the cloud-edge continuum. Nevertheless, the use of machine learning and AI in cybersecurity implies also a need for dealing with the vulnerabilities of AI systems e.g., a need for protecting them from popular attacks against AI systems such as data poisoning and evasion attacks.

- **Data traceability and trust in the cloud-edge era**. Data traceability is a key step to increase trust over data. In particular, taking into account security concerns linked with IoT devices, the tracing provenance of data and the usage of solutions that guarantee that data have not been tampered is essential to increase trust toward IoT systems. Distributed ledgers are becoming the reference solution for data traceability in different scenarios, including, for example food provenance and circular economy. While distributed ledgers have been applied to IoT to increase trust, current protocols are still limited in terms of scalability when it comes to large scale sensor networks. Higher scalability of consensus protocols are needed in the cloud-edge era. Different solutions are promising, including the ones explored by EU initiatives such as IOTA, and mixed approaches that combine ledgers with DHT overlays (e.g., Chord, Pastry, and Tapestry).

2. IoT AND EDGE COMPUTING IN KEY APPLICATION AREAS

The following key application areas demonstrate the potential and opportunities that emerge from the convergence of IoT and edge computing both from the point of view of European competitiveness and from the potential impact of the technology in the specific verticals.

Engagements with representatives from the areas have revealed challenges and barriers, but also identified priorities and propose actions to overcome these and realise the opportunities, which the shift to the edge brings to Europe.

This section presents a short overview, based on the presentations during the NGIoT workshops on IoT and Edge Computing in the application domains:

- Manufacturing,
- automotive industry,
- smart energy,
- smart health,
- agrifood and farming,
- smart cities and communities

These workshops were organised in Spring 2021, enriched with interviews with a broad range of stakeholders.

IoT and Edge Computing: Manufacturing[40]

Current state, trends & opportunities	Challenges & barriers
Europe's **high-tech industry is declining** as biggest tech companies are located outside the EU. The manufacturing industry has a l**ow cloud adoption rate**, but Europe is **leading in industrial IoT** with high edge potential Edge offers a more **dynamic and efficient** environment with customized applications Security and privacy remain a concern	– **Lack of staff** with the right skills – **Hierarchical silo organization** in traditional industry – High investment **costs** – **Secure data management** – **Connectivity outages** – **Legacy & IIoT infrastructure** – **Key technical challenges** (Local AI model definition; 5G network controller – and TSN network controller interaction; Offloading compute capacity from AR glasses to Edge compute node).

Priorities and actions	Key organisations
Developing the glue between edge and cloud, through an open and secure architecture Investments in future employees/digital skills **Organisational change** for adopting and trusting edge and new business solutions Opening up for **partnerships, adopting open source and strengthening ecosystems**, including collaboration between large industry players and SMEs	– Artemis Industry Association – AIOTI – ROS Industrial Consortium – EFFRA – Productive 4.0 – AENEAS – EPoSS – IoT Forum

40 NGIoT, NGIoT Thematic Workshop: Manufacturing, 2021

IoT and Edge Computing: Automotive Industry[41]

Current state, trends & opportunities	Challenges & barriers
The **transformation and fast growth** are driven by electrification and automation, associated with connected services for telematics, infotainment, and charging. The need for local awareness and real-time decisions **drive data to the edge**. While the American approach relies heavily on cameras, **European actors rely on sensors. Sensor with increasingly complex** data analysis and integration. Local computing power gives greater flexibility resulting in **less data sent to the cloud**, although many services will be connected to cloud facilities, at the same time. This requires new ways of orchestration to address data flows across the computing continuum (cloud – edge – IoT). Currently there is a widespread support of **standards like C-V2X, given Interoperability** of subsystems is crucial for the main functionalities. Edge offers opportunities for **real time** solutions, but the full potential of autonomous vehicles remains untapped, with European players at the vanguard, bringing new **HW opportunities**.	– Increased **complexity**, thus costly. **Reliability** is a challenge – **Interoperability** of subsystems in the cars – **Cross-border** service continuity – Security & Cybersecurity – **V2X** communications – **Power & battery** consumption – **Bandwidth** consumption

Priorities and actions	Key organisations
Move to **intelligent sensors. Integrate** car applications and sensor information. **Connectivity** up to the higher-level Edge infrastructure. Cloud infrastructure for **Over the Air** functionality updates. Move from HW applications to SW platforms. Faster **innovation cycles**. **Integration** with other sectors, such as energy. Partnerships and a strong **value network**	– ACEA – CLEPA – EATA – ERTRAC – ERTICO – C-Roads – CAR 2 CAR

41 NGIoT, NGIoT Thematic Workshop: Automotive Industries and Mobility, 2021

IoT and Edge Computing: Energy[42]

Current state, trends & opportunities	Challenges & barriers
Energy is a critical infrastructure. It is also a key sector to progress towards the green transition. Affordable implementation of the Green Deal requires an integrated approach over energy carriers, sectors & governance levels. IoT and Edge are important enablers. Currently, attempts are made to enable SCADA systems and connect them to the Cloud. With this approach, most of the logic still sits within large controllers, now supported by some further intelligence in the Cloud. Decentralisation of the Energy system is driving intelligence, needed for the market & system operations, to the edge.	– **Scalability** (harmonised penetration across Member State) – **Interoperability** – **Security & confidentiality** – **Reliability** – **Trust:** Data at the edge requires trust: The customer will have to be in control over his/her data representing his/her role & responsibility in the future energy system

Priorities and actions	Key organisations
Sustainability: Intelligently integrating distinct and distributed energy sources, and components using AI, IoT, Edge, Fog, Cloud computing, ensures flexibility to balance very large shares of renewables - and obtain substantial reductions in **CO_2 emissions.** The role of Cloud - Edge architectures and 5G is crucial to offload computationally intensive operations to the Edge instead of the Cloud, allowing services like **transactive energy** approaches, which are the future of renewable **integration to the grid**. Cloud-Edge architectures with 5G communications empowers blockchain-powered energy networks. Digital twins could be used for mitigation issues: lower communication latency, faster development lifecycle (faster evolution of services), increased resilience, local data keepers. **New partnerships** are needed, **adoption of open source** and strengthening the ecosystem, including collaboration with SMEs	– EERA – ERA-Net SES – EURAC – COGEN-Europe – European Energy Forum – AIoTI **Relevant H2020 Projects** – StoRIES

42 NGIoT, NGIoT Thematic Workshop: Energy, 2021

IoT and Edge Computing: Smart cities & communities[43]

Current state, trends & opportunities	Challenges & barriers
Edge as post cloud and multitenant technology, combining various data streams into personalized solutions for citizens Edge as a way to create inclusive and sustainable cities European ambition to deploy	– **Trust** (by end-users) – **Security** and **privacy** – Lack of **interoperability** – Vendor **lock-in** – **Scalability** – **Inclusiveness**

Priorities and actions	– Key organisations
Embedding edge in cloud strategies Micro edge Swarm computing Shift to edge computing is a pathway to the green digital transformation of cities and communities Partnerships across the demand and supply side Open source adoption	– OASC – EUROCITIES – ENoLL – Artemis Industry Association – EPOMM – ELTIS – UTA – IoT Forum **Relevant Movements** – Living-in.EU **Relevant H2020 Projects** – AURORAL – dRural – JPI Urban Europe – CIVITAS – SmartEnCity – SMARTER TOGETHER

43 NGIoT, NGIoT Thematic Workshop: Smart Cities & Communities, 2021

IoT and Edge Computing: Agrifood & Smart Farming[44]

Current state, trends & opportunities	Challenges & barriers
Deploying IoT in the agri-food sector has proven to be **difficult despite market demand**, and the large number of **use cases** that would benefit from IoT. A successful digital transformation of the agrifood sector should include an **inclusive** approach to realise new scenarios from **farm to fork**. Acquired data can be transformed into knowledge that will facilitate control of farming activities (e.g. **health control, feeding, growth**) as well as enable an autonomous control of processes and activities along the **agri-food chain**.	– Widespread **Connectivity** – Trust – Security and privacy – **Mindset and culture** – Battery lifetime – **High upfront costs** – Accuracy of sensors – Fragmentation – **Investments have long payback periods, low profit margins**
Priorities and actions	**Key organisations**
Support for **digital innovation** through experimentation can guide the way towards a sustainable **integration** of Edge IoT in the supply chain from farm to fork There is a need for initiatives that create **trust and change culture** (demand side) The transformation of the agriculture sector calls for an inclusive, **partnership approach** and for interactions with and learning from experiences of other sectors in particular smart cities and communities (including **rural development**), logistics, the food industry, meteorological services and retail.	– CEMA – ECPA – CELCAA – COCERAL – COPA-COGECA – EFFAB – Euroseeds – FEFAC – EIP-Agri – AEF **Relevant H2020 projects** – Smart Agrihubs – IoF2020 – AGRICORE

44 NGIoT, NGIoT Thematic Workshop: Agrifood and Rural Communities, 2021

IoT and Edge Computing: Smart Health[45]

Current state, trends & opportunities	Challenges & barriers
Integration of IoT into the healthcare domain is **accelerating quickly**. Most patient interactions involve the use of medical equipment and devices. IoT brings visibility for healthcare professionals what is happening in such systems. EU has been updating its regulations of medical devices.	– Legal and regulatory compliance with the **GDPR** – Lack of **interoperability** – Connectivity – Trust – Security and privacy – **High costs** for research and development

Priorities and actions	Key organisations
A major priority for the eHealth domain is to **ensure data privacy and protection by design** and regulatory compliance (GDPR, NIS, ePrivacy). User **acceptance**, including by users with disabilities is another key requirement, which will require developing new pilots and adequate methodologies for **end-user engagement** in the research process. **Standardization and interoperability** are priority objectives to be addressed.	– MedTech Europe – EIP on AHA – ECHAlliancere – HL7 – AIOTI – IoT Forum – ECCP **Relevant H2020 projects** – GATEKEEPER – ODINS

45 NGIoT, NGIoT Thematic Workshop: Health and Care, 2021.

3. CROSS-CUTTING BARRIERS AND MEASURES TO OVERCOME THESE

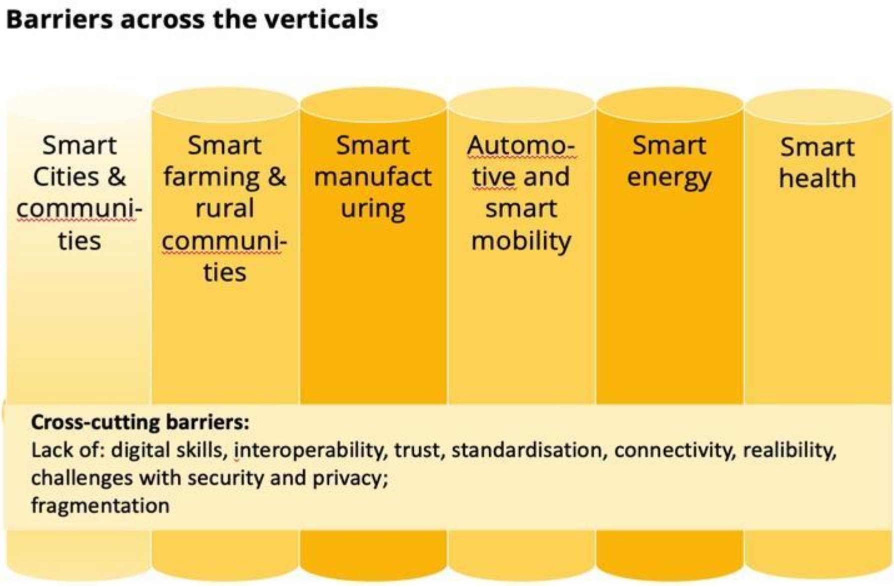

Fig. 10. Cross-cutting barriers

3.1. Safety and security[46]

Safety and **security** are two crucial aspects in the development and use of the aforementioned technologies. In Europe, the discussions around the ethical aspects, especially focused on the AI are still open and constantly discussed. In April 2019, the AI-HLEG[47] issued specific "*Ethics Guidelines for Trustworthy AI*" that explain what is necessary to conceive and develop an AI system respecting actual ethical principles, amongst the others underlying the importance of **technical robustness and safety**, since it must be assessed whether an AI, an edge and/or a cloud-based system may create **adversarial**, **critical** or **damaging effects** (e.g., to human or societal safety) in case of risks or threats to its robustness and safety. Systems and data can also become corrupted by malicious intention or by exposure to unexpected situations.

- Insufficient security processes can also result in erroneous decisions or even physical harm. For AI systems to be considered secure[48], possible unintended applications of the AI system (e.g. dual-use applications) and potential abuse of the system by malicious actors should be considered and a specific prevention plan adopted.

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46 The challenges and barriers 1-8 were identified in the SRIA 2021: https://aeneas-office.org/wp-content/uploads/2021/01/2021_ECS-SRIA-final_1501.pdf

47 The High-Level Expert Group on Artificial Intelligence (AI HLEG) is a group of 52 experts to advise on the implementation of the European Artificial Intelligence Strategy, launched in 2018 by the European Commission. The group members were selected following an open selection process and are representatives of the academia, civil society and industry.

48 See e.g. considerations under 2.7 of the European Union's Coordinated Plan on Artificial Intelligence.

- In order to ensure safe systems a crucial role shall be played by an **insurance system** created in analogy with the existing insurance systems[49].
- With the purpose of enhancing the sense of safety and security, different solutions have been envisaged and discussed in the NGIoT framework, such as: the adoption of new technologies following a **"Human law by default" approach**[50], the development of a **"Labelling Interface approach"** when describing the functionalities - including the privacy and security risks to which a human can be exposed to - of a system.

3.2. Data protection by design and GDPR compliance

Emerging technology in the ICT domain have the legal obligation to comply with article 25 of the European General Data Protection (GDPR) regulation and abide to privacy by design and by default approach. Similarly, Data Protection Impact Assessments (DPIA) are often mandatory. In such a context, all research projects shall dedicate specific effort to comply with the regulation and the data protection by design requirements.

The most important measure in the IoT field is to properly address the data protection by design and by default principle according to Article 25 of the GDPR. This provision, read in conjunction with Recital 78 of the GDPR, determines that producers of products, services and applications based on the processing of Personal Data or which process Personal Data to fulfil their task, should be encouraged to consider this principle when developing, designing, selecting and using these products, services and applications, so to comply with the GDPR.

Recital 78 of the GDPR combines the development and design of products and services with the principle of accountability of the Data Controller or Data Processor who uses those technologies. Thus, compliance with the principle of data protection by design should be considered a criterion for **assessment of the Data Controller or Data Processor's liability**.

In this legislative scenario the development and use of AI, IoT, edge and cloud-based devices in different contexts shall be realized in compliance with the privacy by design principle. The use of the aforementioned devices is not new, but makes the data subject's **control over his/her own personal data** more complex[51].

As such, the major areas which must include the protection of Personal Data by design are, essentially, the following two: i) obligations related to **security**; ii) obligations related to **Data Subjects' rights**. In that sense, products, services and applications should include, ex ante, technical and organisational measures which ensure a **level of security adequate to the risk of the processing** which will be carried out with those products, services and applications (Article 32 GDPR).

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49 See for more insights "9.4 Product Liability Directive (hereinafter also "PLD")" in "End-user engagement and trust building report". L. Bolognini et al. Page 102.

50 See "4.3 Human Law by default (adoption of a code)" in "in "End-user engagement and trust building report". L. Bolognini et al. Page 34. "in "End-user engagement and trust building report". L. Bolognini et al. Page 34.

51 Article 4.1 GDPR states that "[...] 'personal data' means any information relating to an identified or identifiable natural person ('data subject'); an identifiable natural person is one who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person;".

3.3. Lack of trust in IoT

Cloud, edge, IoT technologies are facing growing concern from end-users with regards to their privacy. Beyond the end-user acceptance, the regulatory framework, including the GDPR, NIS directive and alike, are forcing emerging technologies to comply with privacy and data protection by design requirements, which constitute a research domain per se.

The **respect of privacy** and the **transparency in the processing** are crucial to enhance the **trust** that may lack in the use of technologies whose main feature is a black-box processing, or a processing so complex to become not easy to understand by the users (and neither by the developers!).

One of the main elements that can ensure the individual's trust is the opportunity to **know the process and to intervene in it** without losing control over the system.

An opportunity to ensure and reinforce a trusted IoT ecosystem is given by the provisions of the GDPR, especially with its focus on the **lawfulness**, **fairness** and **transparency** towards the data subjects[52]. Being the IoT ecosystem characterized by a constant and extended involvement of data coming also from subjects that can be different from the Data Subjects (as defined in the GDPR provisions), it is important to ensure a **protection** both for them and the individuals "outside" the system, but always part of the processing. This protection may derive from the application of the article 4(1) GDPR[53], which defines the meaning of "personal data", supply the legal instrument able to create a system in which the end-users, the data subjects and the external people involved can be protected by the provisions contained in the GDPR.

In the IoT, edge, cloud-based environments the human is becoming "factorized" regarding **education** could be a solution in order to **empower end-users without factoring them**. In fact, to increase awareness between individuals involved in the IoT ecosystem, it is necessary to create an environment that they can consider "safe" and "manageable". These two purposes could be reached through effective **training** and **education**.

Education and the development of skills in using IoT also increase end-users' awareness of their rights relating to the use of these tools. In particular the **knowledge of the rights** relating to data protection and the technical implementations that these rights involve, push manufacturers' attention to IT security in order to protect end-users from possible violations.

It is important to underline that the way in which personal information is managed may affect not only the data subject who is using the device, but also the **rights of third parties**, which are observed and recorded by the device. So, future investments and trends of these technologies shall always more consider the direct and indirect impacts on them too[54].

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52 Article 5.1 a) GDPR.

53 Article 4.1 GDPR states that "[...] 'personal data' means any information relating to an identified or identifiable natural person ('data subject'); an identifiable natural person is one who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person;".

54 For more, see also "2.1 IoT developments: why privacy and trust?" in P. Annichino et al. "Privacy and Trusted IoT Observatory Report". Page 10.

3.4. Interoperability

The absence of Interoperability is across all domains pointed out as one of the major barriers for the advances of IoT and Edge computing. Fragmentation, and the lack of standards discussed below are related to this.

There is an increasing need to build data ecosystems, where data can be exchanged and combined and move across the various domains. Several initiatives try to address and overcome the challenge of interoperability: Living-in.EU, co-led by the global network Open & Agile Smart Cities (OASC), have adopted OASC's Minimal Interoperability Mechanisms (MIMs) as the technical foundation for the European "MIMs Plus" technical specifications. The MIMs are universal tools for achieving interoperability of data, systems and services across the demand and supply side, ensuring minimal but sufficient system interaction, integrity and impact. Implementation can be different, as long as crucial interoperability points in any given technical architecture use the same interoperability mechanisms. The MIMs are vendor-neutral and technology-agnostic, meaning that anybody can use them and integrate them into existing systems and services. Also, under the umbrella of Gaia-X, a German-French initiative, work is conducted to push for interoperability Project GAIA-X' as the cradle of an open, digital ecosystem where data can be made available, securely collated and shared while enjoying the trust of its users. For edge in particular, interoperability is a matter of avoiding fragmentation and overcoming the proliferation of different approaches at the infrastructure / orchestration level.

3.5. Standards

The cloud, edge and IoT providers and procurers adopt and follows global standards, rather than regional or national ones. This is also the case for the European market. These so-called "de jure" global standards, linked to the WTO system (governing world trade), are impactive in Asia and America too, where most network equipment is produced. While maintaining a crisp and up-to-date Rolling Plan for ICT Standardisation[55], European research and innovation should strengthen its presence in global Standards Development Organizations (SDOs) in order to influence those de jure standards. At the same time, there's a need to recognise the shortcomings of the traditional SDOs and embrace open source and other ecosystem-based for a with strong governance models which tend to create de facto standardised components for both software and hardware in a way that is both more agile and more inclusive. The two approaches both need a clear strategy and related European investments, based on key ecosystem organisations, in order to reduce reliance on proprietary specifications at the intersection between systems as well as in systems with the need of robust audit and accountability.

3.6. Connectivity

IoT is dependent on the availability and affordability of connectivity and investments from the EU side are needed to ensure that connectivity is available and accessible for all EU citizens.

To move connectivity to the next level, protocols need to be made **interoperable,** foster the implementation of **systems of systems and** taking into account **security. Currently** connectivity

55 EU Rolling Plan for ICT Standardisation: https://digital-strategy.ec.europa.eu/en/policies/rolling-plan-ict-standardisation

protocols can be intelligence-agnostic, but with the shift from cloud to edge connectivity protocols need to embed intelligence to make the interactions between the far edge and the devices more effective. Challenges that lay ahead for future `intelligent´ connectivity side protocols for devices

- Embedding intelligence effectively
- Interoperability (heterogeneous protocols
- Trade-offs (distributed computation vs transmission)
- Security (processing vs transmission)

With proper connectivity side protocols, the Far Edge will be the enabler of AIoT.

3.7. Specialised staff and digital skills

The lack of qualified people is a challenge across all sectors in Europe. Initiatives that ensure capacity building in emerging technologies in the industry, SMEs and the public sector as well as specialised education at all levels are crucial for Europe's competitiveness and for ensuring that European key industry can continue to grow and stay competitive.

4. OPEN EDGE ARCHITECTURES AND (META)OPERATING SYSTEMS: PERSPECTIVES

Data is increasingly processed close to where the data is generated: at the Edge. This move from Cloud to Edge requires a paradigm shift at different levels of today's distributed - but still cloud-centric - architectures. Today's cloud-edge paradigm is focusing on bringing data from the edge to the cloud where the edge and the cloud are under a single domain governance. Available multi-cloud solutions are indeed already able to support the orchestration of such distributed architectures (despite having a limited automation capacity). This is anyhow not corresponding to the actual business ecosystems that provide data and resources essential to applications built on top of such cloud-edge systems. For cloud-edge systems architecture to reflect the business ecosystems a shift toward decentralisation of governance (of resources and data) is needed. In this sense rather than centralized orchestration, future architectures should enable collaboration between data and resource providers based on minimal but sufficient interoperability.

Swarm computing provides a solution for such a challenge by enabling decentralised and context-aware collaborative governance not only for computing but also for intelligence. The creation of a cloud-edge system requires a plethora of resources in different parts of the Internet: network, computing, data and others. Thus each “node” taking part in such a cloud-edge system needs to expose the different resources it owns, so that other nodes know what’s available and how to interact with what’s available, resembling what an operating system does. Clearly such mechanisms can reach a critical mass only if standardisation – de jure or de facto but in any case open and well-governed from a European perspective – and open solutions will play a key role, especially with regard to the “collaboration” protocols and the resource interaction.

5. OPEN PLATFORMS AND OPEN SOURCE

Open source enables open innovation and open collaboration and creates a huge opportunity to strengthen European leadership in IoT and Edge Computing. The potential for European leadership is highly connected to the capability of developing and promoting open source, industry-grade software platforms as those platforms allow research organisations, SMEs, and large organisations, to collaborate on core technologies and leverage those technologies to support their researchers, or to enter the market with innovative products built on top of the platforms. Figure 1 below shows how this approach has been formalized and implemented by the Eclipse Foundation, especially in its IoT, Edge Native and Sparkplug working groups[56]. Together, they regroup 50 projects and over 55 member organizations.

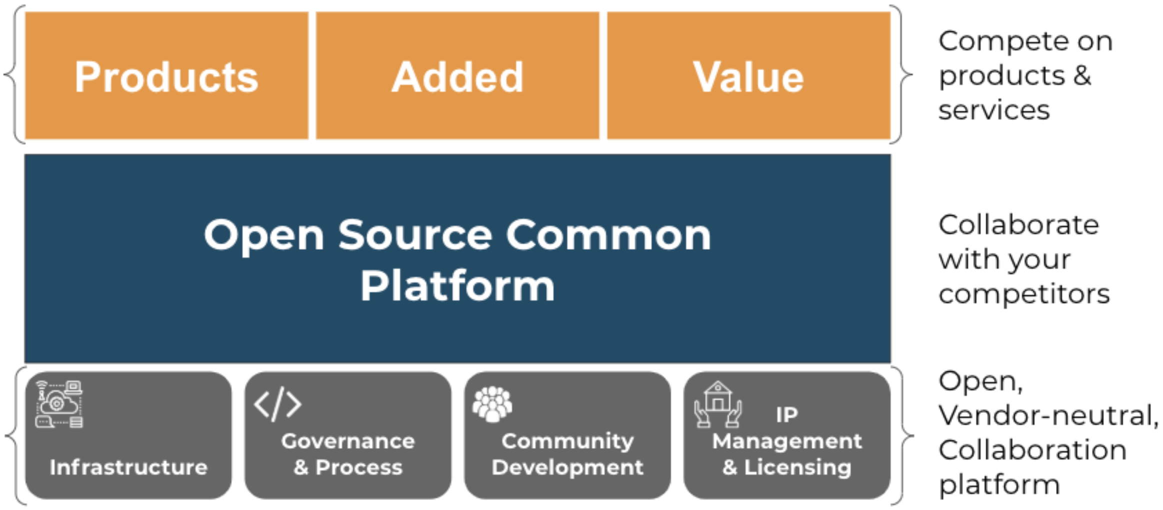

Figure 11: The open source approach of the Eclipse Foundation: Collaborate on platforms / Compete in products

Open source is specifically adapted to the challenges of IoT and Edge Computing as it enables scalability and interoperability, fosters collaboration and adoption, and creates trust. Scalability and interoperability are two characteristics of open source platforms that result from the core characteristics of the openness, royalty free licenses, and of the capability of studying code that ensures better interoperability. Open source is also an accelerator of adoption as developers can use new open source technologies and build prototypes without restriction. Finally, open source is an enabler of trust as it is possible to inspect the code in order to check its characteristics regarding security or privacy constraints.

It is worth mentioning that the 2019 Eclipse IoT Commercial Adoption Survey[57] found that the top three reasons mentioned by the participants to adopt open source technologies were control, cost and flexibility — in that order. Given the rigid constraints that most IoT and Edge Computing solutions have

56 Eclipse Foundation. IoT Commercial Adoption Survey 2019 Results, 2019

57 http://eclipse-5413615.hs-sites.com/iot-adoption-survey-results-2019

to operate under, it is not surprising adopters value the control open source technologies grant them.

Open Source platforms and open standards are global, and Europe, especially with the support of the strong European research ecosystem, can lead the charge in developing and promoting such Open Source IoT and Edge Computing platforms and standards, thus developing the skills and excellence and ensuring European leadership in the domain. Figure 2 shows key open source projects from the EdgeOps ecosystem where projects marked with the European Flag are mainly developed in Europe.

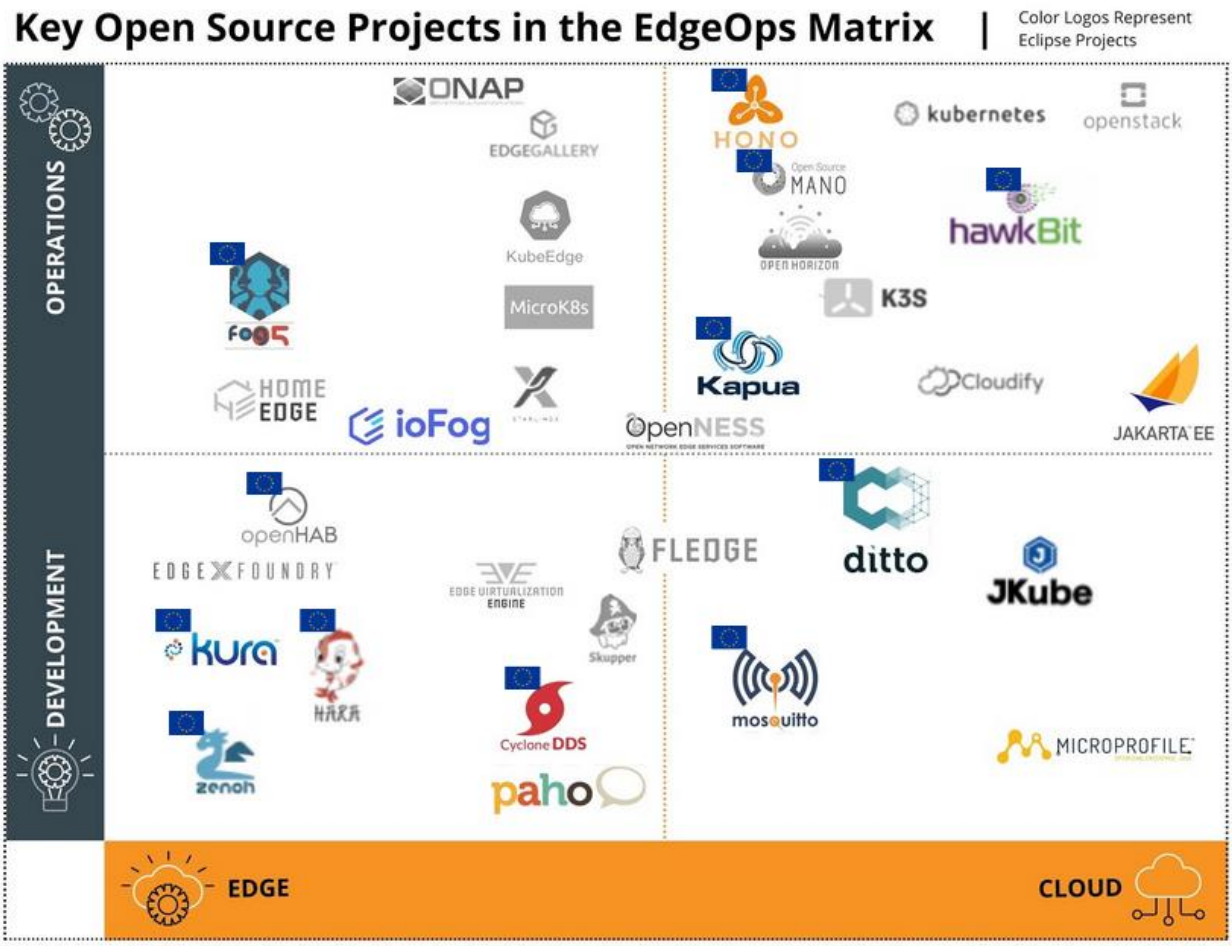

Figure 12: The Eclipse EdgeOps Matrix: Color logos represent Eclipse Projects / European Flag denotes projects mainly developed in Europe

This availability of open source technologies will allow various actors, including SMEs, to create products and solutions and enter the market with a strong competitive advantage if the underlying open source platform is widely adopted.

Recommendations

There is a need to develop open source IoT/Edge platforms that are more ubiquitous, pervasive, scalable, autonomous, light and sustainable. Here are a few recommendations for a more effective use of the open source collaboration model:

- “Don’t reinvent the wheel”: New research projects should use/extend/adapt existing open source platforms when they already exist
- Re-starting a new open source platform from scratch should be motivated by positioning this new open source platform regarding to the existing ones, and explaining why this new platform is needed and why the requirements it covers can not be addressed by contributing or extending an existing platform
- This approach will enable the creation of research platforms that are sustainable, reused and extended by the contribution of several complementary research projects and that have more chances of being adopted by the industry.
- Doing proper open source is more than publishing code: Open Source governance, Open Source IP management, and community development require significant expertise and effort. Research projects should involve experts in these domains, either independent, or affiliated to an open source foundation, to avoid the pitfalls of a naive approach of open source.
- Successful open source does not come for free. Europe (the EC) should invest in training and education for implementing open source platforms to strengthen the European open source ecosystem and foster uptake of open source strategies/business models. This should be integrated deeply into the European research agenda.

6. FROM VALUE CHAIN TO VALUE NETWORK

Europe has the stakeholders to cover the various roles in the value chain: the technologies, business models, managerial skills and operational rules to create IoT solutions and go into a global market. The landscape is and will stay fragmented and, thus, European actors should join forces and collaborate to realise the potential the seismic shift offers. Opportunities are currently mostly linked to industrial IoT, and smaller entities can gain advantage by positioning themselves where there are strong ecosystems, but a different approach to the traditional value chains is needed, as the linear way of seeing the chain is not enough anymore. As mentioned, above, Innovative SMEs can enter the market through open platforms and through investing schemes. Large industry players should reach out to SMEs, which often are innovative, to establish collaborations between them and with their typical competitors, under agreements and schemes like open-source developments, to allow for greater innovations to happen and help the creation of new ways of value creation

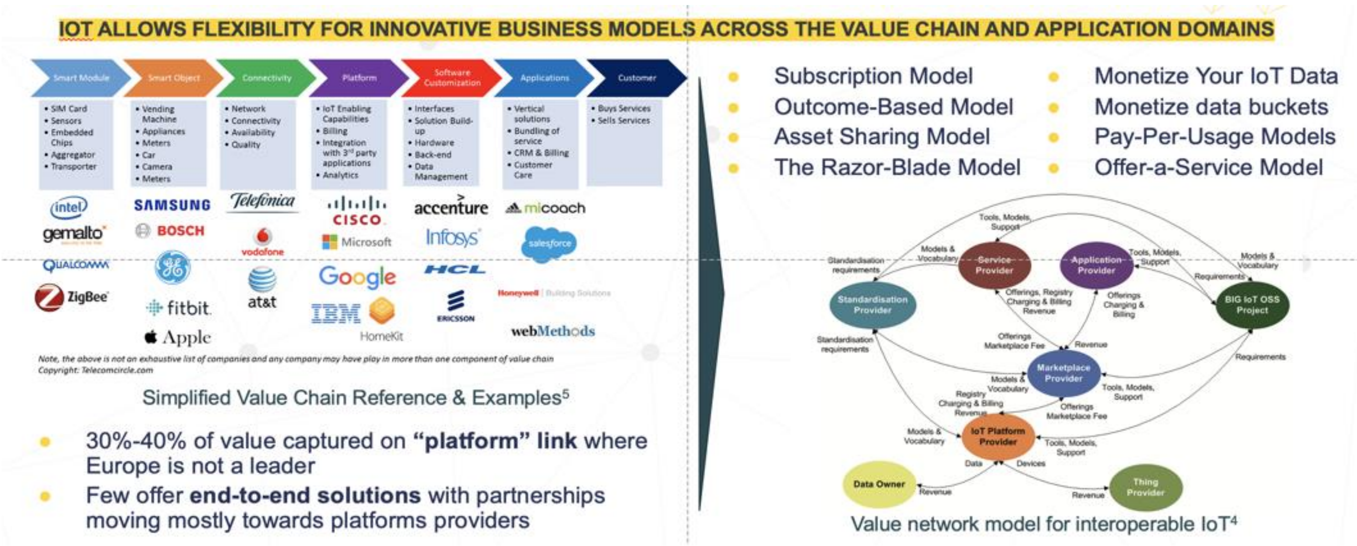

Fig.13 IoT: Innovation business models across the value chain[58]

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58 Schladofsky et al., Business Models for Interoperable IoT Ecosystems, 2016 & https://www.telecomcircle.com/2016/05/internet-of-things-business-models

7. RECOMMENDATIONS AND NEXT STEPS

In the Horizon Europe work programmes for 2021-2022 recently launched, the European Commission defines a number of priorities related to the transition from Cloud to Edge. In the short term, the EC research agenda focuses on: “meta-operating” systems able to orchestrate distributed resources across the cloud-edge to bring computation to the data, low-power and sustainable computing at the edge (2021) and on the role of AI in the continuum (2022), both as cloud-edge automation enabler, and as intelligence application enabler. As regards the medium term (2023-2024), priorities would be around investigation of sector specific platforms and ecosystems, and coordination of decentralised intelligence at edge.

Based on the community feedback received, it is clear that the upcoming work programmes should onboard as well the following priorities - that are not clearly addressed currently - to ensure a rapid development of cloud-edge solutions and ecosystems in Europe:

- Go beyond “meta” Operating Systems. ROS are quite mature examples of “meta” operating systems, lacking though the integration of dev-ops approaches and tool support of modern cloud native technologies. The real challenge today to enable the cloud-edge continuum, is in the scalable distributed/decentralised management of resources and services and their optimization in the cloud-edge continuum to comply with different functional and non-functional requirements. In this respect, the short term research should focus on semi-autonomous orchestration and coordination mechanisms on top of abstraction layers that simplify the interaction with heterogeneous resources. In the longer term, AI may increase the levels of autonomicity and facilitate the move from centralised orchestration toward decentralised coordination.
- Increase emphasis on AI and hardware convergence. The role of microprocessors is essential to enable AI at the edge while ensuring energy efficiency. With major producers being nowadays located outside Europe, it is essential to increase the EU capacity on this front with focus on AI, rather than dispersing resources on multiple areas of specialisation. In the longer term the focus should be on bringing neuromorphic computing based PU to the market.
- Go beyond state of the art data processing architectures for IoT. In the short term research should focus on enabling distributed/decentralised AI and ML tasks leveraging today's state of the art: i.e., supporting distributed / decentralised AI pipelines and AI model training, while increasing through devops approaches the level of automation. In the short-medium term, research should focus on novel approaches to reduce computational requirements of computing and executing AI algorithms. In the longer term, research should look into disruptive approaches that will handle barriers of today architectures. This research is instrumental for the realisation of EU Data Spaces as envisioned in the EU Data Strategy.
- Highlight relevance of IoT in the supporting sustainability goals. While low-power processing and energy efficient data processing are surely essential to ensure sustainability of IoT solutions, more needs to be done in this respect as regards the whole lifecycle of IoT products making them more environment compatible and cheaper to deploy, connect and operate. Research in the longer term should focus on easy to recycle, longer lasting, and more environmentally compatible devices. In the shorter term, research should increase the spectrum of scenarios where IoT is explored as a way to improve sustainability and environmental friendliness of devices.

- Support large deployments of standard and replicable solutions. In several domains, IoT deployments are still at the level of proof of concepts. The lack of large scale deployments is clearly limiting the understanding of requirements to support such deployments in different domains. In the short term, Investments should support large trials in fields not yet covered such as Energy Management, Insurance (IA) and Media, Transportation, and Safety & Defence (RIA). These activities are instrumental for the realisation of EU Data Spaces as envisioned in the EU Data Strategy.
- Increase harmonisation of IoT cloud-edge standards. As off today there are a number of competing initiatives around cloud-edge. While many of them are based on open source, they enforce different “standards” to realise cloud-edge (for IoT), thus increasing the risk of fragmentation and leading to potential interoperability issues. Before the proliferation of standards and open source solutions becomes an actual brake on adoption, it is important to support the harmonisation of existing standards and open solutions.
- Invest on experimental infrastructures to support testing and experimentation of cloud-edge solutions. Developing and testing cloud-edge solutions is clearly more complex than testing solutions for the cloud or on premises. The lack of availability of infrastructures supporting experimentation in the “continuum” may clearly slow down the development and testing of solutions, especially by small players such as SMEs. It is important to build such capacity in the short term, and to maintain it in the longer one, to ensure that EU innovators can be sustained in the access to cloud-edge playgrounds to build, test, and scale their products.

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