D2.2 Research & Innovation Roadmap - b

Revision: v.1.0, submitted 2024-12-19

Work package	WP2	Task	2.1, 2.2, 2.3, 2.4
Submission date	19/12/2024	Due date	31/12/2024
Deliverable lead	RISE	Version	1.0
Authors	Andrew Adams (Meiji), Antonio Álvarez (OpenNebula Systems), Juncal Alonso Ibarra (Tecnalia), Anastasiia Andriievska (RISE), Enrique Areizaga (Tecnalia), Olatz Ibañez (Tecnalia), Valentin Sanchez (Tecnalia), Giacomo Inches (Martel), Anders Lindgren (RISE), Johan Linåker (RISE), Ian Marsh (RISE), Jon Summers (RISE), Alberto P. Martí (OpenNebula Systems), Tajana Medaković (F6S), Sachiko Muto (RISE), Thomas Ohlson Timoudas (RISE), Francesco Panella (Martel), Danijel Pavlica (F6S), Giovanni Rimassa (Martel), Chiara Zincone (OpenNebula Systems), Björn Forsberg (RISE).		
Reviewers	Ana Isabel Torre (Tecnalia)		

Abstract	This document introduces the second version of the research and innovation roadmap for the Cognitive Computing Continuum. It provides an updated analysis of work, roadmaps, research and strategic agendas, and an updated and extended mapping of initiatives to the main topics in the roadmap: AI for the Cloud-Edge, Cloud-Edge for AI, Telco Cloud-Edge, and Cloud-Edge Use Cases. Each main topic has been divided into several subtopics identified as part of this process, and each subtopic is presented with some context and challenges, along with R&D priorities and potential impact.
Keywords	Research and innovation roadmap, Cognitive Computing Continuum

DOCUMENT REVISION HISTORY

Version	Date	Description of change	List of contributor(s)
V0.1	30/06/2024	1st draft version of the roadmap - b	Based on the deliverable D2.1
V0.2	01/08/2024	2nd draft version of the roadmap - b	Thomas Ohlsson (RISE)
V0.3	13/12/2024	Finished draft of the deliverable for review	NexusForum WP leaders, Project Partner experts, NexusForum Working Group Co-leaders
V1.0	19/12/2024	Final version 1.0	Ana Isabel Torre, Juncal Alonso & Enrique Areizaga (Tecnalia), Thomas Ohlsson (RISE)

Disclaimer

NexusForum.EU project is co-funded by the European Union's Horizon Europe research and innovation programme under Grant Agreement number 101135632. This work has received funding from the Swiss State Secretariat for Education, Research, and Innovation (SERI).

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Copyright notice

Project co-funded by the European Commission in the Horizon Europe Programme		
Nature of the deliverable:	R	
Dissemination Level		
PU	*Public, fully open, e.g. web*	**x**
SEN	*Sensitive, limited under the conditions of the Grant Agreement*	
Classified R-UE/ EU-R	*EU RESTRICTED under the Commission Decision No2015/ 444*	
Classified C-UE/ EU-C	*EU CONFIDENTIAL under the Commission Decision No2015/ 444*	
Classified S-UE/ EU-S	*EU SECRET under the Commission Decision No2015/ 444*	

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 2 of 80   © 2024-2026 NexusForum.EU

Executive summary

This is the second public draft version of the Cognitive Computing Continuum Research and Innovation Roadmap for Europe. The roadmap will be released in yet another version close to the end of the NexusForum project, i.e. in mid-2026.

This roadmap identifies several technology priorities for the European Cognitive Computing Continuum, to support the EU Cloud-Edge industry with urgently needed R&D. It complements the industrial roadmaps, innovations, and vision from the EU Cloud Alliance and the new IPCEI-CIS, with a view towards R&D needs in the medium to long term. Appendix A contains a mapping of relevant initiatives that have guided the development of the roadmap.

The roadmap is organised into four main topics, each with its own main section in this document, that are aligned with the four IPCEI-CIS Workstreams:

- **AI for Cloud-Edge**: Orchestration and managing a multi-provider continuum.
- **Cloud-Edge for AI**: Enabling and facilitating AI applications across the continuum.
- **Telco Cloud-Edge**: Telco as the main tenant and implications for infrastructure providers.
- **Cloud-Edge Use Cases**: Requirements from next-generation applications.

These four main topics have been further divided into several subtopics, and each subtopic is presented with some context and challenges, along with R&D priorities and potential impact. The main subtopics identified can be summarised as follows:

- **AI for Cloud-Edge**:
  - Cross-layer optimisation in a multi-provider Compute Continuum.
  - Large Language Models and AI for debugging and root cause analysis.
  - AI for an energy-efficient, carbon- and energy-grid-aware Compute Continuum.
  - Efficient resource allocation for "continuum-native" workloads.
  - Stateful serverless computing for the Compute Continuum.
- **Cloud-Edge for AI**:
  - Integrating (Euro) HPC in the Compute Continuum.
  - Integrating RISC-V hardware in the Compute Continuum.
  - Open compiler infrastructure and lightweight virtualization/container technologies for heterogeneous hardware.
  - Federated computation for Foundation Models.
  - Confidential computing and data privacy & security.
  - LLMOps and GenAIOps.
- **Telco Cloud-Edge**:
  - Open radio access networks (O-RAN).
  - Resilient on-prem 5G/6G edge-cloud for Industry 4.0 and beyond.
  - AI and Generative AI to optimize network resources and operational efficiency.
- **Cloud-Edge Use Cases**:
  - Software-defined vehicles.

Project funded by

Co-funded by
the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 3 of 80   © 2024-2026 NexusForum.EU

- Decentralized spatial computing for AR/VR technologies.
- Satellite communication for edge applications.
- Cyberspace and physical space fusion.

More details can be found in the respective sections of this document. The roadmap additionally identifies several areas that might be interesting to explore in the context of the Cognitive Computing Continuum and further develop in future versions of the roadmap:

- Neuromorphic computing.
- Quantum computing.
- Space edge.
- Hyper-decentralized edge.

Four key transversal topics that are aligned with focus areas under the Cloud-Edge Working Group of the EU Cloud Alliance, have been taken into consideration in the roadmap, and will be covered in dedicated sections in future versions of the roadmap:

- Sovereignty and Open Source
- Sustainability
- Interoperability
- Cybersecurity

Dedicated Working Groups will be set up as part of NexusForum.EU, corresponding to the main topics and the transversal topics, to further develop and validate this roadmap and engage the broader community in its development. More details can be found in NexusForum deliverable *"D4.1 Engagement & Community Report"*.

Table of contents

© 2024-2026 NexusForum.EU

List of figures

Abbreviations

CPU	Central Processing Unit
CSA	Coordination and Support Action
EC	European Commission
GenAI	Generative AI
H2020	Horizon 2020
HE	Horizon Europe
HPC	High-Performace Computing
IoT	Internet of Things
IPCEI	Important Project of Common European Interest
IPCEI-CIS	IPCEI Next Generation Cloud Infrastructure and Services
ISA	Instruction Set Architecture
LLM	Large Language Model
MS	Member State
Nm	Nanometer
OS	Operating System
OSH	Open Source Hardware
OSS	Open Source Software
OT	Operational Technology
RIA	Research and Innovation Action
SME	Small and Medium sized companies
WG	Working Group

1   Introduction

Cloud and edge technologies are key strategic enablers for innovations and uptake of emerging technologies, such as artificial intelligence, the Internet of Things (IoT), and 5G. As Europe positions itself as a leader in a data-driven society and development of trustworthy AI, the European Union acknowledges the significance of cloud and edge computing in shaping its digital future. This significance is reflected, for example, in the digital targets for 2030 of Europe's Digital Decade policy programme.[1] The European data strategy further underscores this significance and the importance of *"investing in next generation tools and infrastructures to store and process data"* and *"joining forces in European cloud capacity"* to create a single market for data in Europe based on European rules, values and regulations, in particular privacy and data protection.[2] These technologies are key building blocks and enablers of the European *common and interoperable data spaces* meant to overcome legal and technical barriers to data sharing to enable data-driven innovation in Europe at scale.[3]

To address the urgent need to *"support research, development, and first industrial deployment of advanced cloud and edge computing technologies across multiple providers in Europe"*, the Commission approved up to €1.2 billion of state aid for the IPCEI Next Generation Cloud Infrastructure and Services (IPCEI CIS) project.

Similarly, the European Alliance for Industrial Data, Edge and Cloud was set up to strengthen Europe's leadership position on industrial data and support the development of next-generation cloud and edge technologies. It brings together businesses, Member State representatives, and other relevant experts, facilitated by DG CONNECT, aiming to *"strengthen the position of EU industry on cloud and edge technologies"*.[4] The Alliance provides recommendations and investment roadmaps for the development of European cloud and edge.

This critical role of computing technologies for the future of European competitiveness and digitalisation of critical sectors is again stressed in the recent Draghi report.[5] Under the topic of *digitalisation and advanced technologies*, Part B of the report identifies and recommends the following three strategic priorities for the coming decade, cited from the report:

- **High-speed/capacity broadband networks and related equipment and software** (i.e. fixed, wireless, and satellite/hybrid networks) to enable connectivity and distribute secure, ubiquitous and sustainable digital services essential to EU citizens and businesses.

- **Computing and AI**, i.e. infrastructure, platforms and advanced technologies needed to autonomously develop and scale up digital services, enabling companies to innovate, boost their productivity and upscale, notably concerning cloud, high-performance computing and quantum, as well as AI and its industrial applications.

- **Semiconductors**, a key driver and enabler for the electronics value chain, and a strategic element of Europe's security and industrial strength across sectors.

The European Cognitive Computing Continuum encapsulates this vision and convergence of cloud and IoT technologies, to provide a seamless data processing environment integrated with AI technologies across European cloud service providers. The European market and policy context for the computing continuum are presented in further detail in Section 2A

---

[1] *https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en*
[2] *https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-data-strategy_en*
[3] *https://digital-strategy.ec.europa.eu/en/library/staff-working-document-data-spaces*
[4] *https://digital-strategy.ec.europa.eu/en/policies/cloud-alliance*
[5] *https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en#paragraph_47059*

European Perspective: Markets, Laws, and Initiatives. Section 3 presents several trends and European challenges and opportunities for creating the European Cognitive Computing Continuum, which will also be referred to as the *computing continuum*.

This is the second official version of the *European Cognitive Computing Continuum Research & Innovation Roadmap*, and an iteration of the previous draft version of the roadmap from July 2024. The work developing this roadmap was initiated in the winter of 2024 and the project will produce a final version of the roadmap by summer 2026. The process for developing the final version will involve consultation activities to gather feedback from relevant experts and communities.

The analysis of the work, roadmaps, research and strategic agendas, and other relevant outcomes from stakeholders discussed in Appendix A has served to cluster and identify relevant areas of research in the topic of European Cognitive Computing Continuum. To this end, the different initiatives, and the topics of relevance in which these initiatives are working has served as input for the identification of the preliminary subjects to be incorporated into the *Research and Innovation Roadmap*.

1.1   Aims and presentation of this document

The aim of the *European Cognitive Computing Continuum Research & Innovation Roadmap* is to identify research and innovation needs and priorities towards achieving this vision, focusing especially on longer term aspects and bridging industry innovation with lower-TRL technologies and excellent academic research. It is developed as part of the NexusForum.EU project, which is funded by the Horizon Europe programme. The project aims to deliver a strategic outlook on the Cognitive Computing Continuum future, by combining the vision, priorities, and advancements of the IPCEI-CIS and the European Alliance for Industrial Data, Edge and Cloud. On the one hand, the project will produce annual research and innovation roadmaps identifying gaps, opportunities, and international synergies, and on the other it will produce annual research and policy recommendations in key strategic areas. The wider aim of the project is to nurture the European computing constituency, incorporating investors, Member State representatives, and users from different sectors. Finally, NexusForum aims to engage the research and industry ecosystems and relevant initiatives in strategic non-EU countries, with a special focus on Japan and the Republic of South Korea.

The present version of the roadmap is divided into four main sections, categorising research and innovation needs according to different perspectives related to the computing continuum. These sections are based on the priorities and needs discussed above, and are as follows:

- **AI for Cloud-Edge**, focusing on the challenges when federating compute infrastructure and services from European providers, and for ensuring energy-efficient and secure data processing across the computing continuum.

- **Cloud-Edge for AI**, focusing on the needs and requirements for the computing continuum to enable and support the development and deployment of AI technologies in Europe, based on European values of trustworthy and ethical AI.

- **Telco Cloud-Edge**, focusing on the role of telecom networks and operators in the computing continuum, both as a tenant/user and as a service provider.

- **Cloud-Edge Use Cases**, focusing on the needs, requirements, and challenges for critical sectors and next-generation use cases to use the computing continuum and adopt cloud and edge computing technologies.

These correspond, in order, to Section 5 through 8 in this document. Additionally, Section 9 presents several innovative technology areas with potentially disruptive impact on the computing continuum in the longer term:

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 10 of 80   © 2024-2026 NexusForum.EU

- Neuromorphic systems

- Space edge

- Integration of quantum computing infrastructure

- Quantum and classic computing fusion

The document is structured as follows:

- Section 2 presents the European market and policy context for the computing continuum are presented.

- Section 3 presents several trends and European challenges and opportunities for creating the computing continuum.

- Sections 4 identifies transversal topics spanning cross most areas.

- Sections 5, 6, 7 and 8 presents research and innovation needs identified under each main section, divided into several subtopics. Each subtopic is structured in the same way, first providing some context about the subtopic, followed by challenges and R&D priorities identified for that subtopic.

- Section 9 presents several innovative technology areas with potentially disruptive impact on the computing continuum, where we believe Europe could position itself as a future leader.

2   A European Perspective: Markets, Laws, and Initiatives

Europe consists of multiple countries with diverse regulations, languages, cultural contexts and markets. This fragmentation can hinder the development of unified technological solutions and the emergence of a fully integrated European Digital Single Market. Therefore, harmonizing standards and creating interoperable systems across borders is essential for technological sovereignty. Despite significant initiatives at EU level to harmonize regulatory standards,[6] the continent's digital market remains fragmented into local realms, individually lacking the critical mass for players to scale and compete with their American and Asian counterparts.

The report *"The future of European competitiveness"*[7] assesses the current state of European competitiveness, with a particular focus on industrial policy, its caveats and hopes for its future. Due to geopolitical instability, the urge of not depending on other countries is higher, because the EU has realized that dependency easily engenders instability. There has been a shift in paradigm, "The era of rapid world trade growth looks to have passed, with EU companies facing both greater competition from abroad and lower access to overseas markets". Europe must radically change for digitalisation and decarbonisation to take place in the European economy, investments need to rise to 1960s-70s levels.

For growth to take place, three key areas have been identified to close the innovation gap with the US and China, i) activate a joint plan aimed at strengthening competitiveness ii) decarbonising the economy; iii) take action to enhance security, while reducing dependencies on third parties. In particular, three main barriers prevent Europe from growth.

- Market *fragmentation* is high, which in return drives innovative companies away to more profitable continents. Administrative and regulatory burdens within the European Internal Market prevent innovative companies from striving.

- The EU is not taking *full advantage* of its common resources. In the field of innovation, collaboration is weak, despite the known spillover benefits of investing in cutting-edge technologies. Here Draghi gives an interesting figure: the EU´s public sector devotes on Research and Innovation (R&I) as much as the US in terms of GDP share, however, only one-tenth of this spending materializes within the EU.

- Europe does not coordinate on its *industrial strategy*, and its slow and fragmented law-making process hinders the bloc's effectiveness in keeping pace with the rest of the evolving world. Overall, the report aims at delivering action points for a new European industrial strategy that can relieve the Union from these barriers.

If The European Union acknowledges the significance of cloud computing, edge computing, and the Internet of Things (IoT) in shaping its digital future toward a European Computing Continuum Infrastructure.[8,9,10] The European Computing Continuum is one of the essential elements for the digital and green transition to take place within the EU and beyond, and the work of NexusForum serves as a facilitation instrument that on one hand asses the current landscape at the technological, economic and legal levels, and on the other, by engaging internally with academic and technical experts, and externally with industry experts, policy makers and more, it advices the European Commission on how.

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 12 of 80   © 2024-2026 NexusForum.EU

2.1 European market context

Mario Draghi's Report "The future of European competitiveness"[11] mentions the lack of innovation as one of the reasons why the EU´s industry lacks dynamism. More specifically, it argues that this is due to the lifecycle of this innovation, starting from the initial product idea to its commercialisation. First, companies encounter financial barriers due to the quantity and the quality of funding dedicated to high risk, breakthrough, Research and Innovation (R&I) areas. In the EU, the capital market is smaller compared to the one of the US, and the Venture Capital sector is far less developed. Considering the global share of Venture Capitalist funds, the EU only raises around 5% of these, while the US accounts for more than half of them (52%), followed by China with a 40% share. Therefore, companies willing to scale-up in Europe, often seek alternative growth opportunities abroad, in markets where they are able to have more reach and have higher remunerative returns; in response to this, the demand for Venture Capital finance in Europe shrinks, alimenting a vicious circle. As a matter of fact, Europe lags behind in innovative technologies that have the power to drive productivity growth. With regards to the innovative technology of cloud, the numbers are loud and clear: 3 US tech giants ("hyperscalers") account for more than 65% of the total share of the global cloud market.

If new companies emerge in the EU, apart from funding and venture capital issues, they are also faced with regulatory obstacles that do anything but assisting them in the scale-up phase. Because of this, ideas born in the EU are ultimately more inclined to seek financing from US venture capitalists, also because the US market is less fragmented than the EU one. In Europe, there is not enough public spending devoted to breakthrough innovation. The venture capital invested into breakthrough technologies at the very early development stages is 80% lower compared to US levels, and once the developed technology reaches a later stage, the lack of investment compared to the American counterparts reaches peak gap levels (-82%).

Furthermore, out of the total spending of EU governments on R&I, only one tenth takes place at EU level, which means that the EU governments' investments are mostly dedicated to projects outside of the EU, even though the spillover effect that such public investment could have on the private sector is significant. The most prominent funding programme of the EU, Horizon Europe, has an extensive budget but bureaucratic barriers and low focus on breakthrough innovation prevent it from being successful. Indeed, the process of capitalizing on breakthrough technologies is hindered by excessive fragmentation. For example, the EU lacks coordination standards which prevent it from having a real presence in the edge computing field. More start-ups need to scale-up, to enhance the innovation of the European digital landscape. The report suggests that the EU should assist innovative companies by reducing fragmentation. In practical terms, this would mean adopting a new EU-wide legal statute - under the label of "Innovative European Company" - that would equip companies with a single digital entity recognised at supranational level, valid in all the European Member States. In this way, the establishment of subsidiaries across the EU would be facilitated. Companies would be informed about harmonized legislation, especially in the areas of corporate law, labour law and taxation, rendering the whole legal process a positive push rather than an obstacle.

The European Innovation Council Pathfinder[12] is a European initiative that was meant to spur innovation, although it has a lower budget compared to similar initiatives in the US. Furthermore, it has been criticised due to a lack of scientific experts on the board. Draghi cites, Figure 1, in 2021, where the share of GDP spent on Research and Innovation was twice for the US compared to the EU. This gap in innovation is directly linked to the gap in productive

---

[11]https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en
[12] EIC Pathfinder - European Commission

investment between the European and the US economy that is shown in Figure 1. This is again due to lower investments in technological aspects.

Productive investment
Real gross fixed capital formation excluding residential investment, % of GDP
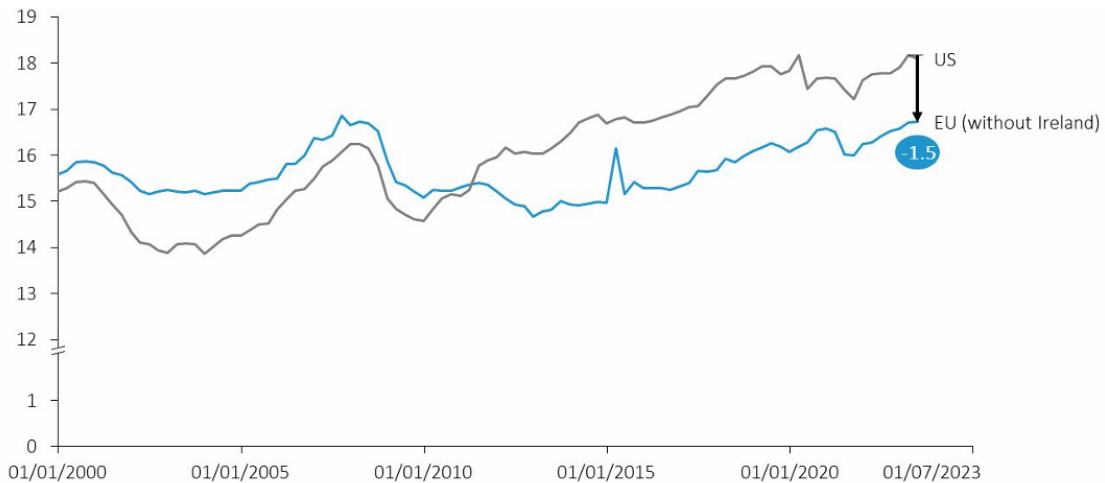
Source: EIB, 2024.

Figure 1 Productive investment over two decades, EIB 2024

Diving deeper into the issue of the productivity gap that exists between the EU and the US, Draghi identifies the tech sector as a key indicator of why this gap exists. Indeed, around the mid-1990s, Europe did not capitalize on the digital age enough. It did not generate equal amounts of innovative tech companies, nor did it let digital technology empower its economy. The result is an ecosystem made of scarce industrial dynamism and low levels of innovation, investments and productivity.

Europe has a strong foundation to build from, but the technical roadmap can only be fulfilled in a receptive EU marketplace and research environment. Therefore, the challenges and opportunities outlined in this roadmap need to be co-addressed across the European economy.

2.2   European legal context

From a European legal context, the digital ecosystem is shaped by several key regulations and initiatives aimed at ensuring a fair, competitive, and secure digital environment. Thus, during the last decade Europe has been developing a regulatory framework aimed at establishing the future European Digital Single Market.[13] Ensuring fair competition and fostering innovation, creating a safer digital space, giving individuals greater control over their data, and promoting digital sovereignty, inclusion, equality, and sustainability are among the primary objectives Europe aims to achieve with this regulatory framework.

Within this context, the European Computing Continuum and its associated activities are playing a crucial role in establishing relevant requirements and guiding the needs for the regulatory landscape. Legislation shapes the European Computing by

- Ensuring robust data protection measures across all stages of data processing.

---

[13] https://www.consilium.europa.eu/en/policies/digital-single-market/

© 2024-2026 NexusForum.EU

- Encouraging the development and deployment of AI systems that are transparent, fair, and accountable.
- Creating a more open and competitive data economy, enabling innovation and collaboration.

These laws collectively aim to create a secure, fair, and innovative digital environment in Europe, balancing the need for data protection with the benefits of data-driven innovation.

The current regulatory landscape in the European Cloud-Edge Continuum is summarised in Figure 2, which shows the timeline and impact of key regulations. These regulations are further described under the figure and can be roughly grouped into regulations aiming to i) create a digital single market in Europe, ii) regulate how data and AI are used in Europe, and iii) safeguard the European digital environment.
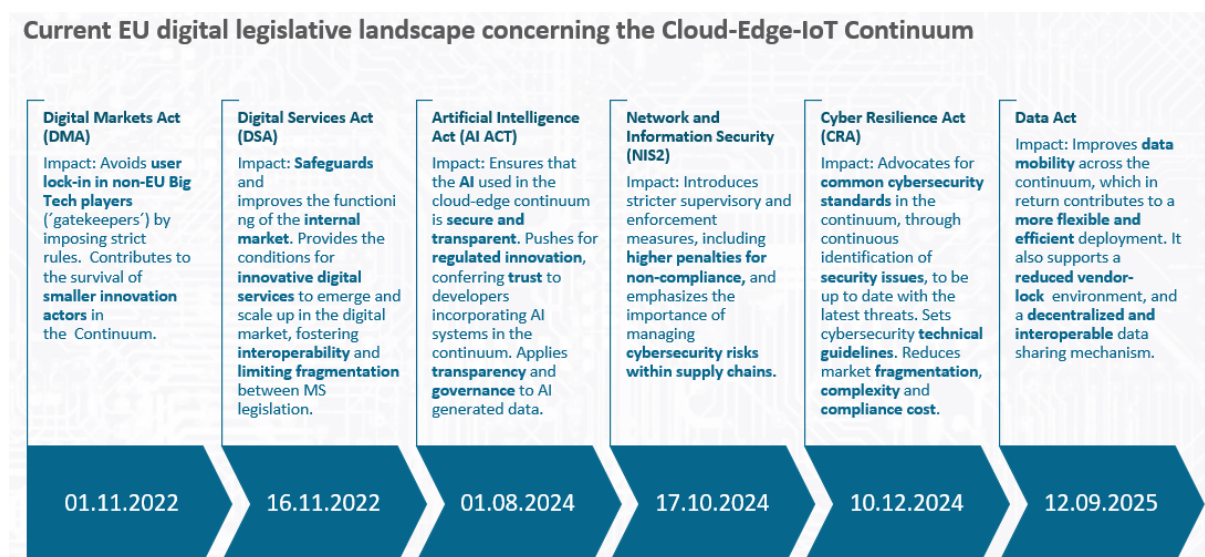
Figure 2. EU laws over time and their impact in the European Computing Continuum.

The Digital Markets Act (DMA)[14] and the Digital Services Act (DSA)[15] are two pivotal regulations in the European Union aimed at creating a fairer and safer digital environment, reducing the dominance of large platforms and promoting a competitive market, enhancing protections for users, fostering a safer online experience and encouraging the growth of smaller companies and startups by creating a fairer market landscape.

A key focus for the European Union is the establishment of a comprehensive legal framework to regulate data in the digital context, ensuring the protection of personal data, promoting fair access, and fostering trust. The General Data Protection Regulation (GDPR),[16] the AI Act,[17] and the Data Act[18] are significant pieces of legislation in the European Union that regulate how data is shared, stored, and processed, and how artificial intelligence (AI) is used within the EU.

Another key objective of the current regulatory framework is to establish a robust system to safeguard the European digital environment. To achieve this, the primary regulations include the Cyber Resilience Act (CRA)[19] and the Network and Information Security Directive (NIS2)[20]

---

[14] *https://eur-lex.europa.eu/legal-content/EN/TXT/?toc=OJ%3AL%3A2022%3A265%3ATOC&uri=uriserv%3AOJ.L_.2022.265.01.0001.01.ENG*
[15] *https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/digital-services-act_en*
[16] *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32016R0679*
[17] *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1689*
[18] *https://digital-strategy.ec.europa.eu/en/policies/data-act*
[19] *https://digital-strategy.ec.europa.eu/en/policies/cyber-resilience-act*
[20] *https://digital-strategy.ec.europa.eu/en/policies/nis2-directive*

aimed at enhancing cybersecurity across the digital landscape. Together, the CRA and NIS2 contribute to a more secure and resilient digital environment by raising cybersecurity standards, building trust among users ensuring the provision of clear information about the security of digital products and services, strengthening incident response capabilities promoting the detection, reporting, and response to cybersecurity incidents across the EU, and encouraging cooperation between Member States and various stakeholders to address cybersecurity challenges collectively. These regulations are crucial for protecting the integrity, security, and resilience of the EU's digital infrastructure and services.

A key policy document when looking more closely at the IoT sector is the Chips Act.[21] The Regulation aims both at monitoring the European semiconductor sector and at supporting the development of *next-generation semiconductor* and *quantum technologies*, thus having a potentially far-reaching impact on the wider IoT technology ecosystem.

In the future, new legislation will also be proposed to address Europe's future challenges in the computing continuum. In her confirmation hearing, Henna Virkunnen, the Commissioner for Tech Sovereignty, Security and Democracy, stated her intentions to progress an EU Cloud and AI Development Act. [22] The Act aims to *"bring this much needed independent computing capacity for our small businesses"*, bridging the gap in data centre premises in the USA and in the EU.

The broader aim of the Act would be to reduce technological dependency on foreign providers. The legislation aims to address the EU's productivity gap like China and the USA[23] by boosting investment in cloud and AI technologies. The spillover effects would be felt by SMEs but also by bigger market players, boosting investments in the subsectors of Cloud and AI, while building decarbonization compliance incentives, to ensure a speedy innovation and green targets can go hand in hand, thus fostering the twin transition objectives as outlined in the Political Guidelines 2024-2029.[24]

2.3 European initiatives related to cloud and edge

European companies need data infrastructure which is in line with European laws and regulations, further described in Section 2.2. The European perspective this far has been on creating data spaces and markets for companies to share data. Reverse chronologically, there are four important data space initiatives: SIMPL, GAIA-X, IDS and FIWARE. Each have their takes with SIMPL addressing edge-to-cloud federations and integrating components and solutions from previous initiatives, GAIA-X with strong focus transnational platforms/frameworks and compliance checking, IDS providing toolkits and APIs, and FIWARE with its context information management for "smart X" applications. In sections 5, 6 and 7 the report will come back to the cloud and edge areas.

To address the technical challenges, the EU has launched several initiatives to develop foundational cloud technologies in Europe, support the development of AI in Europe, and incentivise data sharing between organizations in Europe, some of which are:

- The Important Project of Common European Interest on Next Generation Cloud Infrastructure and Services (IPCEI-CIS), recently approved by the European Commission. IPCEI-CIS is a stakeholder in this roadmap.

---

[21] *Regulation (EU) 2023/1781*
[22] *virkkunen_verbatimreporthearing-original.pdf*
[23] *https://www.usnews.com/news/technology/articles/2024-10-23/eus-tech-security-nominee-to-boost-ai-use-battlefield-technology*
[24] *https://commission.europa.eu/document/e6cd4328-673c-4e7a-8683-f63ffb2cf648_en*

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 16 of 80   © 2024-2026 NexusForum.EU

- The European Alliance for industrial Data, Edge and Cloud[25] financed by EU businesses and Member States under the sponsorship of DG CONNECT. The Alliance is similarly a stakeholder in this roadmap.

- Simpl, an open-source smart middleware platform funded by the European Commission, that enables cloud-to-edge federations for the development of Common European Data Spaces.

These are all expanded on in the bullet points below. Also, Figure 3 illustrates how these initiatives fit together with the overall EU vision for cloud and data.

Figure 3 How different European initiatives and policies related to cloud computing fit together.

Important Project of Common European Interest on Next Generation Cloud Infrastructure and Services (IPCEI-CIS)

At the end of 2023, the European Commission approved the Important Project of Common European Interest on Next Generation Cloud Infrastructure and Services (IPCEI-CIS), the first ever IPCEI focused on cloud technologies; 19 companies from 7 Member States are taking part in it as Direct Participants, with a total of around 100 organizations currently active in this initiative.[26]

The aim of this innovative approach is to foster a multi-provider Cloud-Edge Continuum in Europe, that can create an open environment where data is processed based on a network of interconnected cloud and edge infrastructures.[27] This kind of cloud and edge ecosystem is expected, in return, to contribute to the development of data processing technologies that are federated, energy-efficient and trustworthy, thus touching upon European businesses and citizens through the advancement of the EU's transition towards a green, digital, resilient, secure and sovereign future.[28]

---

[25] *https://digital-strategy.ec.europa.eu/en/policies/cloud-alliance*

[26] *https://competition-policy.ec.europa.eu/state-aid/ipcei/approved-ipceis/cloud_en*

[27] *https://ec.europa.eu/competition/state_aid/cases1/202412/SA_102517_707E5C8E-0000-C216-8C1C-3081176554C2_287_1.pdf*

[28] *https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_23_6246/IP_23_6246_EN.pdf*

European Alliance for Industrial Data, Edge and Cloud

EU businesses and Member States have come together under the sponsorship of DG CONNECT to form the *European Alliance for industrial Data, Edge and Cloud*,[29] an initiative targeting the development and deployment of next generation edge and cloud technologies, willing to empower the EU industry's position in the field, while fostering effective and secure processing of sensitive data across businesses and public administrations.

The EU Cloud Alliance produces roadmaps to identify priorities for co-investment in cloud and edge technologies, providing recommendations on how to implement such investments and finally, it advises legal and commercial conditions for cloud services. Industry stakeholders willing to join the EU Cloud Alliance must be legally based in the EU and must comply with the overall objectives defined by the EC.[30] The work of the EU Cloud Alliance underlines the importance for more technological sovereignty as a crucial approach for the development of a competitive digital European single market.

Simpl

Simpl is the open-source smart middleware platform that enables cloud-to-edge federations and all major data initiatives, in particular the development of Common European Data Spaces in a modular and interoperable way, funded by the European Commission[31]. Common European Data Spaces are a federated data ecosystem based on shared policies and rules. It also works on Data Sovereignty where Data holders remain in control of who can access and use their data, for which purpose and under which conditions. Simpl is made of three parts:

- Simpl-Open: The open-source smart middleware
- Simpl-Labs: The playground environment for Simpl-Open and interoperability test for existing data spaces
- Simpl-Live: instances of Simpl-Open for common European data spaces

The Simpl-Open product will have its first Minimum Viable Prototype (MVP) by the end of December 2024 and will be presented in the first Annual Community Event on January 30, 2025. They are in the phase of continue requirements gathering and their message is "*Reuse if it is available and develop when it is not*". It is possible to contribute to the community at their website.[32]

---

[29] *https://digital-strategy.ec.europa.eu/en/policies/cloud-alliance*
[30] *https://ec.europa.eu/eusurvey/runner/EU-Cloud-Alliance*
[31] *https://digital-strategy.ec.europa.eu/en/policies/simpl*
[32] *https://simpl-programme.ec.europa.eu/dashboard/community*

3   Towards a European Cognitive Computing Continuum

In order to understand what the Cognitive Computing Continuum, also known as the Cloud-Edge Continuum, is, this introduction will present how the technology could be defined. As well as delimiting the scope, the technical topics can fit in below within such definitions. Let us start with how others see the continuum:

The EU H2020 H-CLOUD project states that:

"The progressive convergence between Cloud Computing and the Internet of Things (IoT) is resulting in a Computing Continuum. The multi-faceted concept of Edge Computing first became to represent a middle ground between data centres and IoT hyper-local networks of sensors and actuators"[33]

The Federal Ministry for Economic Affairs and Climate Action in Germany:

"The Cloud-Edge Continuum enables greater adaptability to the specific requirements of an application. It offers both the ultra-low latency and real-time processing of edge technology as well as the scalability and resource diversity of the cloud"[34]

The Compute Continuum can be seen a multi-dimensional manner. One dimension is from a technical prerogative: AI for Cloud-Edge, Cloud-Edge for AI and Telco Cloud -Edge. A second dimension is the Compute Continuum through the lens of Open-Source code, Digital Sovereignty, Interoperability and Cybersecurity, as well as energy consumption. A third dimension is markets, rules, policies and regulation. These aspects are particular to Europe, with its stricter rules on the use of personal information, AI and data. A fourth dimension is the missing components. This deliverable, the roadmap, outlines some of the missing components for Europe to produce a competitive Compute infrastructure.

The "Multi-Provider Compute Continuum" represents a seamless integration of cloud and edge computing. Resources and applications are moved both to the cloud and to the edge of the network. This enables dynamic distribution of data processing tasks as required.

---

[33] https://h-cloud.eu/
[34] https://www.bmwk.de/Redaktion/EN/Artikel/Industry/ipcei-cis.html

Project funded by
Co-funded by the European Union
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI
Page 19 of 80   © 2024-2026 NexusForum.EU

Figure 4: Main dimensions of the emerging Cloud-Edge Computing Continuum infrastructure.

Challenges and opportunities: some important aspects:

- Fragmented datacentre and cloud market (missing segments)

- EuroHPC JU and AI Factories

- Establishment of a European ecosystem based on RISC-V open standard

- Convergence of networking and compute and O-RAN

- Convergence of Operational Technologies and Information Technologies

- Data privacy and access to European data

3.1   Fragmented European Data Centre Market

The three largest data centre markets are North America (36%), APAC (31%) and Europe (22%)[35]. The European data centre market's dynamics differ from others, in part due to the prominence of Internet Exchange Points (IXPs). IXPs play a more critical role in Europe, significantly shaping the structure and development of the data centre market. Europe has a dense network of IXPs that facilitate regional and international internet traffic exchange. Major IXPs like DE-CIX (Frankfurt), AMS-IX (Amsterdam), and LINX (London) anchor Europe's

---

[35] *https://www.precedenceresearch.com/data-center-market*

© 2024-2026 NexusForum.EU

connectivity, which influences the location and concentration of data centres in Europe, particularly in IXP-heavy cities[36].

The European data centre market is fragmented, as evidenced by the diversity of operators and the FLAP-D markets (Frankfurt, London, Amsterdam, Paris, and Dublin) dominate (80% of total power demand in Europe with a recent 17% CAGR and utilisation growing to 88%)[37], other countries like Spain, Italy, and the Nordics are emerging as growth hubs due to favourable regulations, renewable energy resources, and lower operational costs (23% CAGR and utilisation rising to 82%). This geographical diversity demonstrates that no single region monopolizes the market. The fragmented nature of the market allows for competition and innovation but also poses challenges such as inconsistent regulatory environments, varied energy efficiency standards, and differing market maturity levels across regions. This fragmentation requires data centre operators to adopt region-specific strategies and leverage partnerships to thrive. The market is highly competitive without dominant players and 26.68% of the market is represented by five major companies, namely Digital Realty Trust Inc., Equinix Inc., NTT Ltd, SFR and Virtus Data Centres Properties Ltd with other important companies including CyrusOne Inc., Data4, Global Switch Holdings Ltd, Leaseweb Global BV, Stack Infrastructure Inc., Telehouse (KDDI Corporation) and Vantage Data Centres LLC.

The European data centre market is experiencing significant growth, driven by increased demand for digital infrastructure, cloud computing, and data storage solutions. The size of the European data centre colocation market by revenue is estimated to be between $16.99 billion in 2023[38] and $35.46 billion in 2024[39] with a forecasted CAGR of 13.21% (2023-2028) and 10.2% (2024-2029). One report[40] forecasts the market (colocation and more) CAGR to be 26.7% (2023-2028) growing to a market size of $291.7 billion at the end of the period, 2023 - 2028. This expansion is fuelled by rising data consumption, the adoption of hybrid and multi-cloud solutions, and the increasing need for high-performance computing, particularly for artificial intelligence and machine learning applications and to certain extent regularity data sovereignty requirements.

The market size by power (IT load capacity) is estimated to be 12.22 GW as of 2024 and estimated to grow to 17.92 GW by 2029 and dominated by tier 3 data centres (with high redundancy level and multiple paths for power and cooling with an uptime of 99.982% and less than 1.6 hours of downtime per year) and this segment is expected to grow due to the adoption of edge and cloud connectivity. The UK market is the largest and hosts the maximum number of tier 3 data centres with Slough and Greater London holding the major share. However, land prices in London are expected to shift investments to other cities such as Amsterdam with its lowest land price in the FLAP-D market. The Spanish market has numerous third-party data centre projects under construction focussed on Madrid and Barcelona. The lack of land availability and skilled workforce in the FLAP-D hubs is expected to help emerging regions in Italy, Poland, Belgium and Sweden. Sweden's market boasts one of the most connected locations in the Nordic region and the country has adopted the district heat concept for data centres.

---

[36] https://www.cbre.com/insights/reports/european-data-centres-overview
[37] https://www.rolandberger.com/en/Insights/Publications/State-of-the-European-data-centre-market.html
[38] https://www.globenewswire.com/news-release/2024/02/21/2832512/28124/en/Europe-Data-Center-Market-Overview-and-Forecast-2023-2029-Top-Five-Companies-Hold-25.33-Share-Led-by-CyrusOne-Equinix-Global-Switch-Holdings-NTT-and-Vantage-Data-Centers.html
[39] https://www.mordorintelligence.com/industry-reports/europe-colocation-market-industry
[40] https://www.researchandmarkets.com/report/europe-data-centers-market

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 21 of 80   © 2024-2026 NexusForum.EU

3.2   Fragmented European Cloud Market

The European cloud market is fragmented, characterised by challenges in scalability, regulatory diversity, and competition from global cloud providers, particularly the US hyperscalers like Amazon Web Services (AWS), Microsoft Azure, and Google Cloud. Europe accounts for 24.7% of the global cloud computing market in terms of revenue in 2023[41].

However, the investment disparity between Europe and the US in the cloud and ICT sectors, amounting to a significant $1.36 trillion, presents a formidable challenge for European companies striving to remain competitive[42]. To bridge this gap in the next 10 to 20 years, European technology firms would need to dramatically scale annual investments, ranging from $157 billion to $1.2 trillion, equivalent to 0.8% to 6.4% of the EU's GDP. Such a leap would demand substantial resource allocation and strategic prioritisation.

Despite commendable initiatives, such as state aid for R&D in cloud and edge technologies, the current funding levels are far below what is necessary to address this shortfall. This underscores the urgency for Europe to adopt open, inclusive policies that attract global investment and foster competitiveness in an increasingly dynamic and technologically advanced global market[43].

An inward-focused approach to cloud computing and data policies within Europe risks undermining innovation and competitiveness by favouring local champions over accessing global cloud solutions. Such a strategy could reduce market diversity, increase costs, and slow digital transformation across sectors. A more effective approach would involve embracing cross-border cooperation and open market policies. This includes leveraging global expertise while maintaining strong regulatory frameworks to enhance competition, encourage investment, and drive innovation.

The UK's cloud market, though outside the EU post-Brexit, remains an integral part of the European digital ecosystem. It has pursued policies that encourage cloud adoption through initiatives like the G-Cloud framework and a "Cloud First" policy in government procurement. These policies highlight the potential for a dynamic regulatory environment that fosters competition and innovation without imposing restrictive localisation requirements. This model could inspire broader European efforts to maintain global competitiveness while addressing local sovereignty concerns[44].

Meanwhile, in the EU, initiatives like the European Alliance on Industrial Data, Edge, and Cloud focus on technological sovereignty, aiming to localise data storage and infrastructure. While this approach seeks to retain control over critical assets, it faces significant challenges. For instance, purely European providers like OVHCloud and Deutsche Telekom require massive investments to compete with global giants. Similarly, in the UK, domestic players such as UKFast have struggled to scale in the face of competition from hyperscalers like AWS and Azure.

A successful European-wide strategy must emphasize collaboration, enabling cross-border cloud integration, scaling R&D investments, and fostering innovation. Policymakers across the continent, including the UK, should shift focus from catching up with global leaders to pioneering new technologies and services. This would require policies that encourage interoperability, support competitive markets, and prioritise digital transformation over rigid market share metrics.

---

[41] https://www.grandviewresearch.com/horizon/outlook/cloud-computing-market/europe
[42] https://ecipe.org/publications/eu-gap-ict-and-cloud-computing/
[43] https://markwideresearch.com/europe-cloud-computing-market/
[44] https://www.grandviewresearch.com/horizon/outlook/cloud-computing-market/uk

Efforts by EU policymakers to establish a self-sufficient ICT infrastructure, exemplified by initiatives like the European Alliance on Industrial Data, Edge, and Cloud, emphasize technological sovereignty. These policies aim to maintain control over critical infrastructure and data while focusing on localisation for emerging technologies like AI and quantum computing. However, achieving this goal would require enormous resources that could detract from other sectors, as purely European firms face substantial challenges in competing with global leaders. A strong indication of this challenge is exemplified by the fact that European cloud providers have grown their revenues by 167% from 2017 to 2022, but their market share of the European cloud market has declined from 27% to 13% as their growth rate lags the market growth.[45]

It is important to note there are private efforts to build a European cloud infrastructure. Some examples include OVHCloud[46], primarily a French undertaking or the LiDLCloud[47], from the well-known German supermarket chain. Cloud for compute is being rolled out by companies such as Nebious[48] and Nscale[49] in the UK.

3.3   Convergence of networking and compute, and O-RAN

The convergence of networking and compute will be crucial in transforming Europe's telecommunications sector to support modern complex, data-driven applications. This strategic integration is essential for enhancing network performance by reducing latency, optimizing bandwidth utilization, and improving overall efficiency. This convergence is vital for ensuring that European infrastructure is robust enough to support an economy and society that are increasingly digital. By processing data closer to the source, these converged networks greatly reduce response times and increase the reliability of digital services, fostering technological resilience and operational efficiency across Europe.

The adoption of open network technologies, including aspects of Open Radio Access Networks (O-RAN), plays a part in this transformation by introducing more flexibility and vendor diversity into the network architecture. This approach allows for a more dynamic allocation of resources, adapting in real-time to varying traffic and service demands, which is crucial for the bandwidth-heavy and latency-sensitive applications prevalent today. The O-RAN Alliance[50] is defining the leading architecture that exemplifies this broader movement towards open and seamless integration of compute and networking capabilities in radio access networks, but it is important for European sovereignty to also support other approaches to this open networking landscape.

The goal of a fully converged network and compute infrastructure cannot be reached without first addressing some challenges. Technical issues like interoperability between different network components, complexity in managing distributed architectures, and heightened security risks are significant. However, Europe is well-positioned to approach these challenges through joint regulatory frameworks, strategic partnerships across the industry and society, and continuous innovation in cybersecurity and network management.

To remain competitive and secure, the EU need to focus on strategic investments in digital infrastructure, which includes enhancing connectivity through advanced mobile networks and robust data services. This will not only support the immediate needs of European citizens and businesses but can also position Europe as a leading player in the global digital economy.

---

[45] https://www.srgresearch.com/articles/european-cloud-providers-continue-to-grow-but-still-lose-market-share
[46] https://www.ovhcloud.com/en/
[47] https://horovits.medium.com/lidl-is-taking-on-aws-the-age-of-eurocloud-b237258e3311
[48] https://nebius.com/
[49] https://www.nscale.com/
[50] https://www.o-ran.org/

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 23 of 80   © 2024-2026 NexusForum.EU

3.4   Convergence of Operational Technologies and Information Technologies

Operational Technology (OT), such as PLCs and SCADA systems, are widely used for automation and monitoring applications in many industry sectors. These have traditionally used industry-specific hardware components, programming languages and toolchains, and communication protocols, such as Modbus or CAN bus. Each vendor often has its own implementations, leading to vendor lock-in effects, and difficulties upgrading legacy systems as modern technologies become available.

The trend among many vendors in recent years is to offer cloud platforms, connecting their monitoring and automation systems to offer data-driven cloud services and applications. Many have even developed platforms to allow third party vendors to create services and applications that can be integrated with their cloud platforms.

This trend has seen an increased adoption of IoT technologies and modern communication protocols. In addition to the traditional vendors, many SMEs have entered the market to compete with them, providing gateways to integrate legacy systems, offering IoT solutions that include hardware and analytics platforms in the cloud, and other cloud services that can be deployed on top of existing data infrastructure/platforms.

In the future, the expectation is to see further convergence between OT and IT, as adoption of commodity hardware in OT increases, and monitoring and automation systems are further integrated with cloud platforms. Hence, traditional automation systems incorporating modern IoT and cloud technologies could be seen as an emergence of a new edge paradigm.

While the trend of certain OT vendors has moved towards cloud, there could be a very strong use case for the development of an on-prem OT edge paradigm that separates functions between edge and cloud, based on operational constraints. For example, many critical system functions must be maintained even if connectivity to the cloud is lost. Moreover, there are security concerns in use cases with highly distributed automated systems, which is the case for example for building owners that often own many buildings spread out geographically.

The convergence of OT and IT technologies should therefore not take the route of moving everything to a central cloud provider but rather seek to combine the strengths of local processing with the peak power of cloud to perform aggregated analytics and advanced AI tasks.

3.5   Establishing a European ecosystem based on RISC-V

Over the past decade and a half there has been significant investment in implementing European processors, developing and maintaining their roadmaps, targeting both HPC and embedded and IoT applications. The EU goal is the production of cutting-edge and sustainable semiconductors in Europe, with at least 20% of world production in value by 2030. By that time, Europe should have manufacturing capacities below 5nm nodes, aiming at 2nm, and improve energy efficiency in the domain by a factor ten. To achieve this the RISC-V open standard Instruction Set Architecture (ISA)[51] plays a central role in EUs strategy. RISC-V is royalty-free and open-specification allowing any market actor to implement microprocessors or accelerators using it. This lowers the barriers to innovation and market entry, and through collaborative efforts lessens the overhead for individual actors to develop and maintain non-value-adding supporting hardware and software needed for intellectual properties (IP) being developed and brought to market. For this reason, RISC-V has been called "the Linux of

---

[51] *RISC-V International, "About RISC-V," https://riscv.org/about/*

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 24 of 80   © 2024-2026 NexusForum.EU

hardware"[52]. For Europe RISC-V offers the opportunity to develop fully European processors, in contrast to today's reliance on processors and IPs owned by and developed on other continents.

EuroHPC JU (see section 3.6) aims to build a diverse IP portfolio of processors, accelerators, quantum chips, and AI accelerators, the pilots and demonstrators needed to realize them, as well as the necessary ecosystem to scale them to exascale including the associated software stack and applications. In the short term (2024-2026) this builds on the efforts in the European Processor Initiative (EPI) to build ARM-based processors, but in the medium term (2026-2028) this shall be complemented with competitive RISC-V general purpose processors and GPUs, with EuroHPC JU post-exascale systems being one of the first customers to drive demand in Europe and fulfil the EU goal of autonomy in strategic processing technologies[53].

The European Processor Initiative, EPI[54], is a Framework Partnership Agreement under EuroHPC JU (150 MEUR) to develop European supercomputing technologies, including European microprocessor and accelerator technologies, to improve performance and power ratios. EPI develops general purpose processors based on the ARM ISA, and accelerators based on the RISC-V ISA. The EPI project is complemented by EUPILOT[55] (30 MEUR) aiming to deliver all-European open-source and open-standard based software and hardware HPC systems, EUPEX[56] (40 MEUR) to produce a European pilot for exascale computing, and the eProcessor[57] (8 MEUR) to develop a European out-of-order high-performance RISC-V CPU.

European processor investment has been targeting both ARM and RISC-V ISAs and while the ARM ISA continues to play an important role in the coming years (2024-2029), there has been a shift towards more investment in European RISC-V based technologies, up to 2030 and beyond, with the establishment of the Digital Autonomy with RISC-V in Europe[58] (DARE, 240 MEUR) Framework Partnership Agreement to develop large-scale high-performance computing ecosystem based on RISC-V. DARE is expected to run 2025-2030 to deploy RISC-V pilot systems with a path towards post-exascale RISC-V development and procurement in the next decade. These projects do not only leverage technology, IP, and lessons learned from previous European efforts but constitute a coherent and strategic approach to co-develop European RISC-V processors, their software stacks, but also the porting of applications of key European value to the new platforms.

The European Partnership Chips Joint Undertaking, Chips JU, was established following the European Chips Act to succeed the Key Digital Technologies JU with the goal to reinforce EU strategic autonomy and address European challenges in electronic components and systems to establish scientific excellence and innovation leadership through the establishment of pilot lines, design platforms, and competence centres.[59,60] Chips JU and its predecessors has a strong involvement in European RISC-V which with renewed EU strategic significance today is guided by the 2022 Recommendations and Roadmap for European Sovereignty in Open-Source Hardware, Software, and RISC-V Technologies[61] and the 2023 Roadmap towards a

---

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Co-funded by
the European Union

Page 25 of 80   © 2024-2026 NexusForum.EU

High-Performance Automotive RISC-V Reference Platform[62]. In 2024 Chips JU had contracted two projects in this area; TRISTAN[63] (54 MEUR, 2022-2025) and ISOLDE[64] (39 MEUR, 2023-2026). TRISTAN develops a repository of European RISC-V quality building blocks for SoC designs in key European application domains such as automobile, industrial, as well as the necessary Electronic Design Automation (EDA) tools and the full software stack. The follow-up ISOLDE project expands the European RISC-V ecosystem by maturing the CVA6 and NOEL-V European RISC-V superscalar processors for applications including safety- and security-critical systems, system-level hardware components and their software stacks to contribute to the European RISC-V strategy in embedded high-performance computing and industrial IoT.

Taken together these European efforts, spanning the Compute Continuum, expose a strong European commitment to a joint European ecosystem based on RISC-V.

3.6   EuroHPC and the establishment of AI Factories

The European High Performance Computing Joint Undertaking (EuroHPC JU) was created in 2018 to make Europe a world leader in supercomputing, with a budget of EUR 7 billion for the period 2021-2027. It is a legal and funding entity that allows the EU and participating countries to coordinate their efforts and pool their resources to develop a European supercomputer ecosystem based on European technologies.[65]

EuroHPC aims to boost scientific excellence and industrial strength in Europe and support the digital transformation of its economy. EuroHPC aims to develop and maintain a *"world-leading federated, secure and hyper-connected supercomputing, quantum computing, service and data infrastructure ecosystem,"* and increase the use of HPC in both public and private sector.[65]

The *AI Innovation Package*, proposed in January 2024, proposed the establishment of AI Factories in Europe, leveraging the EuroHPC supercomputer ecosystem to develop trustworthy AI in Europe.[66] In July 2024 an amendment to the EuroHPC Regulations went into force,[67] expanding its mission to include the development and operation of *"AI Factories located around EuroHPC supercomputing facilities to support the growth of a highly competitive and innovative AI ecosystem in Europe."*

This amendment allows EuroHPC to acquire and operate dedicated AI-optimised supercomputers, in particular for training generative AI and general-purpose AI models that require significant computing resources. The purpose of these AI factories is to offer a one-stop shop for startups, the scientific community, and other innovative AI users to develop powerful AI models for a variety of emerging AI applications. The first AI factories are expected to be deployed in 2025.

The first seven AI factories will be deployed in 2025 across Europe, specifically in Finland, Germany, Greece, Italy, Luxembourg, Spain, and Sweden.[68] These sites were selected to host the new AI factories, which will include brand new AI-optimised supercomputers in five of these countries. Notably, some of these will leverage cloud technologies to provide cloud-style interfaces and services that are more familiar to the AI community.

---

[62] *Jariu Kinaret (Chips JU), https://eurohpc-ju.europa.eu/document/download/7e21bf39-bb19-43b8-88b6-dd51650d348e_en?filename=pdf%20chips%20parrt%202.pdf*
[63] *https://tristan-project.eu/*
[64] *https://www.isolde-project.eu*
[65] *https://eurohpc-ju.europa.eu/about/discover-eurohpc-ju_en*
[66] *https://digital-strategy.ec.europa.eu/en/factpages/ai-innovation-package*
[67] *https://digital-strategy.ec.europa.eu/en/news/setting-ai-factories-now-possible-after-eurohpc-regulation-amendment*
[68] *https://eurohpc-ju.europa.eu/selection-first-seven-ai-factories-drive-europes-leadership-ai-2024-12-10_en*

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 26 of 80   © 2024-2026 NexusForum.EU

These AI Factories will act as dynamic ecosystems that foster innovation by providing comprehensive support, including access to AI-optimised HPC resources, training, and technical expertise. They will serve as hubs for AI startups, SMEs, and researchers, promoting collaboration across Europe and driving advancements in areas like healthcare, energy, and climate.

The EuroHPC AI Factories initiative represents a collaborative effort from across 17 European countries, pooling together EU and national resources to create a robust and interconnected network of AI hubs. This initiative aims to position Europe as a leader in AI innovation and development.

3.7 Access to European data, common data spaces, and data privacy

Data sharing is a fundamental problem, yet it remains an essential ingredient of the emerging data economy. There is an abundance of national and international (EU-level) legislation and initiatives meant to stimulate data sharing across the economy. In the EU, the EU Data Act[69] mandates equipment manufacturers to make the data collected and produced by the equipment available to users and third parties, supporting ecosystems such as the Common European Data Spaces[70]. Other ongoing initiatives like the International Data Spaces[71] and Gaia-X[72] work to bridge the gap between policy, legislation and technical implementation of workable solutions. In Singapore the Infocomm Media Development Authority offers a Trusted Data Sharing Framework and regulatory sandbox to allow businesses and public authorities to experiment with secure data sharing solutions and accelerate innovation[73]. Similarly, in Japan the Ministry of Economy, Trade and Industry and the Information Processing Promotion Agency launched an initiative for interoperable cross-border data infrastructures dubbed the "Ouranos Ecosystem"[74]. The European Commission funds a wide range of projects and initiatives to implement the European data strategy[75]. For example, European Research initiatives such as the European Open Science Cloud[76] are working on developing a cloud infrastructure for sharing data for scientific and public services purposes.

In February 2020, the European Commission recognized the need to establish the foundations of a "European Strategy for Data"[77]. Their aim is for the EU to take a leading role in empowering society through data, enabling better decision-making in both business and the public sector. This initiative was followed in May by the Recovery and Resilience Facility's "20% Digital EU Flagship Scale Up", in October by the Members' declaration for a "European Cloud," and in March 2021 by the Digital Decade Strategy, which set targets for Edge and Cloud by 2030.

The "data space" concept was created to facilitate the sharing of data between European entities. Several initiatives have been launched in Europe to this end:

- The Data Spaces Support Centre (DSSC), funded by European Commission as part of the Digital Europe Program, establishes a network of relevant organizations and initiatives involved in the development of Data Spaces.

---

[69] EU Data Act https://digital-strategy.ec.europa.eu/en/policies/data-act
[70] Common European Data Spaces https://digital-strategy.ec.europa.eu/en/policies/data-spaces
[71] International Data Spaces Association: https://internationaldataspaces.org/
[72] Gaia-X Federated Data Sharing Infrastructure: https://gaia-x.eu/
[73] Singapore Infocomm Media Development Authority: https://www.imda.gov.sg/how-we-can-help/data-innovation
[74] Japan's Initiatives for Interoperable Data Infrastructures Officially Named "Ouranos Ecosystem" https://www.meti.go.jp/english/press/2023/0429_001.html
[75] A European strategy for data https://digital-strategy.ec.europa.eu/en/policies/strategy-data
[76] European Open Science Cloud: https://research-and-innovation.ec.europa.eu/strategy/strategy-2020-2024/our-digital-future/open-science/european-open-science-cloud-eosc_en
[77] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0066

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 27 of 80

© 2024-2026 NexusForum.EU

- Gaia-X was established in 2021 as a privately funded not-for-profit organization with the support of BMWK. GAIA-X has funded 11 consortia until 2024, with a total budget of 122 million Euros. While initially focused on building the European Cloud, Gaia-X later opened participation to Cloud Hyperscalers, ensuring their compliance with EU values through a Label Framework.

- The International Data Spaces Association (IDSA), one of the first non-profit organizations to contribute to the European strategy for data, formed in 2017 and incorporated under German law. The IDSA evolved from the Fraunhofer Society project called the Industrial Data Space in 2014, which was renamed to International Data Spaces (IDS) in 2015. IDSA is working on the "Dataspace Protocol," focusing on the Data Exchange layer of Data Spaces, with the aim to make it an ISO standard. Expanding beyond Europe, the IDSA now has a network of hubs globally, including in Japan, Malaysia, and a competence centre in China.

- FIWARE, originally funded under the European Union's Seventh Framework Programme for Research, was a non-profit association of industry, academia and SMEs worldwide providing standards and technology development around Data Exchange and Data Sharing and a full framework of open-source components to build smart solutions, digital twins and data spaces.

4 Transversal topics

4.1 Digital Sovereignty

Europe's heavy reliance on technologies developed by non-EU vendors, especially those from the United States and China, poses challenges to its ability to control critical infrastructure and data processing services. Meanwhile, non-EU hyperscalers are rapidly advancing in the race to dominate the future compute computing value chain. Although European cloud offerings span a wide spectrum of services, customers often need to collaborate with multiple providers to match the quality and breadth of services offered by leading global cloud providers. European providers differentiate themselves by focusing on specific niches where they excel. European cloud providers (including telcos) are in a unique position to be able to leverage proximity, resource optimisation, QoS evaluation, and regulatory compliance to enhance edge computing performance and address latency challenges.

Securing Europe's strategic autonomy in the digital world is not only a technical hurdle; it also presents a geopolitical puzzle. Europe contends with other global regions in the race for becoming technological leaders. Navigating the delicate balance between economic interests, security imperatives, and strategic partnerships demands thoughtful management and governance. The impact of this process goes beyond individual choices by end-users and businesses, as illustrated by Ursula von der Leyen's February 2020 op-ed[78], where she described tech sovereignty as" the *capability that Europe must have to make its own choices, based on its own values, respecting its own rules."*

For instance, ensuring data privacy and security is crucial for maintaining sovereignty. European citizens and businesses rightfully anticipate that their data will be treated with care and shielded from unauthorized access. Balancing the imperative of data sharing for innovation with the need to protect privacy remains a formidable challenge. While regulations like the General Data Protection Regulation (GDPR) aim to tackle this issue, their implementation across the EU members states can be intricate and geopolitical threats are also an issue to be addressed.

Furthermore, in 2022, ENISA was commissioned to include sovereignty requirements into the EUCS. These requirements requested that CSPs of "high" assurance level have their headquarters in the EU, and "not be controlled by any non-EU entity" and be "completely independent from non-EU laws". After almost two years of controversy, the latest news[79] indicate that cybersecurity related sovereignty requirements are likely to be removed from the final EUCS proposal with the aim to ensure fair access to EU market for non-EU CSPs. Whether this is a profitable decision for European Cloud market is still to be seen, and in any case it most like will significantly impact the Cloud market evolution in the EU. Mechanisms to monitor the business benefits of CSPs whose headquarters reside within EU vs. abroad should be established.

4.2 Open Source

Open technologies, including standards, open-source software (OSS) and hardware (OSH), contribute to economic growth and innovation, and they hold significant potential in

---

[78] https://ec.europa.eu/commission/presscorner/detail/es/ac_20_260
[79] https://www.euractiv.com/section/data-privacy/news/sovereignty-requirements-for-cloud-providers-will-not-make-it-to-commissions-proposal-for-implementing-act/

strengthening European digital sovereignty.[80] Recognising that foundational Cloud-Edge technologies are currently, to a large extent, being developed and maintained within opensource foundations like the Linux Foundation and the Eclipse Foundation, the roadmap of the *European Alliance for Industrial Data, Edge and Cloud* outlines several priorities aimed at improving European capabilities and autonomy in the global open-source sector, including the need to "*strengthen existing (and create new) open source software communities, led by European organisations, to manage and maintain important technologies in the long term as well as to lead open source reference implementations*".[81]

While the critical importance of OSS for cloud computing is well established, interest in OSH has developed more recently and is centred on the role that it can play in lowering barriers to entry and thereby mitigating strategic dependencies in the fields of processors and, more broadly, semiconductors. Such dependencies were made salient by disrupted supply chains during the COVID-19 and increased geopolitical volatility in recent years. Currently, the growing role of AI across various sectors is further heightening the strategic importance of semiconductors and the need for the EU to address particular areas of strategic weakness, including chip design.[82]

Of particular interest in this context is the surge in open innovation, catalysed by the development and adoption of RISC-V, a free and open instruction set architecture (ISA) standard. Initiatives like the Chips for Europe initiative, supported by legislations such as The European Chips Act,[83] is providing an impetus for increased collaboration within Europe, emphasising the importance of RISC-V and open-source. Building on open and shared standards, open-source licenses facilitate seamless collaboration between researchers and industry, helping to accelerate innovation and counteract dependencies. However, to fully harness the potential of open technologies in achieving digital sovereignty, a strategic approach is required to build and strengthen competencies in key areas, ensuring Europe has the capacity to fork projects and maintain the code it relies on, thereby reducing dependencies.[84]

As an example, the report *"Open Source Software in Automotive and its transition towards Software Defined Vehicles"*[85] presents a vision for open source in the automotive industry. While the conclusions target mainly applications in automotive, they are far-reaching and apply more generally:

- *Better standardisation through EU organisations*: Leverage open source, as in IT as de-facto solutions. Ensure that any standards promoted are implementable in open-source software (OSS). Implement educational initiatives about the benefits and best practices of OSS for businesses, particularly in sectors like automotive.

- *Establish Functional Safety Norms*: Collaborate with industry consortia and stakeholders to develop clear guidelines and standards for functional safety certification that consider and leverage the benefits of OSS characteristics. Cultivate

[80] *Blind et al. (2021). The impact of Open-Source Software and Hardware on technological independence, competitiveness and innovation in the EU economy. Final Study Report. https://digital-strategy.ec.europa.eu/en/library/study-about-impact-open-source-software-and-hardware-technological-independence-competitiveness-and*

[81] *https://digital-strategy.ec.europa.eu/en/news/european-alliance-industrial-data-edge-and-cloud-presents-its-first-deliverables.*

[82] *Kleinhans (2021). The lack of semiconductor manufacturing in Europe. Policy Brief. SNV Berlin. https://www.stiftung-nv.de/de/publikation/lack-semiconductor-manufacturing-europe*

[83] *EC (2022). European Chips Act: Communication, Regulation, Joint Undertaking and Recommendation. European Chips Act: Communication, Regulation, Joint Undertaking and Recommendation, https://digital-strategy.ec.europa.eu/en/library/european-chips-act-communication-regulation-joint-undertaking-and-recommendation*

[84] *EC Working Group on OSH and OSS (2022). Recommendations and roadmap for European sovereignty on open-source hardware, software and RISC-V Technologies, https://digital-strategy.ec.europa.eu/en/library/recommendations-and-roadmap-european-sovereignty-open-source-hardware-software-and-risc-v*

[85] *Found on LinkedIn; (27) Open Source Software in Automotive and its transition towards Software Defined Vehicles | LinkedIn and also at Open Source Software in the Automotive Industry*

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 30 of 80   © 2024-2026 NexusForum.EU

environments that promote collaboration among OEMs, suppliers, and OSS communities to drive innovation.

- *Consider OSS as a Geopolitical Concern*: Take proactive steps to understand the geopolitical landscape of software and its implications for the industry. Adopt and support open technologies, including OSS, open standards, and open hardware, both in industry and government, to enhance regional sovereignty and global competitiveness.

- *Engage with Global OSS Sustainability Efforts*: Governments should engage in and encourage industry participation in global OSS sustainability efforts to ensure the longevity and support of OSS. Support may include diverse options such as funding critical projects, promoting OSS in public procurement, raising awareness and knowledge of the risks related to the global supply chain, and encouraging organisations to sustain their own upstream dependencies.

4.3   Sustainability and Energy Efficiency

The European Union is increasingly prioritising sustainability and energy efficiency as central components of its digital transformation. This emphasis is enabled by Europe's ambitious climate goals, regulatory frameworks, and the growing demand for environmentally responsible computing solutions.

The EU has positioned itself as a global leader in sustainable digital transformation with policies such as the European Green Deal and the Climate Law, and strong intentions for climate neutrality by 2050. The computing ecosystem, including data centres and cloud providers, are expected to play an important role in achieving these targets.

The EU Code of Conduct (CoC) for Energy Efficiency in Data Centres[86] provides voluntary guidelines for reducing energy use. It promotes best practices such as optimising cooling systems, increasing server utilisation, and integrating renewable energy sources as well as aspects of waste heat recovery.

The recast Energy Efficiency Directive (EED) establishes critical requirements for data centres within the EU[87] and operates as part of a broader effort to enhance sustainability and energy security. By aiming for the 2030 energy efficiency target, the recast EED seeks to reduce energy costs and achieve substantial reductions in greenhouse gas emissions. These objectives are closely tied to the adoption of transformative technologies, including numerous innovations essential for the green transition. The EU CoC for Energy Efficiency in data centres will become part of the framework to audit data centres for the deployment of energy efficient practices.

Improved energy efficiency also plays a pivotal role in strengthening the EU's energy supply security. By decreasing reliance on fossil fuel imports from third countries, the Directive addresses vulnerabilities that have been highlighted by recent geopolitical tensions, such as the energy crises resulting from conflicts in Eastern Europe.

This dual focus on sustainability and resilience ensures that the EU's energy systems are not only greener but also more robust in the face of growing external challenges. The strategic alignment of the EED with other policies under the European Green Deal reinforces its role in achieving climate neutrality by 2050 while ensuring that data centres contribute to this overarching goal through efficiency-driven operations.

---

[86] *https://e3p.jrc.ec.europa.eu/communities/data-centres-code-conduct*
[87] *https://eur-lex.europa.eu/eli/reg_del/2024/1364/oj*

Co-funded by
the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 31 of 80   © 2024-2026 NexusForum.EU

Data centres are integral to Europe's computing ecosystem but are also significant energy consumers. As of 2023, they account for roughly 2-3% of the EU's total electricity demand, with projections to grow due to expanding cloud services, AI applications, and edge computing.

To combat this, the EU has introduced measures to increase energy efficiency:

- By pushing for Renewable Energy Integration. Many data centres in Europe now operate on renewable energy. For instance, Equinix and OVHcloud have pledged to use 100% renewable energy across their European operations, with OVHcloud claiming 92% Renewable Energy Factor in 2024[88] and Equinix claiming 96% use of renewables in 2024.[89]

- By incentivising and mandating Waste Heat Recovery, Nordic countries, such as Sweden, Finland, and Denmark, lead in recycling waste heat from data centres into district heating networks, showcasing an innovative approach to energy efficiency. The EED recast mandates the data centres with greater than 1MW of IT load should deploy waste heat recovery with a specific Energy Reuse Factor (ERF) and only not to enforce this if it is demonstrated to be technically or financially infeasible.

The European digital infrastructure ecosystem is embracing innovative technologies to reduce environmental impact, such as:

- Liquid Cooling Systems. These systems are more energy-efficient from the cooling perspective than traditional air-cooled systems and are increasingly adopted in HPC (high-performance computing) and AI data centres.

- AI for Energy Optimisation, where AI and machine learning are used to predict and manage energy use, thus enhancing efficiency. Google's data centres in Europe, for example, supposedly leverage AI to optimise their cooling systems.

- Edge Computing that enables the processing of data closer to the source, edge computing reduces the need for long-distance data transfers, cutting energy costs and improving latency for certain applications that require very fast response.

Cloud computing, which constitutes a significant part of the European digital ecosystem, offers inherent sustainability benefits compared to on-premises solutions. These include:

- Resource Efficiency, coming from a shared infrastructure in cloud environments, which therefore enables better utilisation rates and lower energy per unit of computation compared to traditional setups.

- Commitments from Providers, for example leading cloud providers like AWS, Microsoft Azure, and Google Cloud have data centres in Europe that are claiming to be carbon-neutral or powered by renewable energy. Local players such as OVHcloud and Atos/Eviden are also investing heavily in green energy solutions.

Despite the progress, the European digital ecosystem faces several significant challenges, namely:

- Balancing Growth and Sustainability with the exponential growth in data usage, driven by AI, IoT, and 5G, risks outpacing sustainability efforts, especially against an electrical grid that is becoming more constrained in places.

- Standardisation and regulation. Even though voluntary initiatives like the EU CoC exist, there is a need for standardised, enforceable sustainability regulations across

---

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 32 of 80   © 2024-2026 NexusForum.EU

member states, although this is currently being attempted for data centres by both the recast EED and the CSRD reporting requirements.

- E-waste Management is also becoming a strong requirement. In this case, upgrading data centres often generates electronic waste and therefore good strategies for sustainable disposal and recycling currently remain underdeveloped.

Opportunities include expanding green energy partnerships, adopting circular economy principles in hardware production, and fostering cross-border collaboration to share best practices and technologies.

4.4   Cybersecurity

One of the major milestones in the cybersecurity landscape in Cloud will be the inception of the adoption of the European Union Cybersecurity Certification Scheme for Cloud Services (EUCS)[90] when it is finally ready and approved. The EUCS is one of several schemes framed within the EU cybersecurity certification framework, as set out in Regulation (EU) 2019/881[91] While adopting EUCS is voluntary, the NIS 2 Directive, in force from October 15, 2024, allows EU MS mandating that essential and important entities use only EUCS-certified cloud services. The scheme defines sets of common reference security requirements for different assurance levels of cloud services, ranging from "basic" to "high+", through 'substantial' and 'high'.

The latest draft of the EUCS was released in November 2023 and its approval is suffering significant delays. The draft EUCS involved several key updates, most importantly the removal of the data localisation requirement for basic and substantial assurance levels, leaving it to only CSPs seeking for "high+" assurance level the obligation of storing European citizens' data within the EU and establishing contracts governed by the laws of the EU or a Member State.

At the practical level, security processes and controls in the cloud will need to go strengthening as the threat diversity and virulence intensify. For example, solutions that enable seamless security will raise in popularity, such as Multicloud Key Management as a Service (KMaaS) solutions that enable the handling of secrets (e.g., SSH keys, API keys and certificates) in the cloud, both in hybrid environments and environments where multiple cloud providers are used. Other zero trust technologies will also be crucial in the protection of Clouds, enabling the evolution from add-on and reactive security to security-by-design and multi-layered distributed security of networks, edges, devices and servers.

In the short term, Artificial Intelligence (AI) and Generative AI will make Cloud cybersecurity even more challenging since they will be the means for sophisticated and combined attacks, malicious content generation, raising automation and complexity of multiple types of attacks such as malware, ransomware, APTs, etc. In parallel, these technologies are also expected to boost the intelligence capabilities of preventive security and response automation. Therefore, they will play a dual role, aiding in making both offensive and defensive solutions smarter.

Latest years have witnessed a vertiginous increase in the number of IoT devices connected all over the globe. With Cyber Physical Systems (CPS) and Cyber Physical Systems of Systems (CPSoS) gaining momentum with a myriad of related applications, it becomes fundamental to research on light yet effective SIEM solutions that can be embedded / onboarded in those devices that usually present challenging hardware constraints., Additionally, it is important to make a leap forward by defining and extensively testing efficient SIEM hierarchical multi-tier architectures where SIEMs of growing capacity and complexity are placed as we move from lower, IoT, to upper layers, edge and cloud.

---

[90] *https://www.enisa.europa.eu/publications/eucs-cloud-service-scheme*
[91] *https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:JOL_2013_165_R_0041_01&qid=1397226946093&from=EN*

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 33 of 80   © 2024-2026 NexusForum.EU

As reported above, cybersecurity is expanding at the same speed as the digital concept does, computing continuum (Cloud, edge, IoT), software, hardware, etc. Therefore, a holistic and systems-centric approach is essential, encompassing not just computing, networks, infrastructure, hardware, software, data, platforms, people, and services. This approach highlights the importance of understanding 'cascading risks' and 'systematic risks' and how to overcome them ensuring that all potential vulnerabilities are addressed to prevent widespread damage. Cyber capabilities by any and all malicious actors threaten all segments and sectors. In this Digital age access to affordable computing power, data, AI capabilities, and the collaboration among cybercriminals have led to the industrialization of cybercrime, making it one of the fastest-growing markets. However, industries, users, consumers, and the public sector are still not taking cybersecurity seriously enough. A major issue in addressing these significant challenges is the lack of effective implementation, support to the stakeholders and collaboration.[92,93,94]

In a longer term, *homomorphic encryption* will see practical implementations in the Cloud, allowing for confidential processing of both sensitive (confidential, secret) and private data without the need of decrypting them. While major limitations are currently being addressed[95], such as speed and costs, homomorphic encryption is a promising technology which will make it possible that applications run on top of encrypted data that can only be decrypted by the owner of the secret key.

As it gets more and more mature, quantum computing technology will also be beneficial for Cloud services as a means to accelerate the cryptographic processing in all those communication and data protection algorithms that require high compute power.

In a quantum-enabled cloud, quantum computing can potentially be used to enhance cloud security protocols and privacy. For example, quantum key distribution (QKD) could be used to create very strong cryptographic keys that can be used to establish secure communication channels theoretically immune to eavesdropping. Hybrid security models that combine the strengths of classical and quantum cryptographic techniques to create secure cloud environments will also be possible.

Since the powerful quantum computers may in the future be able to break many of the currently used encryption algorithms to protect data in the cloud, quantum-resistant technologies and solutions are currently being researched. Therefore, it is expected that post-quantum cryptographic algorithms and protocols will also be increasingly adopted to avoid quantum threats to encryption and ensure secure communications and storage in the cloud. In this line, the initial public draft of the NIST IR 8547 Transition to Post-Quantum Cryptography Standards[96] issued November 12, 2024 has already pioneered the path towards clarifying the rationale and challenges of the change.

Real-time cyber risk monitoring systems combine information about vulnerabilities in the target infrastructure, information about threats and attacks detected by SIEM systems, the business profile of the company and the involved digital assets with the purpose of measuring the economic exposure related to the cyber climate in which such an infrastructure is operating. Research could be conducted in evolving the state of the art of the cyber risk models used to calculate this economic exposure so that they can take advantage of the valuable information generated by different monitoring and detection tools. This information is larger and larger in volume and contains insights that are fundamental in obtaining close-to-reality economic cyber risk estimations. Fine-tuned cyber risk monitoring systems are extremely useful when

---

[92] https://digital-strategy.ec.europa.eu/en/news/commission-calls-23-member-states-fully-transpose-nis2-directive/
[93] https://www.enisa.europa.eu/news/eus-first-ever-report-on-the-state-of-cybersecurity-in-the-union
[94] ttps://www.consilium.europa.eu/en/press/press-releases/2024/12/02/cybersecurity-package-council-adopts-new-laws-to-strengthen-cybersecurity-capacities-in-the-eu/
[95] https://medium.com/@allen.westley/homomorphic-encryption-in-action-f8b7e11b885e
[96] https://nvlpubs.nist.gov/nistpubs/ir/2024/NIST.IR.8547.ipd.pdf

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 34 of 80   © 2024-2026 NexusForum.EU

estimating the price of cyber insurance, in the case when a company decides to transfer the cyber risk to a third party by paying a periodic fee.

Internet of Behaviour (IoB) is based on the detection of behavioural patterns both in the network and the infrastructure that can potentially be mapped to threats. IoB seems highly promising due to the fact that it is not necessary to access data themselves, just detect an anomalous behaviour in comparison to what would be considered a normal pattern. It allows anticipation in risk management and the chance to put in place mitigation measures before an actual attack takes place.

The potential of IoB is connected to Cyber Threat Intelligence (CTI) and in particular to sharing threat information to third parties, modelling the behaviour and building a common knowledge base that permits the detection of long-term attacks. Since its very conception, CTI has faced the issue of reluctance of organizations to share information labelled as delicate, since it is related to threats and attacks on their digital assets. Working groups like MISP have tried to provide answers to this challenge. It is important to foster research on how to guarantee that information is shared in a fully anonymous way to encourage more organization to participate and strengthen common knowledge.

4.5   Interoperability

In open and fragmented business ecosystems which foster innovation and competition, the systems capability to collaborate, being interchangeable and evolve together is a key success factor. This set of capabilities are part of the interoperability concept, which is a side benefit of long-term and occasional collaboration initiatives between organisations. Interoperability is an open and broad term that covers different collaboration aspects, such as data exchange, communication, process integration, and system compatibility.

The interoperability of digital systems is a cross-cutting concern in the European Union that has been materialised through different initiatives and regulations.

From the *EU policy perspective level* several initiatives have become relevant to foster interoperability in the Computing Continuum.

The European Interoperability Framework (EIF)[97] is a set of recommendations for promoting interoperability in the delivery of European public services. The EIF was first published in 2004 and the latest version, EIF 2.0, was published in 2017 and provides a set of guidelines for promoting interoperability in the delivery of European public services.

The European Interoperability Act[OBJ] is a regulation that aims to promote interoperability between, and with, European public administrations by establishing a legal framework for the exchange of data and information between different systems and platforms. It addresses issues in the application of the European Interoperability Framework (EIF) and its limitations due to their voluntary nature. European Entry Exit System (EES)[98] results from the European Union initiatives to promote the interoperability of the members' large-scale IT systems in the field of borders, visa, police and judicial cooperation, asylum and migration.

At the domain-specific level, various initiatives have been launched to enhance interoperability within each vertical sector.

In the energy sector, the European Commission launched the Bridge initiative[99] to promote continuous sharing of information among research projects. As a result, a supporting topic

---

[97] https://ec.europa.eu/isa2/eif_en/
[98] https://ec.europa.eu/home-affairs/what-we-do/policies/borders-and-visas/smart-borders/entry-exit-system_en
[99] https://h2020-bridge.eu/

'interoperability community' was included as a call for proposals in the Horizon Europe programme.[100]

In the *air traffic sector*, the Regulation (EC) No 552/2004 on the interoperability of the European air traffic management network, and aims to promote the single European sky by establishing a legal framework for the exchange of data and information between different systems and platforms.[101] It´s worth mentioning that this regulation was repealed by the Regulation (EU) 2018/1139 on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency. This new regulation also addresses the interoperability of the European air traffic management network.[102]

In the *rail sector*, the European Union, while keeping the high level of safety, is promoting the interoperability of the rail system to facilitate the entry of new operators and the development of new services. This is mainly regulated by the directive 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union.[103]

In the *health sector*, under the EU4HEALTH programme[104] the European Commission and the World Health Organization (WHO) announced the 11 of December 2023 that they signed an agreement to launch a four year project to strengthen health information systems and boost health data governance and interoperability in Europe.[105]. In the **food sector**, the European Food Safety Authority (EFSA) and the German Federal Institute for Risk Assessment (BfR) are developing a Universal Traceability data eXchange (UTX) and a multi-actor tracing software ecosystem to harmonize tracing data across Europe.[106]

Other initiatives have been originated by non-public bodies such as:

- In the financial sector, the 6 of August of 2024, the European Round Table for Industry (ERT) sent a letter to the European Union Commissioner for Financial Markets, Mairead McGuinness, on the need of interoperability between sustainability reporting frameworks.[107]

- Eurocity, which is a community of more than 200 European cities, presented and Interoperability Framework for electric charging related technology.[108]

In the European computing sector, it is crucial to first understand the regulatory priorities regarding interoperability in Europe. These regulations aim to address the European social and economic needs. In this context, the Cloud Computing Policy[109] foresees the rise of cloud and edge computing for data processing. Among other aspects, they anticipate an increase of edge nodes in the coming years until 2030, when 10,000 edge nodes are expected to be deployed. This paradigm shift will require *interoperability-oriented initiatives to reap the benefits and avoid the drawbacks of increased fragmentation*. The foreseen interoperability needs are addressed by some of the measures initiated by the European Commission:

---

[100] *https://cordis.europa.eu/programme/id/HORIZON_HORIZON-CL5-2021-D3-01-03/en*
[101] *https://eur-lex.europa.eu/EN/legal-content/summary/interoperability-of-the-european-air-traffic-management-network.html*
[102] *https://www.atc-network.com/atc-news/easa-european-aviation-safety-agency-germany/single-european-sky-easas-air-traffic-management-responsibility-consolidated-through-new-regulations*
[103] *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32016L0797*
[104] *https://ec.europa.eu/health/funding/eu4health_en*
[105] *https://ec.europa.eu/newsroom/sante/newsletter-archives/49640*
[106] *https://link.springer.com/article/10.1007/s00003-024-01522-8*
[107] *https://ert.eu/documents/ert-letter-to-commissioner-mairead-mcguinness-on-the-need-for-interoperability-between-esrs-and-issb-standards/*
[108] *https://eurocities.eu/resources/interoperability-framework-for-electric-charging-related-technology/*
[109] *https://digital-strategy.ec.europa.eu/en/policies/cloud-computing*

In the European Data Strategy, the objective of the Data Act[110] is to make it easier to switch between different data service providers and achieve free flow of non-personal data. This will require interoperability among different cloud service providers.

In the European Industrial Strategy, the *European Alliance for Industrial Data, Edge and Cloud*[111] aims to bring together relevant stakeholders from the private and public sector to jointly define strategic investment roadmaps to enable the next generation of highly secure, distributed, interoperable and resource-efficient computing technologies.

Finally, it is worth mentioning that there are other acts such as the Digital Services Act[112] (DSA) and the Digital Markets Act[113] (DMA) that may have applicable interoperability requirements. For example, the DMA establishes an "Obligation for gatekeepers on interoperability of number-independent interpersonal communications services".[114]

---

[110] *https://digital-strategy.ec.europa.eu/en/policies/data-act*
[111] *https://digital-strategy.ec.europa.eu/en/policies/cloud-alliance*
[112] *https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/digital-services-act_en*
[113] *https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/digital-markets-act-ensuring-fair-and-open-digital-markets_en*
[114] *https://www.eu-digital-markets-act.com/Digital_Markets_Act_Article_7.html*

Project funded by

Co-funded by
the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 37 of 80   © 2024-2026 NexusForum.EU

5   AI for Cloud-Edge: Orchestration and Managing a Multi-Provider Continuum

Creating a federated, energy-efficient, and trustworthy European data processing ecosystem, spanning a multi-provider cloud to edge continuum, requires the development of new automated management technologies for the Cloud-Edge stack and new mechanisms for interoperation between different providers.

The management of the Cognitive Computing Continuum should enable real-time and low-latency services by distributing workloads in the Compute Continuum and reduce transmission of large volumes of data to centralised cloud data centres. The computing continuum needs to be energy-efficient and sustainable, with as low carbon footprint as possible. Methods that use AI, specifically using data-driven machined-learned patterns, to automate predominately the management of the Compute Continuum are given preference.

Three aspects to enable European centric automated management systems. Following on are six identified sections which play to the strengths or needs that European Cognitive Computing Continuum can build on. Focusing on federating compute resources in Europe and on the foundational technologies needed to make it happen and importantly efficient.

AI FOR CLOUD-EDGE - WORKING GROUP SCOPE:

Meta-orchestration, federation of multi-cloud, IaaS, integration monitoring of continuum, OS and virtualization, containers, hypervisors, virtual networks, virtual storage.

Services for serverless services spanning edge-cloud-HPC, service management, application lifecycle orchestration, data services.

Infrastructure services to run on the multi-provider Compute Continuum. Load balancing, protocol optimisation (See 4.1)

5.1   Sustainable, energy-efficient, and energy-grid-aware Compute Continuum

Context: The increasing demand for AI services, their augmented complexity as well as the growing volume of data these services ingest, process and produce are all directly related with the demand for energy in the data centres hosting such services. As the global share of energy used by data centres increases, the carbon footprint of the computing continuum will play an increasingly important role in achieving the ambitious climate goals, se section 4.3.

The management and operation of the computing continuum needs to become not only more energy-efficient, but also carbon-aware. The electricity consumption of data centres in the EU accounted for almost 4% total electricity demand within EU in 2022, at an estimated total of almost 100 TWh. Electricity consumption in the data centre sector in the EU is expected to reach almost 150 TWh by 2026[115]. This is at a time when decreasing energy use and emissions across the board have been mandated by the EU and most national governments. Energy consumption by the edge, although not trivial to calculate is modest, some 2% of that by data centres in 2018, but expected to grow to 12% by 2025[116].

---

[115] The IEA published a forecast from 2024-2026
[116] https://digital-strategy.ec.europa.eu/en/library/energy-efficient-cloud-computing-technologies-and-policies-eco-friendly-cloud-market#:~:text=There%20is%20a%20growing%20trend,rise%20to%2012%25%20by%202025

The intensive computing processes that are run within these services have an effect on the temperature of the physical machines, that tend to increase notably therefore needing a cooling-down process to compensate this effect and safeguard not only the integrity of this infrastructure, but also that of the premises where it is operated. Cooling-down processes increase the demand for water, which has to be monitored in a global context that demands efficient and rationale usage and consumption of this vital resource.

Challenges: The main challenges are related to the development of algorithms that assist in the management of cloud resources considering the need for optimisation in energy consumption and prioritization in the usage of renewable energies, on one side, and the evolution of cooling systems to achieve better efficiency in the usage of water. These algorithms rely on the availability of data to ignite their learning capabilities and enable decision making. The availability of widespread data in this area is hampered by the natural urge of companies operating in this area to regard their power usage and heating/cooling data as key confidential business data. Similar issues in the electricity generation market have been hampering developments in that area as well. The Open Energy Modelling Initiative[117] has been seeking to help solve this problem via a multi-pronged strategy. Similar approaches in the area of energy use in cloud computing need consideration.

R&D priorities:

- *Carbon- and energy grid-aware scheduling* and orchestration can allow workloads to be shifted in time and space to react to local fluctuations in renewable energy supply, as well as take advantage of excess energy supply.

- *Beyond energy-efficiency and towards energy grid-and carbon-aware*: Incorporate advances in open energy data, carbon-aware grids, and forecasting of local energy mixes to optimize carbon emissions rather than just energy efficiency. The recovery of waste heat needs to be further investigated and implemented.

- *Establish a standardized set of sustainability metrics and benchmarks*: While metrics like Power Usage Effectiveness (PUE) are valuable, they fall short in capturing the efficiency of processing per unit of energy, especially in the context of a highly heterogeneous continuum.

- *Implementation of accurate energy consumption measurement in Ccloud-Edge systems*: In close connection with the previous priority, it is about developing the needed probes and data collectors that will gather the needed raw data that will subsequently go through an aggregation process to be shown in the shape of a series of metrics to evaluate the energy consumption and the efficiency in the management of cloud resources from a sustainability perspective. The developed probes and collectors must be easily integrable and in this sense open-source solutions should be strongly promoted to ensure wide adoption.

- *Digital twins* using a mix of physical models, CFD and AI models e.g., scientific/physics-based ML to control cooling, management and optimisation of the digital infrastructure for the Compute Continuum. By enabling a detailed simulation and understanding of energy flows within data centres and their integration into electricity and thermal grids, digital twins facilitate a nuanced analysis of operational efficiencies and inefficiencies. This deep insight allows for the identification and implementation of strategies that can significantly enhance energy efficiency. For instance, by closely monitoring critical operational variables such as CPU temperatures and dynamically adjusting data centre loads, it becomes possible to optimize the balance between IT performance and cooling energy consumption.

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 39 of 80   © 2024-2026 NexusForum.EU

- Whole-system approach: It's vital to recognize that power consumption isn't confined to data centres alone but extends to the network and specific applications, necessitating benchmarking considerations based on workflows. Innovation should also target energy-efficient software for IoT devices and energy-restricted devices to minimize power consumption.

- New cooling solutions, e.g., different liquid or even submersion cooling, to enable next-generation high-performance hardware.

- Hardware and software co-design for specific use case applications, e.g., highly energy-efficient AI inference or AI training at the edge.

Potential impact: Moving towards a carbon- and energy grid-aware computing continuum that minimizes the carbon emissions of the energy it uses. The availability of renewable energy does not always match the demand and transmission capacity limits the possibilities to transfer electricity between regions. Storing renewable energy in batteries incurs lifecycle costs that negatively impact the sustainability of the energy system. Taking advantage of excess energy when it is available, and where it is available, improves the overall sustainability of the energy networks.

The role of a holistic data centre management system, overseeing both hardware and software components, ensures that every aspect of the data centres' operation is aligned with efficiency goals. Traditionally, data centres have operated under the paradigm of maintaining the lowest possible temperature to safeguard hardware integrity. However, with real-time insights provided by digital twins into the actual cooling needs based on operational loads and external conditions, data centres can afford to safely increase set temperatures. This adjustment not only reduces the energy consumed in cooling but also extends the lifespan of cooling equipment, further contributing to environmental sustainability.

Green Computing (including carbon-neutral computation) for all aspects of cognitive computing continuum is a key interest for government and industrial players in Japan and South Korea.

5.2 AI-assisted operation maintenance of large-scale systems

Context: Systems are becoming ever more complex. Whether new functionality is being bolted onto legacy systems, alternatively functionality creep, there are many systems millions of people rely on. So complex, such systems will never be completely understood, often maintained by teams of support people. A software engineering perspective is it takes **x1** time unit to find a bug when code writing, **x16** times when debugging and **x256** times when deployed or operational, see Software Engineering by Ian Sommerville.[118] Probably this is a very conservative estimate. And it is a time estimate only, not a cost estimate. DevOps is a strategy to mitigate or ameliorate the software engineering software doctrine.

Challenges: Components will fail in the computing continuum due to infrastructure or network failures, or an error during application deployment or operation. It is generally hard to track down the relevant information in the system logs and extract insights from them, and there is a large gap between human-operator insights, for example in network operations centres, and system-generated logs. New solutions and tools are needed both for collecting relevant metrics and logging information across the lifetime of an application in the continuum, and for extracting relevant insights from those logs and metrics, will be needed. Not only this, automatic

---

[118] https://amzn.eu/d/d5KWtm0

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 40 of 80   © 2024-2026 NexusForum.EU

interpretation of those insights and proposal of remediation actions to be approved by the user can make the fixing process more efficient.

AI can also help in transforming descriptions of actions in human language into commands scripts used in the fixing process. In addition, another challenge might be the automatic deployment of temporal monitoring dashboards based on descriptions provided using natural language. AI can assist in the interpretation of the requirements and in making available a user interface to make easier for the user to follow-up the process of handling issues. The resources devoted to running these temporal dashboards can be released once it is not needed anymore. In any case AI agents can learn from each case, using such a knowledge in the next incident. All these tasks can be carried out by specialised AI agents that could be eventually combined to generate end-to-end applications.

But not only maintenance can benefit from the usage of AI agents. Daily operation can make a leap forward thanks to AI agents able to understand natural language. Prompt engineering is emerging and will make operations more accessible for a wide variety of profiles, not only purely technical ones. As an example, AI agents can interpret natural language to carry out a zero-touch deployment with certain requirements being met. In addition, AI can make such a deployment optimal meaning it is the best solution for a problem that involves a series of parameterized constraints

R&D priorities:

- Developing and applying AI technologies for debugging and root cause analysis: State-of-the-art AI technologies, such as large language models (LLMs) and multi-modal models, have shown an impressive ability to understand context and extract insights from semi-structured data.

- Synthesize large quantities of data, including system logs, while providing a flexible human-machine-interface to query the system for relevant insights.

- Automatic interpretation of failure contexts and proposal of remediations, as well as AI-powered monitoring mechanisms such as temporal dashboards.

- A cybersecurity perspective for Security Operations Centre (SOC) teams to assess the degree of visibility they have over security incidents in the continuum for different Tactics, Techniques and Procedures (TTPs) from real-world threat scenarios.

  – Carry out the identification of the different data sources in the cloud environment.

  – Train an LLM to classify which information can be extracted and verify its completeness

  – Align the results with the techniques from well-established security frameworks (i.e., MITRE ATT&CK) to pinpoint how the threat monitoring capabilities of a SOC can be extended.

- AI-assisted log analysis capabilities to alleviate the workload of SOC analysts, reduce their fatigue and help them make informed and accurate decisions.

See also, section 6.5.

Potential impact: Large scale systems are key in many areas of most countries and trans-country operations. Disruption, outages and even partial operation affects many citizens. Investment in large-scale, particularly legacy systems is needed.

5.3 New paradigms for Compute Continuum

Context: Data is increasingly generated by devices and systems at the edges of the network. Continuous analytics of such data streams will require data management and analytics solutions that work in highly distributed environments. In use cases where these analytics workflows depend on previous data, or where the processing is distributed between edge sites, there is a need for efficient state synchronization mechanisms. Hence, there is a need for new paradigms for state management and continuous analytics in the Compute Continuum.

Both stateful and stateless architectures are widely used in applications[119]:

- In stateful applications, client data is saved on the server and carried over from one session to the next. This leads to faster processing an improved performance.

- In stateless applications, client data is not preserved between sessions. Instead, they use external entities such as databases or caches to manage state.

The choice of adopting either a stateful or a stateless architecture has important implications in terms of performance and scalability.

Serverless computing simplifies the deployment and operation of applications, by abstracting away the infrastructure layer. Stateful serverless could further simplify this by abstracting away state management and synchronization, especially in a distributed computing continuum.

Challenges: The EU has some way to compete with marking leading companies such as Amazon or Microsoft. Although small research projects on novel data structures exist (e.g. on Conflict Free Data Types), there is some way to go that could provide such functionality, at least to the public sphere. The perennial question of a European cloud infrastructure is pertinent. Some issues are computer science related, see the R&D challenges in the bullet point list below. A company to compete with the scale and reach of Amazon is probably beyond the scope of this document, however there are smaller challenges:

R&D priorities:

- State Synchronization: Develop mechanisms for seamless state synchronization between cloud and edge, ensuring consistency and reliability.

- Programming Models: Create programming models that simplify the development of stateful serverless applications for edge computing.

- Resource Utilization: Optimize resource utilization on edge devices to balance/trade-off workload distribution and energy efficiency. Multi-objective optimisation is one method to address resource utilisation.

- Data logs consumption: facilitating the decision-making and the automation of operational and cyber-incident handling. See also section 4.4.

Potential impact: Enable future stateful continuous analytics at the edge, which include various advanced IoT and digital twin use cases and applications. This would greatly reduce network traffic and latency for such use cases. Combining the stateful and serverless computing paradigms could similarly simplify management of applications that need to manage and synchronize state between sessions or users.

---

[119] *https://aws.amazon.com/blogs/architecture/converting-stateful-application-to-stateless-using-aws-services/*

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 42 of 80   © 2024-2026 NexusForum.EU

5.4   Safety critical applications in the computing continuum

Context: Complex systems (TOSCA).

Challenges: an increase in the number of dedicated critical software functions and complexity of the underlying hardware, operating systems, and communication networks is expected. This complexity creates the need for an orchestration layer that ensures the functioning of the overall system, especially when it comes to safety-critical operations.

At the same time, it imposes new challenges in system design practices and, consequently, in gaining acceptance from the public. Due to limited compute resources on devices, it is necessary to integrate compute resources from cloud data centres and edge. It is also necessary to address privacy concerns, particularly for distributed learning models.

R&D priorities:

Seamless cloud-device integration: Develop platform features that can seamlessly integrate cloud resources in onboard applications. Such integration with cloud infrastructure also enables the use of big data applications in the cloud. Thus, instead of being restricted to the data produced only within one owned system, other data sources become instantly usable using a high-availability database.

Security requirements: For safety-critical systems, the orchestration layer should be able to provide the hosting process with the capability to communicate with other processes through secure and real-time communication channels. Due to this security requirement, the operating system must ensure a safe environment such that the processes interact only through authorised channels.

Orchestration: Orchestration of computing resources and services is the key to enabling smart and compute-intensive services in the Cloud-Edge-IoT continuum. Many orchestration frameworks have been proposed in the recent past for cloud applications. However, the current orchestrators mainly focus on resource allocation and load balancing of small-scale hardware and additionally do not take real-time requirements into account. In this context, we should not only study how to reconfigure the node resources but also the impact of the reconfiguration on functional safety and the real-time requirements.

Potential impact: Next-generation intelligent systems are distributed by design, connecting multiple spatially distributed sensors, with high safety requirements and having to cope with a limited amount of energy and often limited cooling capabilities. However, their demand for integration of state-of-the-art AI components e.g., used for perception or classification tasks, typically require high-performance hardware. High-availability Cloud-Edge solutions with real-time considerations are key to bridging these constraints. To achieve this, we can use an AI-powered orchestrated approach, with a reduced response time relying on performance metrics as well as on non-functional ones such as energy consumption and security, among others.

5.5   The continuum performance: cross-layer optimisation

Networking context: A layer, often standardised, in an IT system implies the same behaviour on separated subsystems. Each layer has an identifiable functionality that designers and users depend upon. By optimising the layers, performance increase can be achieved at the cost of interoperability. In this section, network optimisation is selected somewhat as a forerunner, and as a runner up; the cloud infrastructure.

In a multi-provider Cloud-Edge continuum, *Cloud optimisation* becomes a distributed optimisation problem in which each entity has partial information and possibilities to adjust

operational parameters. Trying to optimize each layer separately will lead to suboptimal performance – this is the problem of local vs. global optimisation.

To exemplify why layering exists, a well-known system is TCP/IP, the dominant protocols of the Internet. TCP resides over IP. IP has two major versions, IPv4 and IPv6. The key insight is TCP needs minimal change to support to v4/v6 *due to protocol layering*. Again, these layers are defined as standards, in this case by the Internet Engineering Task Force, or IETF.

Challenges: The different layers of the continuum must be operated in a coordinated fashion. For example, in a data centre the distribution of workloads should be coordinated to optimize resource utilization and energy use of the cooling system.

R&D priorities:

System: Cross-layer protocol and mechanisms to coordinate the optimisation across different levels: 1) the cooling and resource utilization of the data centre infrastructure and individual servers; 2) meta-orchestration and workflow execution across machines and clusters; and 3) optimisations at the application and service levels. It is important that these coordinate network, data, and compute resources.

Network: Establishing a set of "standard" services and APIs to facilitate the optimisation across the Compute Continuum, service discovery, etc.

The "continuum" concept itself and the cross-layer approach with the existence of diverse APIs and different integration points, marketplaces, add-on catalogues and related resources have the drawback of dramatically expanding the attack surface for cyber criminals. A comprehensive approach to cybersecurity in the continuum is thus necessary so that European citizens will make the most of its multiple benefits. Internet of Behaviours (IoB) approaches the problem by means of analytical algorithms that study the behaviour of the network and the infrastructure and can anticipate the unfolding of cyberattacks without needing actually to access the data, just looking into behavioural patterns.

Moving towards "digital shadows" and "digital twins" of the continuum, here focusing on the data flows and the integrations needed to optimize the management of network, data, and compute resources across the Compute Continuum.

Potential impact: Hyperscalers have a big advantage, since they control their entire cloud stack from facilities to servers/hardware to service offerings. New AI-based solutions for managing the emerging Compute Continuum in a holistic way will improve resource utilization and reduce energy use across the multi-provider continuum. This will help cut down the costs of operation and provide a more viable and competitive EU alternative.

5.6   Towards a hyper-decentralized continuum

Context: A financial and technical solution where functionality is pushed away from the cloud to small and individual enterprises. An extreme variant example when moving away from the centralisation of the Internet and its services to customers and their hardware.

© 2024-2026 NexusForum.EU

Figure 5: Illustration of a future hyper-decentralized continuum

Challenges: Are we ready for millions of privately-owned edge nodes as part of a future hyper-decentralized continuum? It will be difficult for centrally governed continuum federation models to deal with scenarios in which many new providers join the edge computing market, or in cases in which the market becomes hyper-fragmented.

It may be possible for individuals or small entities (e.g. under a cooperative model) to purchase and set up their own edge computing servers powered by green energy, and to make them available for hosting locally-produced data under a principle of sovereignty or even to be commercialized under a pay-per-use business model to third-parties (including local cloud service providers (CSPs) requiring to occasionally increase the capacity of their data centres with additional resources in order to deal with unexpected peaks of demand).

This will challenge our current models of service discovery, trust, and management of the application lifecycle in the continuum, as well as the scalability of many of the platforms and services that initiatives like the IPCEI-CIS are expected to produce in coming years.

R&D priorities:

- Decentralized service discovery, for example using distributed hash tables, and payment methods in highly dynamic multi-provider scenarios.

- New decentralized security and trust mechanisms.

- New approaches for managing the continuum and application lifecycles in such a hyper-decentralized computing continuum. The enormous potential of Generative AI and the size of Large Language Models (LLM) pose challenges in terms of resources requirement in a constrained environment such as that of the Edge. It means that LLM architectures should be optimized and made smaller to make them suitable for Edge deployment, needing less memory, CPU, GPU resources for both training and inference. Using LLMs in the Edge can definitely contribute to hyper-decentralized continuum, to a more optimized use of resources, to energy saving and in general to

a better use experience with the applications and the data being closer to the user location.

- Mechanisms for smaller operators (even for individuals) to offer available compute resources when available.
- Trustworthy certification of program execution, proof of execution.

Potential impact: Greater flexibility for new players to join the cloud-edge market. It could enable a more sophisticated market that could take advantage of market dynamics, such as smaller players providing edge nodes that can take advantage of local availability of distributed renewables. Opening up for smaller entities to offer up their spare compute capacity would lead to more efficient use of existing compute resources. The quick response of starting/stopping computing workloads, hyper-distributed edge nodes could help take advantage of sudden bursts of local availability of distributed renewables, that otherwise would lead to grid instability and energy curtailment, to increase the sustainability and resilience of the overall energy system.

© 2024-2026 NexusForum.EU

6   Cloud-Edge for AI: Enabling and Facilitating AI Applications Across the Continuum

The Coordinated Plan on Artificial Intelligence[120] outlines the EU's strategy and approach to AI built on excellence and trust, putting people first and building strategic leadership in high-impact sectors, as elaborated in the *"White Paper on Artificial Intelligence: a European approach to excellence and trust"*[121]. The importance of securing critical computing capacity in the EU can be seen in several actions that have been implemented towards this plan, for example:

- The European Chips Act and Chips JU[122] (also section 3.5) which aim to address semiconductor shortages and enhance the European semiconductor industry.

- The European High Performance Computing Joint Undertaking (EuroHPC JU)[123] (also section 3.6) initiative to develop a world class supercomputing ecosystem in Europe.

- The Testing and Experimentation Facilities (TEFs)[124] to support technology development of components and systems for edge AI.

- The Important Projects of Common European Interest on Next Generation Cloud Infrastructure and Services (IPCEI-CIS)[125].

RISC-V has been identified as a key next-generation technology, and alternative to proprietary processor and accelerator solutions for the European computing continuum and High-Performance Computing (HPC) ecosystem.[126] The recent amendment of the EuroHPC JU Regulation to include the development and operation of AI factories,[127] further highlights the critical role of HPC in strengthening and supporting the European AI ecosystem. In the following sub-sections, several research and development needs for the medium to long term are listed, that can be identified from these challenges and developments. They are also aligned with the AI Innovation Package[128]. Although European cloud offerings span a wide spectrum of services, customers often need to collaborate with multiple providers to match the quality and breadth of services offered by leading global cloud providers. European cloud providers (including telcos) are in a unique position to be able to leverage proximity, resource optimisation, QoS evaluation, and regulatory compliance to enhance edge computing performance and address latency challenges.

---

[120] *https://digital-strategy.ec.europa.eu/en/policies/plan-ai.*
[121] *https://commission.europa.eu/publications/white-paper-artificial-intelligence-european-approach-excellence-and-trust_en.*
[122] *https://digital-strategy.ec.europa.eu/en/policies/european-chips-act, https://www.chips-ju.europa.eu/.*
[123] *https://eurohpc-ju.europa.eu/index_en.*
[124] *https://digital-strategy.ec.europa.eu/en/activities/testing-and-experimentation-facilities.*
[125] *https://www.bmwk.de/Redaktion/EN/Artikel/Industry/ipcei-cis.html.*
[126] *https://eurohpc-ju.europa.eu/new-call-developing-hpc-ecosystem-based-risc-v-2023-02-01_en.*
[127] *https://eurohpc-ju.europa.eu/ai-factories-amendment-eurohpc-ju-regulation-enters-force-2024-07-09_en.*
[128] *https://ec.europa.eu/commission/presscorner/detail/en/ip_24_383*

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 47 of 80   © 2024-2026 NexusForum.EU

Cloud-Edge for AI – Working Group scope:

Datascapes, Data exchange (advanced capabilities), AI tools for FL and lifecycle of AI models, support data-driven applications, digital twins, application deployment, things that need to run on a Cloud-Edge infrastructure, require complex orchestration, identity and observability across multi-provider continuum.

Provide integrated services such as application lifecycle management to build, deploy and maintain apps all over the Compute Continuum - platform services -; data management to ease data ingestion, transformation and analysis in a multi-provider, federated environment in accordance with European regulation - data platform; and innovative data processing leveraging AI and ML - smart processing services.

6.1   Portable AI applications and an open AI ecosystem

Context: Cost and ease of use are major factors when choosing cloud service providers. For many organisations, the high costs and specialised expertise required to develop, operate, and maintain its own technology stack for developing and deploying AI applications, are a major challenge. Portability refers to the ability to move (AI) applications from one platform or service provider to another, without any or extensive adaptations to the software stack. Many have been drawn into the cloud service ecosystems of the global hyperscalers, due to the convenience provided by the broad and integrated service ecosystem offered by them. These service ecosystems make it easy to develop and deploy data-driven applications and AI but also lead to vendor lock-in since it is prohibitively expensive to move a system from one provider to another. This applies both to private and public sector, and in particular SMEs that can use free credits to quickly create systems based on cloud technologies and AI.

Challenges: One major challenge for Europe is that European datacentre providers lack the resources required to offer such broad and complete AI service ecosystems. Different use cases and applications will require different types of AI models, and different ways of training and deploying them. We can expect increased hardware heterogeneity as new AI-optimised hardware becomes available for different parts of the spectrum, for example supercomputers and devices. AI technology stacks should not be restricted to Cuda and x86. One approach is porting ML libraries, and another one is creating ML compilers – both need to be supported to facilitate a "technology neutral" computing continuum. There is a need to standardize models/formats that are used for communication, so they can execute efficiently on different platforms. Public funding can help develop an AI service ecosystem by building and demonstrating it on open standards and open-source components.

AI workloads can be resource-intensive and require careful orchestration to ensure efficient use of cloud resources. EuroHPC provides high-performance computing (HPC) resources for AI development, with plans to expand the capacity, but traditional HPC is sometimes considered too different or too complicated for some companies. For example, file management, such as moving files from the cloud to the supercomputer, can take time during (AI) model training.

Tools like the meta-orchestration platform ColonyOS[129] can be beneficial as they create a level of abstraction, for example simplifying file management and deploying cross-platform applications.

---

[129] https://colonyos.io/

© 2024-2026 NexusForum.EU

R&D priorities: Develop an AI service ecosystem built on open standards and open-source components, including:

- Efficient and scalable data management from IoT devices in the continuum.

- Inference in the continuum, including i) where to perform inference in the most energy-efficient way, ii) capabilities for running inference, which connects to virtualization topics (section 6.4), iii) compatibility with a distributed network of compute services.

- Training in the continuum, for example integrating HPC resources or solutions for distributed/federated learning use case.

- MLOps solutions in the continuum.

Develop technology-neutral and efficient execution on different platforms:

- Software-hardware co-design and solutions for optimising the AI stack as new hardware architectures become available, in collaboration with efforts in 6.3.

- Develop AI compilers, e.g. from Python to native, to facilitate cross-platform by design.

- Develop more energy-efficient AI solutions through software-hardware co-design.

- Efficient resource allocation for AI workloads in the HPC integrated continuum: Develop strategies for dynamic resource allocation based on workload requirements to optimize resource usage in the Compute Continuum for AI.

Lastly, there is a need to establish open standards and APIs for an AI ecosystem in the computing continuum by standardizing models and formats used for communication, so they can execute seamlessly on different platforms.

Potential impact: An open AI service ecosystem can enable a seamlessly interconnected multi-provider computing continuum, facilitate collaboration between different parts of the value chain, and increase "technology neutrality" in the continuum. Open standards and APIs can create new markets and opportunities. For example, it would be possible to have brokers that provide AI services that are portable in the computing continuum.

Investing in technology-neutral technologies will address hardware heterogeneity and make the software stack and skills more portable and robust, avoiding high reliance on vendor-specific hardware-optimized software, such as cuDNN.

See also section 6.2 and 6.5.

6.2   Integrating HPC in the Cognitive Computing Continuum

Context: With a budget of EUR 7 billion for the period 2021-2027, the EuroHPC JU coordinates efforts and pools resources across Europe to develop and maintain a *"world-leading federated, secure and hyper-connected supercomputing, quantum computing, service and data infrastructure ecosystem,"* to boost scientific excellence and industrial strength in Europe.[130] The *AI Innovation Package* further establishes the important role of the EuroHPC supercomputer ecosystem in the future development of general-purpose AI in Europe, through the development and operation of AI Factories and supercomputers optimised for AI.[131] As an example, the flagship initiative Destination Earth (DestinE)[132] will exploit the distributed high-

---

[130] https://eurohpc-ju.europa.eu/about/discover-eurohpc-ju_en
[131] https://digital-strategy.ec.europa.eu/en/factpages/ai-innovation-package
[132] https://destination-earth.eu/

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 49 of 80   © 2024-2026 NexusForum.EU

performance computing provided by EuroHPC to develop a highly accurate digital model of the Earth on a global system. DestinE will further consolidate access to valuable sources of data across Europe and represents a key component in the European strategy for data and will contribute to the twin transition, green and digital.

In May 2024, the United Kingdom joined the EuroHPC Joint Undertaking, becoming the 35th participating state. This inclusion allows UK researchers and scientists to apply for Horizon Europe-funded EuroHPC JU Research & Innovation calls, enhancing collaboration and resource sharing across Europe. The UK's expertise in supercomputing will contribute significantly to Europe's objective of becoming a global leader in HPC and quantum computing. Additionally, the Hanami Project, a collaboration between Europe and Japan, was established. It aims to promote scientific projects involving both European and Japanese institutes. This project facilitates access to supercomputers in both regions, tackling exascale areas and beyond. Hanami focuses on priority domains such as climate and weather modelling, biomedical sciences, and materials science, fostering a sustainable collaboration between Europe and Japan.

Challenges: It is difficult for industry to adopt EuroHPC JU supercomputers due to various challenges associated with HPC environments, such as differences in software stacks compared to cloud services. For example, there are significant differences in IT environments (e.g., Kubernetes vs. Slurm), and processes for deploying multi-cloud federations involving cloud, edge, and HPC resources. Additionally, the heterogeneity of HPC constitutes a challenge. For instance, the EuroHPC system LUMI, which uses AMD processors, uses the ROCm open-source software stack, while NVIDIA has its proprietary CUDA stack. However, machine learning libraries are not as mature on AMD GPUs compared to NVIDIA. Development and improvement of these open-source stacks are required to help bridge the gap between different HPC systems. Over time, as EuroHPC adopts new processors manufactures in Europe based on ARM and RISC-V, there will be a need for optimizing software for different hardware architectures. For example, HPC systems can have compatibility issues with standard Machine Learning (ML) libraries due to differences in their software stacks, which can hinder the development and deployment of AI services in the cloud.

R&D priorities: Reduce the skill gap for HPC by providing concrete scenarios and guidelines to help industries understand and overcome these challenges. There is a particular need to bridge the gap between EuroHPC supercomputers and EU cloud ecosystems, embracing a hybrid cloud paradigm:

- Promote the development of an open-source ecosystem to facilitate the integration of HPC and Cloud services.

- Encourage the use of and further develop open-source software stacks to enable highly performance training of AI models in EuroHPC supercomputers.

- Simpler user interfaces and better portability of workflows would make it easier for companies to adopt HPC and integrate it with their cloud deployments.

- Support projects like EPICURE, which aims to enhance user support by establishing and operating a distributed but coordinated European HPC application support service. EPICURE encourages the best possible uptake of HPC systems by European researchers, fostering a collaborative environment for HPC and AI development.[133]

- Optimize strategic open-source software, including system software and libraries for AI, for EuroHPC architectures to enable full use of emerging and installed architectures.

---

[133] https://epicure-hpc.eu/

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 50 of 80   © 2024-2026 NexusForum.EU

Potential impact: Foster the industrial uptake of EuroHPC and AI. If implemented, this solution would make it easier for European startups and industries to adopt HPC and leverage the EuroHPC initiative, potentially leading to more efficient use of resources, significant cost savings, improved competitiveness of EU industry in AI technologies, and advancement towards the Computing Continuum. These challenges are also relevant for cloud computing and the introduction of new hardware architectures, synergizing with 6.3 and 6.4.

6.3   RISC-V in the Cognitive Compute Continuum

Context: Over the past decade and a half there has been significant investment in implementing European processors targeting both HPC and embedded and IoT applications. The EU goal is the production of cutting-edge and sustainable semiconductors in Europe, with at least 20% of world production in value by 2030, including manufacturing capacities below 5nm nodes, aiming at 2nm, with an aim to improve energy efficiency by a factor 10. To achieve this the RISC-V ISA plays a central role in EUs strategy. The European efforts, spanning the Compute Continuum, expose a strong European commitment to a joint European ecosystem based on RISC-V.

Challenges: Today's Compute Continuum is dominated by Intel's x86 in cloud/HPC and by ARM's 32- and 64-bit Instruction Set Architectures in edge and embedded domains, and most tools and techniques used in these domains are specialised for this architecture. ARM has recently made the push towards cloud and HPC which has resulted in significant efforts to port applications such as container managers, hypervisors, AI frameworks, as well as OS drivers for hardware. For broad adaption RISC-V also needs to address these software aspects as outlined in previous roadmaps and identified in the RISC-V community through collaborations such as RISE[134]. Recent results points to a performance gap to established non-European proprietary instruction set architectures[135] which must be closed to enable wide-spread adoption of RISC-V. Furthermore, the openness of RISC-V leads to faster innovation cycles which opens the question of how to manage and abstract increasing diversity of RISC-V computing hardware from end-users (and expose when necessary)[136].

R&D Priorities: Software tools and technologies to handle the unique challenges and opportunities with fast-innovation open instruction set architectures should be researched to abstract and manage expected increase in hardware diversity. Additional development needs are required to port software tools and technologies relevant to the Compute Continuum to RISC-V and close the performance gap to systems deployed on established platforms, these include above identified known challenges as well as other challenges identified in this chapter, including the challenges in section 6.2 and 6.4. The efforts rely on retained momentum in ongoing RISC-V hardware efforts, including for AI, supported by EuroHPC JU and Chips JU to drive demand and generate necessary spillover effects in European RISC-V hardware. Industry sectors across the Compute Continuum may have other needs than e.g., HPC, automotive, and space. Therefore, key use cases from these cognitive computing continuum industry sectors, and their supply chains, should be identified and used to drive additional software and hardware research and development needs for the European ecosystem, complementing ongoing Chips and EuroHPC initiatives.

---

[134] RISE: RISC-V Software Ecosystem, Linux Foundation, https://riseproject.dev/

[135] Francesco Lumpp, et al, "On the Containerization and Orchestration of RISC-V architectures for Edge-Cloud computing," ESAAM'23, 2023.
Robert Balas, et al, "CV32RT: Enabling Fast Interrupt and Context Switching for RISC-V Microcontrollers," IEEE Transactions on VLSI Systems, 2024.
Andrea Bartolini, et al, "Monte Cimone: Paving the Road for the First Generation of RISC-V High-Performance Computers," SOCC'22, 2022.

[136] https://digital-strategy.ec.europa.eu/en/library/recommendations-and-roadmap-european-sovereignty-open-source-hardware-software-and-risc-v

Co-funded by
the European Union

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 51 of 80   © 2024-2026 NexusForum.EU

Potential impact: European RISC-V hardware and software ecosystem can be extended to encompass the entire cognitive Compute Continuum, extending the European ecosystem and leveraging technology spillover effects from R&D in HPC (EuroHPC JU), automotive, and space (Chips JU), while at the same time strengthening the ability to adopt RISC-V across more European industrial sectors. Ongoing European efforts in selected industries serve as key locomotives in this strategy, but as outlined in e.g., 6.2, there is additional potential for the European RISC-V ecosystem in making it adoptable by a larger share of the economy. Efforts in this domain synergize with 6.2 and 6.4.

6.4   A Middleware Toolkit for the Continuum

Context: The Compute Continuum will almost certainly be a heterogeneous set of hardware and software systems. Therefore, running applications on different architectures, such as ARM, Intel (x86), RISC-V and differing operating systems makes it hard to find a one size fits all for software developers coding in the continuum. In large organizations even specialised teams e.g., IOS, Android are needed. Tools applying the Infrastructure as Code (IaC) approach, such as Ansible, may help, but are still often too error prone. There are several ongoing open initiatives to address this problem, including the open W3C standard called WebAssembly[137] and the open LLVM[138] project, a collection of modular and reusable compiler and toolchain technologies, with its associated Multi-Level Intermediate Representation (MLIR)[139] project. These initiatives enable producing code from (m)any high-level languages. The expression "write once, run everywhere" typically formulates this principle.

Challenges: Closing the performance gap with native binaries. There is about 1.2 performance penalty compared to natively compiled code. For full utilization of MLIR domain specific languages offer higher levels of abstractions that facilitate multi-level code generation across heterogeneous targets. AI development is strongly driven by domain-specific languages, but this is less pronounced in software development in many industry domains.

EU-specific Challenges: Europe is strong in compiler and programming language technology. Startup ecosystem needed around WebAssembly, as well as large company adoption. Promoting usage in series such as the Dagstuhl seminars[140].

R&D priorities:

- A modern middleware, and support for lightweight virtualization/container technologies: Use compiler technology to produce machine-like code for any architecture. Support for lightweight virtualization technologies on devices, such as WebAssembly or Unikernels, is needed.

- Heterogeneous Computing Support: Improve support for heterogeneous computing environments to ensure efficient AI workload execution across different hardware architectures, and in particular interoperability with RISC-V.

- Open and community-driven development: Promote a community-driven approach to foster innovation and contributions to open ecosystems, such as the LLVM and MLIR ecosystems.

- Standardization and collaboration: Encourage standardization and collaboration among industry stakeholders to accelerate the development of open compiler infrastructures.

---

[137] https://www.w3.org/groups/wg/wasm/, https://webassembly.org/.
[138] https://llvm.org/.
[139] https://mlir.llvm.org/.
[140] https://www.dagstuhl.de/en/seminars/dagstuhl-seminars

© 2024-2026 NexusForum.EU

Potential impact: Harmonize the Compute Continuum, using open standards, according to the principle "write once, run everywhere". Factory 4.0 and 5.0 as well as systems with many IoT devices are ideal candidates.

6.5 Operationalization of future AI systems in the Computing Continuum (GenAIOps)

The term GenAIOps refers to successfully implementing, overseeing, and refining AI applications in a heterogeneous and constrained networked computing environment. [141] The term encompasses best practices from other operational best practices such as DataOps (Data Operations), LLMOps (Large Language Models Operations), and DevOps[142].

Context: It is common knowledge that the implementation of AI techniques in the computing continuum is not only desirable but also necessary to support future applications and continue to evolve. Certain requirements, like power consumption or storage, make the application of AI techniques particularly difficult when discussing certain computing continuum components, like Internet of Things devices. Moreover, the deployment is made even more difficult by the inherent heterogeneity of the computing. Mechanisms to function and improve the AI implementation are essential in this situation.[143] For instance, the minimization of the various elements that comprise the computing continuum can facilitate the operationalization of Generative AI applications. Techniques such as the reduction of the data transmitted between the various computational layers, and the minimization of the operational resources of the models facilitate the operationalization of such models.

Challenges: Deploying emerging AI learning technologies in the continuum introduces new challenges. Specifically, Large Language Models (LLMs) and Foundation Models (FMs) are very large and costly in terms of resources such as power, time, and storage, and therefore challenges the lower/smaller end of the continuum. Other issues for the continuum are heterogeneity and full-stack dependencies. Infrastructure needs for FM training and inference, i.e., pre-trained on vast amounts of unstructured data to learn complex concepts, need to be addressed. [144] [145]

R&D priorities:

- *Dynamic Orchestration*: Implement comprehensive OS solutions to simplify the deployment of future AI systems in the continuum addressing the specific needs of future AI models, such as FMs and LLMs plus the combination of classic ML models. A computational aspect is to use compression techniques to reduce computational cost, memory footprint and energy consumption. An example is to enable edge-based deployment such as using TinyMLOps.

- *Computational strategies for AIOps*: Training and deploying generative AI models can be resource-intensive, requiring significant computational power and storage. A computational strategy to address this challenge might imply the usage of compression techniques to reduce computational cost, memory footprint and energy consumption. An example is to enable edge-based deployment such as using TinyMLOps.

- *Security and privacy*: Security and privacy are critical concerns when it comes to generative AI systems. Given the widespread and diverse nature of computational

---

[141] *Continuum AI: Integrating Foundational AI Agents with the Cognitive Computing Continuum*
[142] *https://www.karini.ai/blogs/navigating-genaiops-in-enterprises*
[143] *The Operationalization of AI*
[144] *https://dl.acm.org/doi/full/10.1145/3625289*
[145] *Autonomy and Intelligence in the Computing Continuum: Challenges, Enablers, and Future Directions for Orchestration*

resources and the intensive use of ubiquitous data in generative AI systems, security and privacy challenges must be addressed from a holistic perspective. Issues such as data poisoning, output manipulation, an increased attack surface, and limited resources for robust security measures necessitate novel approaches to secure the entire supply chain of generative AI systems.

Potential impact: European competitive advantage and independence for upcoming AI solutions deployed in the continuum.

6.6   Federated computation for Foundational Models

Context: The radical shift of Federated computation for Foundational Models training could lead to more specialised and efficient AI architectures that are capable of handling the complex demands of training large-scale neural networks while preserving privacy and leveraging distributed data sources. This shift is part of the broader trend towards more powerful and versatile AI systems that can be adapted for a multitude of business and consumer applications.

Federated computation could play a significant role in the future of AI training by enabling more efficient and privacy-preserving methods to train foundational models. The creation of foundation models, which are a subset of large language models, has changed the methodology of how AI can be created. These models can be adapted for a wide variety of use cases with much higher productivity than before. Federated computation could further enhance this by allowing for distributed training across various devices and data centres, potentially leading to more robust and widely applicable AI models. Federation computation also has the potential to comply with the stringent requirements of existing regulations outlined in section 2.2. In addition, it promotes the potential of efficient use of resources by leveraging the computational power of the infrastructural devices in the edge of the network, which can reduce the load on other servers in the architecture and the network. Finally, the possibility of keeping the data on local devices significantly reduces the risk of data breaches and unauthorized access. Further information is found e.g. in the reports by Woisetschläger et.al and Zhuang et.al. [146], [147]

---

[146] *Woisetschläger, H., Isenko, A., Wang, S., Mayer, R., & Jacobsen, H. A. (2024). A survey on efficient federated learning methods for foundation model training. arXiv preprint arXiv:2401.04472.*
[147] *Zhuang, W., Chen, C., & Lyu, L. (2023). When foundation model meets federated learning: Motivations, challenges, and future directions. arXiv preprint arXiv:2306.15546.*
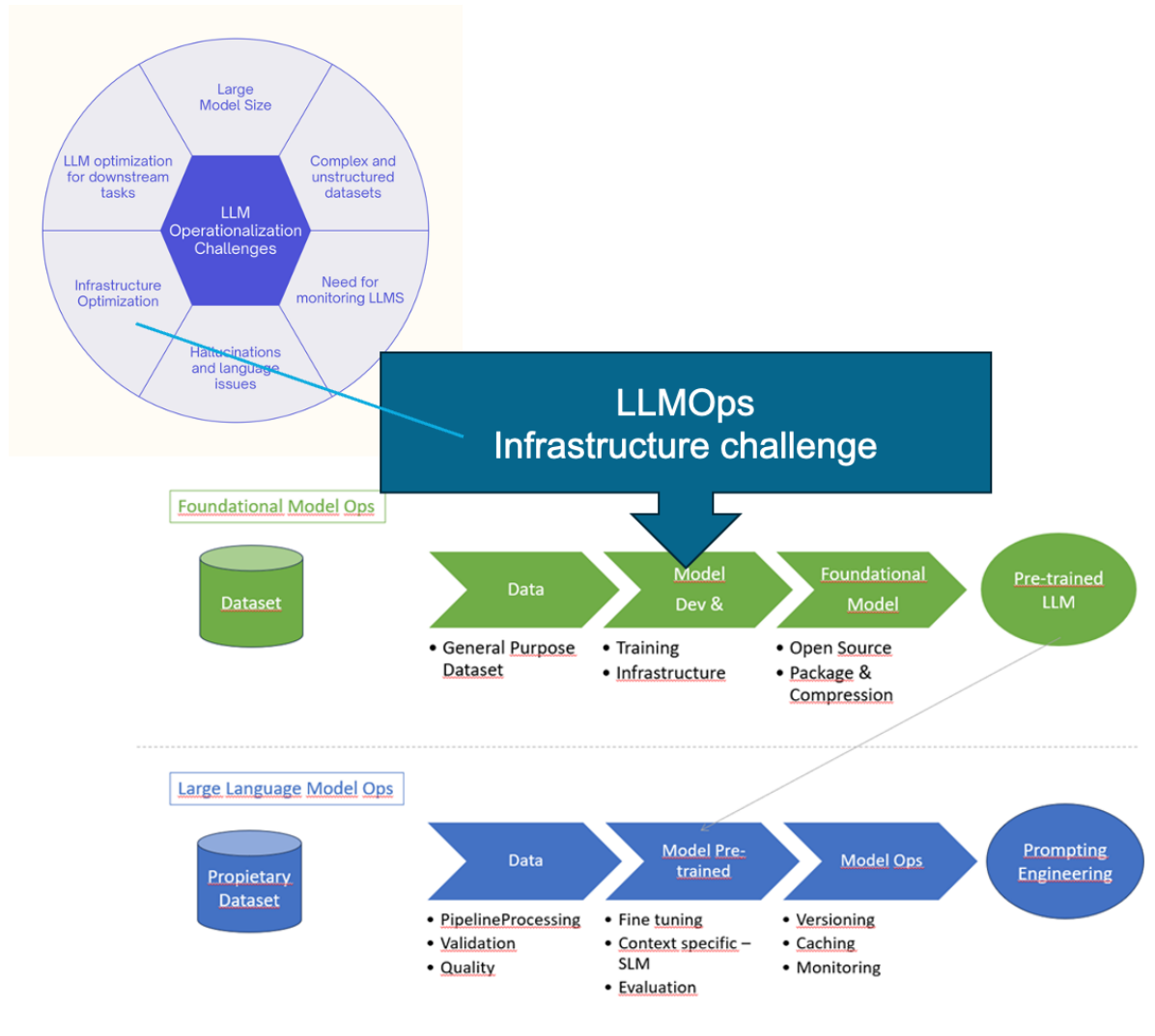
Figure 6 Large Language Models Operations (LLMOps)

Challenges: Most LLMs are highly demanding and mainly use high performance computing grade equipment. The training of the foundational models (FMs) can take advantage of the recent advances on GPUs and use the computation offered by the Open continuum in what is called "Federated Computation". Implementing federated computation in LLMs is a complex task that requires careful consideration of technical, ethical, and legal aspects. It's a multi-disciplinary effort that involves advancements in machine learning, data privacy, and distributed systems. The high complexity of foundational models and the resource heterogeneity found in federated computation makes the process even more cumbersome. In addition, communication efficiency and scalability issues must be addressed, as well as data privacy and security concerns.

R&D priorities: Implementing federated computation for large language models (LLMs) requires several key considerations:

- The implementation of federated computing for Large Language Models (LLMs) requires establishing a distributed network infrastructure with reliable communication protocols.

- Prioritizing data privacy through techniques like differential privacy or secure multi-party computation.

- Adapting LLM designs to support federated computation may involve modifying them for decentralized data sources and partial updates.

Potential impact: Developing efficient federated computation algorithms capable of handling LLM complexity is imperative for effective model aggregation. Additionally, optimizing resources ensures scalability and efficiency, while rigorous evaluation and testing across diverse data distributions and network conditions ensure performance. Encouraging user participation through transparency and trust-building measures and continuous monitoring for issues like data drift are also vital. Fostering collaboration among academia, industry, and regulatory bodies is essential for standardizing federated computation methodologies and advancing LLMs.

6.7   Large-scale testbeds for AI services

Context: there is a dominance from US actors that develop AI with possibly non-EU values. Which makes it urgent to enable both information exchange and to create environments where information can be shared, i.e. there is a need for similar infrastructure environments. These areas tie into many common technical challenges, and in this section, there is a focus on the regulations and barriers, and which types of specific AI Testbeds will be needed in practice.

Challenges: There is a need for large-scale testbeds that can simulate real-world conditions for testing AI services, pipelines, and workflows in the computing continuum. Without such test environments, it's challenging to validate and optimize these services for use in operational conditions. There is demand for an International Testbed for "Cross-border Data flows", for example with Japan and South Korea, considering the "Cross-border Data flow deal" signed between EU and Japan.

R&D priorities:

- Develop large-scale testbeds that can accurately simulate real-world conditions, enabling thorough testing and optimisation of AI services, e.g. AI Factories.

- Real life 5G/6G-integrated Compute Continuum testbeds for projects developing applications using the low latency introduced by edge computing in 5G networks, and for projects optimizing the digital infrastructure, software architectures, and operations and management of such networks of computation and communication.

- Managing cross-border data flows.

Potential impact: Implementing this solution would allow for more robust testing of AI services, leading to improved performance and reliability in operational conditions. They would provide a "testing ground" for gathering operational data to drive further advances in AI-enabled Cloud-Edge management.

6.8   Data privacy and security in AI services

Challenges: Data-driven insights can contribute to vital decisions in many domains (e.g. crisis management, predictive maintenance, mobility, public safety, and cybersecurity). However, obtaining the trust of decision makers to exploit data-driven insight is still a pending issue due to i) the data and their fluctuating quality and volumetry and ii) the finality of big-data processing not necessarily suited to decision-maker comprehension.

R&D priorities: Implement robust data protection measures and comply with regulations like the AI Act to ensure data privacy and security in AI services:

- The development of advanced privacy toolkits. Solutions that can focus on the encryption of data records by exploring attribute-based encryption and proxy re-encryption, symmetric encryption, and searchable encryption. Additionally, could consider the combination of Searchable Encryption and Distributed Ledger Technology (DLT) platforms.

- End-to-end secure privacy-preserving AI pipelines leveraging confidential computing technologies.

- Ensure privacy in the information exchange and certification processes. The application of Zero Knowledge Proof technology and Layer 2 solutions like ZK-EVM (Zero Knowledge Ethereum Virtual Machine) could help too as a part of the solution.

Potential impact: AI services often require access to sensitive data, making data privacy and security a significant challenge. This is especially true in multi-provider cloud federations where data might be stored and processed in different jurisdictions with varying data protection laws. Implementing this solution would increase trust in AI services and could lead to wider adoption, particularly in sectors handling sensitive data.

6.9   Confidential computing

Context: Confidential Computing comes into scene to solve the persistent problem related to the security of data when they are outsourced to the cloud. With the wide acceptance and adoption of the Continuum concept including all its advantages, the security problem has been amplified and extended to all tiers of the Continuum. Confidential Computing provides security to the data-in-use by means of operations performed in a hardware-based Trusted Execution Environment (TEE). Executing code inside a TEE makes it both invisible and inaccessible to any unauthorized party, including the operating system itself. Extending this reasoning, the concept of Confidential Virtual Machine (CVM) was born. CVMs are characterized by the fact that they are run entirely within a TEE, what makes them secure. Secure and confidential computing supported all the way down to the hardware level could enable new applications with stricter data privacy requirements. Parts of this solution exist today, such as secure enclaves and Trusted Execution Environments, in a commercial context, for example solutions from Intel, SGX and TDX, AMD, SEV-SNP and IBM.

Challenges: The usage of confidential VMs have to do with the more general concept of Confidential Virtualization. Despite the notable progress in the subject, there are still notable challenges posed by heterogeneous platforms that work on top of extremely dynamic multi-provider infrastructures that are geographically distributed, present constraints in the use of computation resources and are connected to public networks

The various CPUs and solutions require different toolchains, as compiler support is needed to mark code parts that should execute in the enclave. A turnkey confidential computing functionality not dominated by a large, single player does not really exist. This fragmentation and lack of standardization is similar with, for example, HPC.

R&D priorities: All the R&D efforts should go in the direction of achieving confidential clouds to eventually have a confidential continuum well protected end-to-end against external threats, where data is secure at rest, in transit and in use, while at the same time satisfying the requirement of being multi-provider and avoiding vendor lock-in. Open source management, automation, and orchestration of resources with the support of AI need to be adapted to be an effective part of a confidential environment.

Portability of confidential VMs across the Continuum. Open architectures for the hardware part, see further regarding the enclaves at RISC-V[148] and section 6.3. Increased support for different hardware solutions in virtualization/container technologies. Multi-tenancy in data centres allows access to parts of datasets, often Kerberos based. Securing and trusting the endpoints, think "TLS++" as a concept, in which one can trust the endpoints of the connection, the keys, and the end architecture.

Potential impact: Confidential computing is enormous and up till now, unresolved. People, companies, organisations, even countries could gain value by sharing data, or parts thereof, but they do not or cannot. Therefore, it is a huge opportunity for Europe to take the initiative and the leadership in the race with hyperscalers to achieve a confidential continuum that protects sensitive data and communications. In consequence, confidential computing becomes a fundamental characteristic for the future European Technology Stack meant to lay the foundation of the European Digital Sovereignty. Additionally, it can boost the European Technology Ecosystem based on open source solutions and increase European digital competitiveness

6.10 Data spaces for AI

Context: Within the EU Artificial Intelligence Act (AI Act), GenAI is considered as a type of general-purpose AI model (GPAI)[149], and it is described as a highly capable model trained on large and diverse datasets and designed to perform a wide variety of tasks with a significant generality, allowing them to be integrated in a variety of downstream systems[150]. Data Spaces are "Interoperable frameworks, based on common governance principles, standards, practices and enabling services, that enable trusted data transactions between participants. Data Space enabling services are implemented by one or more infrastructures"[151]. The common European data spaces were introduced in the EU data strategy[152] and are also referenced in the Data Governance Act[153] and the Data Act[154] fostering qualities or characteristic related to interoperability, collaboration and the creation of synergies among data spaces, as well as promoting European values and rules, and the extended purpose beyond business value, Both GenAI and common European data spaces are interrelated components of the EU digital strategy to foster a robust and secure digital economy and promote innovation.[155]

Challenges: Artificial Intelligence (AI) systems require robust and diverse datasets to learn, adapt, and provide accurate outputs. These datasets can be produced by different stakeholders or companies and stored along the cloud continuum from edge devices to fog or cloud environments. Each data producer can have different strategies for data sharing, including monetization of data, constraints on the companies allowed to use the data and the expected use of the data. Furthermore, trust, data sovereignty and data quality are paramount to create a data governance framework able to build AI solutions using data spread all along the cloud continuum. Data Spaces are crucial in this context as they provide the infrastructure for secure data sharing and management, which is essential for the development and

---

deployment of AI. Data space technology still lacks the maturity level needed for seamless deployment in a cloud continuum environment. However, current initiatives in the EU, like Gaia-X, IDS and the SIMPL project among others are designing and developing the standards, tools and frameworks needed to facilitate the creation and operation of data spaces.

R&D priorities: Data spaces hold significant promise in enabling diverse opportunities within Generative AI (GenAI). However, to fully capitalize on this potential, several critical challenges must be addressed. These challenges, inherent in the current design and implementation of data spaces, can hinder the seamless and efficient integration of data spaces with GenAI technologies. The following challenges outline the key barriers and their implications for realizing the synergy between data spaces and GenAI:

- *Interoperability and simplicity*: AI systems must effectively work with data from diverse domains and sources. To achieve this, Data Spaces must adopt interoperability standards that enable seamless integration and analysis of data across various platforms and environments. However, the current state of Data Spaces lacks simplified and harmonized access to cross-sectoral and federated data. For stakeholders such as startups, SMEs, and initiatives contributing to European AI infrastructure (e.g., AI factories), connecting to each individual data space to meet training data needs is impractical. Ad-hoc solutions to data access reduce efficiency, highlighting the urgent need for a unified approach to accessing these diverse and distributed data resources.

- *Data Representation, Diversity, and Quality in GenAI Development*: For Generative AI (GenAI) models to perform effectively across a variety of scenarios—both within specific contexts and while generalizing—the datasets accessible via data spaces must be diverse, high-quality, balanced, and represent a wide range of domains, topics, contexts, and modalities. Achieving this requires rigorous data cleaning, validation processes, and continuous monitoring to maintain the integrity and usefulness of the datasets. High-quality data must capture a broad spectrum of variations, including different modalities and linguistic differences, ensuring models can adapt to diverse inputs and scenarios. The development and management of data spaces face several challenges:

  - Scaling Adoption: Encouraging broader adoption of common European data spaces is critical to enhance access to diverse data sources and expand possibilities for training GenAI models.

  - Complexities in Design and Management: Addressing design and management issues is crucial to meet the requirements of GenAI. This involves creating design methodologies and components that cater to GenAI-specific needs, such as data models, provenance, traceability, data quality, governance, and ethical considerations. Failing to address these complexities could lead to inefficiencies, inconsistencies, and obstacles in leveraging data spaces effectively.

- *The Role of Data Spaces in the Compute Continuum*: Data spaces are distributed across the computing continuum, where data may be produced and processed at multiple levels by entities with differing data policies. To support GenAI effectively, data space solutions must accommodate this diversity and enable seamless operation across the Compute Continuum. The key considerations include:

  - Data Availability: AI models require access to large volumes of data to train effectively. Data spaces facilitate the aggregation of data from various sources, making it readily available for AI processing, including methods derived from high-performance computing (HPC) workloads.

  - Data Governance, Security and Privacy: Security and Privacy: Protecting sensitive data is critical, especially when used in GenAI applications. Data

Spaces provide secure environments that protect data privacy and ensure that GenAI systems are not exposed to data breaches or unauthorized access.

- Data Quality and Integrity: The performance of AI models is directly linked to the quality of data they are trained on. By leveraging data spaces to maintain high-quality standards, it is possible to ensure that training data is accurate, complete, and reliable, thereby improving AI outputs.

Potential impact: Ensuring that GenAI models are built on a foundation of diverse, high-quality, and well-governed data is crucial. This requires overcoming challenges in scaling adoption, managing complexities in data space design, and addressing issues related to data quality and governance. Data spaces play a pivotal role in supporting GenAI development by providing robust, ethical, and efficient frameworks across the Compute Continuum.

7 Telco Cloud-Edge: Telco as One of the Main Tenants and Infrastructure Providers

Europe has enjoyed a long-standing history as a global leader in the telco industry, but there are potential risks to this position. As the telco industry moves toward a landscape with increasing integration of cloud-native frameworks and open paradigms, such as Open Radio Access Networks (O-RAN)[156], the traditional telco industry in Europe faces competition from non-EU cloud and tech industry. This marks a pivotal shift towards more dynamic and interoperable infrastructure. The transition is crucial not only for maintaining Europe's leadership in the global telco industry but also for enhancing its competitive edge in an increasingly digital world.

Furthermore, Europe's economy faces a considerable risk due to the EU's slower progress in expanding fibre coverage reaching 56% of European households[157] and rolling out standalone 5G networks covering 81% of the population[158], but lagging behind in 5G standalone deployment, particularly in contrast to the advancements seen in regions such as South Korea and China. This not only hampers the industry's ability to remain competitive but also reduces the possibilities for collaboration, underscoring the urgency for Europe to accelerate its cloud and network infrastructure developments to support the capabilities of the telco industry.

These challenges, and the convergence of connectivity and computing, are outlined and discussed in the white paper *"How to master Europe's digital infrastructure needs?"*[159] which proposes the creation of the *"Connected Collaborative Computing Network"*, or "*3C Network*". Several research and development needs for the medium to long term can be identified from these challenges and developments.

- *Open reference architectures* that include standards for open cloud and edge infrastructure, AI-based predictive maintenance of datacentres and cloud and edge infrastructure, advanced networking, synchronization of time and requirements across providers, automated operations, and APIs for bare-metal as a service.

- *Optimized infrastructure design* focusing on innovative data centre designs that include advanced simulation and digital twin technologies for predictive capabilities. This is done alongside improvements in security, accessibility of physical infrastructure, open hardware and operating systems, operation management & monitoring (including network orchestration with multi-cloud orchestration), network functions at the edge, and connectivity between cloud and edge at scale.

- *Scalable and secure edge deployments* by establishing robust next generation edge infrastructure (forward-looking data centre facilities, servers, storage, mobile and fixed/stationary interconnections) to manage the technological complexity of the meshed continuum.

- *Forward-Looking infrastructure for building next-generation data centre* facilities and network connections that support the complex requirements of a fully integrated Cloud-Edge continuum. Develop and set up physical and logical linking of networks including integrated smart network services for the Compute Continuum to ensure seamless connectivity between cloud services and edge devices across the entire network at scale. Looking further ahead, this can also include satellite communication and other non-terrestrial networks as discussed in more detail in Section 9.2.

---

[156] https://www.o-ran.org.
[157] https://www.europarl.europa.eu/RegData/etudes/BRIE/2024/762298/EPRS_BRI%282024%29762298_EN.pdf
[158] https://5gobservatory.eu/wp-content/uploads/2023/10/BR-19_October-2023_Final-clean.pdf
[159] https://digital-strategy.ec.europa.eu/en/library/white-paper-how-master-europes-digital-infrastructure-needs.

Project funded by

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 61 of 80   © 2024-2026 NexusForum.EU

It is also important to take other strategic documents into account such as the IPCEI-CIS Value Chain[160], European Industrial Technology Roadmap[161] and the New Telco Cloud Thematic Roadmap[162], which highlight the urgent need for an upgraded infrastructure capable of supporting the next generation of cloud and edge applications.

The 6G-IA Vision Working Group has published in November 2024 the second version of the *"European Vision for the 6G Network Ecosystem white paper"*[163]. This white paper presents a comprehensive vision for the development and standardisation of 6G networks in Europe, with a target commercial launch around 2030. The paper emphasises the importance of global collaboration while highlighting the specific contributions and priorities of the European 6G research and innovation landscape. Section 3 of the white paper defines eleven areas of technological enablers for the complete 6G vision, ranging from energy efficient technology to new hardware. Among these, four can be seen as more directly connected to the Telco Cloud-Edge as understood in this roadmap:

- *Edge-Cloud Continuum*: 6G networks will leverage a distributed computing architecture that spans from the edge to the cloud. Research and innovation in edge computing technologies, including edge orchestration, data management, and application optimisation, are essential for enabling low-latency and context-aware services in 6G.

- *Network Softwarisation and Disaggregation*: This involves the virtualisation and softwarisation of network functions, enabling greater flexibility, scalability, and agility in network deployment and management. Research and innovation in this area are crucial for building cloud-native 6G networks.

- *Network Intelligence*: AI and ML will play a pervasive role in 6G networks, enabling intelligent automation, optimisation, and management of network resources. Research and innovation in AI/ML algorithms, models, and frameworks for network optimisation and control are crucial for achieving the performance and efficiency goals of 6G.

- *Security*: As networks become more software-defined and distributed, ensuring security and trustworthiness becomes increasingly challenging. Research and innovation in security technologies, including zero-trust architectures, intent-based networking with AI assistance, and secure data sharing mechanisms, are essential for protecting 6G networks and services.

Moreover, the 6G-IA white paper also mentions specific technologies and approaches covered by this roadmap even if they are not yet to be considered at the core of Telco Cloud-Edge, such as Neuromorphic Computing (section 9.1) or Digital Twins of the network.

7.1   Open radio access network (O-RAN)

Context: The radio access network (RAN) is mostly closed in terms of an "open development space" except for large OEM telecommunications companies. Unlike cloud native, where 3rd parties can develop microservices, advertise and sell/license, the RAN is a HW+SW monolith which is a hurdle to enter and offer services within and existing licences, limited standards access, and protective patents further limit the possibilities to enter the market. Antennas, base stations, MSCs, 3GPP + IETF protocol development + plus global testing are huge

---

[160] https://www.bmwk.de/Redaktion/EN/Downloads/I/ipcei-cis-value-chain-description.pdf?__blob=publicationFile&v=1
[161] https://digital-strategy.ec.europa.eu/en/news/european-alliance-industrial-data-edge-and-cloud-presents-its-first-deliverables
[162] https://digital-strategy.ec.europa.eu/en/news/new-telco-cloud-thematic-roadmap-european-alliance-industrial-data-edge-and-cloud
[163] https://doi.org/10.5281/zenodo.13708424

undertakings. One way to make the barrier to market entry lower is through the use of common off-the-shelf hardware, open software APIs accessible to anyone, as well as willing customers interested in easing entry into RAN & its development.

An open RAN that decouples vendors and software suppliers is the vision of some, who are out of the traditional OEMs group, through alliances such as the O-RAN Alliance[164] and the Telecom Infra Project (TIP)[165] which consolidate interested parties, identify missing parts and provide a base on which to build projects. O-RAN is very much discussed, and as of 2024 fall into 2 categories: i) large players 'promising' to develop an open solution for the benefit of all, e.g., the Ericsson - AT&T $14 billion deal,[166] or ii) smaller component-like development, a la Cloud native. Either way it remains to be seen whether either will deliver a truly open, competitive RAN.

Challenges: As systems start using components from multiple vendors, there are multiple challenges in coordinating both their technical integration and assigning accountability between parties, such as when SLAs are unfulfilled[167], specifically:

- *Increased security threats* due to the increased system complexity and involvement of multiple vendors and 3rd party applications. It will be important to ensure that the system is protected, both the interfaces between different apps, and more importantly between 3rd party apps and the system as a whole.

- *Conflicts between RAN Intelligent Controller Apps*: Current AI/ML solutions typically target a single network layer and perform one intelligent network task. The development towards an AI native 5G and beyond network, we can expect a massive number of AI models co-existing and collaborating in a distributed manner, addressing different layers of the network and optimizing different KPIs. This complexity will increase risks of conflicts between different Intelligent Controller Apps, that need to be resolved and prevented.

- *Cross layer optimisation*: As the number of RAN Intelligent Controller Apps increase, there will be many components triggering various actions to optimise RAN performance, such as triggering policies and modifying RAN configurations. To deal with this complexity, it will be necessary to introduce coordination mechanisms to ensure that the optimisations performed by the Apps do not degrade the overall system performance. This is especially interesting from the computing continuum perspective, which adds additional optimisation layers for data and compute orchestration.

R&D priorities:

- *New security solutions for an open RAN ecosystem*: Develop cybersecurity solutions that can manage the multi-vendor security challenges of O-RAN and allow secure deployment of 3rd party apps in a secure manner.

- *Cross-layer optimisation*:
  - Joint optimisation of different RAN network layers and network tasks
  - Using RAN to optimize network-data-compute orchestration from device to cloud

- Develop and demonstrate *reference architectures* for how O-RAN could be used and integrated with Cloud-Edge orchestration solutions for different use cases.
  - O-RAN implementations, software and hardware co-design

---

[164] https://www.o-ran.org.
[165] https://telecominfraproject.com.
[166] https://www.ericsson.com/en/news/2023/12/ericsson-and-att-in-major-future-network-of-the-future-deal.
[167] https://6g-ia.eu/wp-content/uploads/2024/05/6g-ia-open-sns_open-networks-status-and-future-development_ran-final.pdf

Project funded by

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 63 of 80   © 2024-2026 NexusForum.EU

- *Simulation/validation environment* to ensure that different RAN Intelligent Controller Apps play well together

- Identify parts outside the existing alliances that could be promoted as *topics for future EU calls* with OEM partnerships. Delve into the 6G and 7G generations that are still open before they are subsumed by the 4 major telecom players.

  – How to include developments related to seamless data connectivity described in section 7.2 in future O-RAN

Potential impact: Promote open and fair competition in the telecoms market. Lower entry cost for new operators resulting in a more competitive market. Make the possibility of European lead in telecoms whilst breaking the dominance of US hyperscalers in the Cloud market. Much more open source in telecommunications solutions in the future, à la SIP servers, Asterisk (Open PABXs). This does however not mean that we need more operators, on the contrary, we need less operators but bigger in Europe to compete with global cloud players.

7.2 Seamless data connectivity and predictive handover across different networks

Context: Many industry sectors and use cases are increasingly adopting technologies from robotics and autonomous systems, such as drones, for various monitoring or delivery applications. In many applications they will need to cover large distances and/or operate in remote areas with limited dedicated communication infrastructure and bandwidth. Yet, they will need to maintain connectivity at all times with a human operator, and therefore an edge/cloud server, possibly due to regulations. If the network experiences issues, or they move outside the range of the network, there is a risk of communication blackout when it must change to another network, such as between telco 4G/5G and satellite communication.

Seamless handover between networks could also be needed in case of network disruptions, caused either by human intervention or natural events. In such cases, it is important to quickly identify a new network channel and hand over communication from the primary communication channel with minimal disruptions.

Challenges: In terms of networking and communications, the European Union's connectivity infrastructure is still unprepared to meet the demands of a society and economy increasingly driven by data. For example, handover between common and future networks (4G, 5G, 6G, LoRaWAN, Wifi7, SatCom, StarLink) is not totally seamless, causing disruptions in ongoing continuous data flows when moving between them.

R&D priorities: A set of measures that will enable a more seamless handover between networks in the Compute Continuum:

- *Secure base accessibility to all networks.*

- *Predictive and fast hardware communication channel switch*, accompanied by channel switch software protocol.

  – Sensing and QoS detection of all physical network channels.

  – AI prediction of near future channel QoS.

- *New mechanisms for predicting and responding* to network handovers and failures.

  – Buffer and recovery mechanism on the edge devices to bridge switch over phase.

  – APIs and support for application design that can handle network disruption with graceful performance degradation and quick recovery on reestablishment of connectivity.

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 64 of 80

© 2024-2026 NexusForum.EU

– *Develop hardware and software stack* that enables easy integration of SatCom connectivity, utilizing multiple services in the background (Inmarsat, Iridium, Starlink, etc.).

Potential impact: We are seeing a shift from standalone connected devices to highly interconnected systems, where products like cars and smart home devices communicate and integrate to offer enhanced services. This transformation, driven by digitization and AI integration, depends heavily on consistent data connectivity, as many devices rely on backend systems for AI processing and seamless service delivery. Thus, many applications require robust data connectivity to an edge node or operations centre. Ensuring seamless handover between networks and predicting network failures is a key factor in enabling a resilient connected society where IoT/edge devices or humans on the move continuously become disconnected from the cloud continuum.

7.3   Generative telco cloud

The Generative Telco Cloud refers to the use of cloud computing and generative AI in mobile networks to provide a transformative approach to the way telcos operate.

Context [168]: The telecommunications industry worldwide and specifically in Europe is facing significant growth and revenue challenges. As traditional revenue streams become stale, telcos need to find a way to improve their operational efficiency and reduce costs. This requires increasing automation and flexibility in their operations. Furthermore, the quick development of new technologies and the demand for high-speed connectivity are driving the need for robust cloud and network infrastructure. Europe needs to accelerate its cloud and network developments to support the telco industry's capabilities.[169],[170],[171]

Challenges: A major challenge is developing and deploying solutions for automation and AI to improve operational efficiency and reduce costs. Another major challenge is the integration of services. That is, designing networks that can seamlessly incorporate mobile operators and cloud services to create an ecosystem of service providers and network operators. On the other hand, customer expectations keep rising, with an increasing demand for personalized services; the adoption of AI-powered can help Telco providers in this regard. Finally, predictive maintenance and optimisation strategies are key to prevent service disruptions and maintain network performance.

R&D priorities: Combine generative AI tools to automate procedures, maximise network resources, and improve operational efficiency with cloud computing to scale infrastructure dynamically based on demand. An ecosystem of network operators and service providers is needed to accomplish this. To integrate cloud services and mobile operators, networks must be designed horizontally and federate open network APIs.

Potential impact[172]: Efficiency and Scalability: Telcos will enhance their flexibility, cost-effectiveness, and the ability to rapidly deploy and manage services, ensuring efficient infrastructure utilization and capacity management[173].

[168] *State of AI in Telecommunications: 2024 Trends*
[169] *GSMA Open Gateway - Open Gateway*
[170] *Huawei drives innovation with AI-read... - Mobile World Live*
[171] *CNEC Global Leap Program Debuts in Barcelona, Highlighting Seven Tech Leaps to Accelerate Intelligence-Huawei Cloud*
[172] *The Impact of AI In Telecommunications | European Business Magazine,*
https://europeanbusinessmagazine.com/business/the-impact-of-ai-in-telecommunications/
[173] *"A Primer on Generative AI for Telecom: From Theory to Practice", https://arxiv.org/abs/2408.09031*

Customer Experience Improvement: Chatbots and virtual assistants driven by AI will respond to consumer enquiries, resolve problems, and customise communications. Proactive service offerings will result from predictive analytics' ability to foresee client needs. [174]

Revenue Growth and Cost Reduction: they will be able to monetize AI by offering data analytics services to other industries. Insights derived from telco data can drive business decisions across sectors. AI-driven content recommendations can boost revenue by increasing user engagement.

Predictive Maintenance and Network Optimisation: Telcos will be able to enhance network reliability by identifying potential issues before they impact services as well as automate processes, optimize network resources, and enhance operational efficiency.

Predictive Protection Actions: User's exposure to specific threats, leveraging the information of threat frameworks to facilitate the adoption of preventive actions. Behaviour based analytics through artificial intelligence techniques will assess if the behaviour of a group of users is akin to the behaviour of a known threat changing Network level security posture dynamically.

7.4 Resilient on-prem 5G/6G edge-cloud for Industry 4.0 and beyond

Context: Many industries are in the process of connecting their equipment to their IT infrastructure to gather data to enable predictive maintenance and inform decision making processes, coordinate work across the plant, and for using unmanned vehicles and robots. The seamless delivery of advanced data services and AI-based applications is integral to Industry 4.0. Necessitating robust on-premises 5G/6G edge cloud infrastructure to ensure resilience and reliability amidst the challenges of integrating legacy automation systems with cutting-edge cloud technologies. In many industrial applications resilience and reliability are critical. Key initiatives in this area are the telco global API alliance[175] and the open source 5G Core network developed by the Magma initiative[176].

Challenges: The automation systems in industry often rely on old computer systems, making it difficult to seamlessly integrate them with modern cloud technologies and keep the systems up to date. Most of the systems need to be on-prem very close to the production line and it is therefore not possible to use public telecom and cloud resources that might suffer from short disconnects, making it necessary to have private on-premises 5G/6G edge cloud deployments.

R&D priorities:

- *Reference designs* for different environments and use cases.
- *Portability* between public telco operator environments and private 5G/6G environments, compatibility with APIs, and using cloud-native technologies.
- *Seamless management* of IoT devices that do not use 5G/6G.

Potential impact: Easier to seamlessly port applications and services between private on-prem environments and public cloud-edge. Help boost the deployment and use of 5G technologies and edge computing.

---

[174] *Unleashing the Power of Edge-Cloud Generative AI in Mobile Networks: A Survey of AIGC Services,*
https://ieeexplore.ieee.org/document/10398474
[175] *https://camaraproject.org*
[176] *https://magmacore.org*

Project funded by

Co-funded by the European Union

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 66 of 80   © 2024-2026 NexusForum.EU

8 Digitalisation of Industry Sectors: Requirements from Next-Gen Applications

The computing continuum will enable both new use cases and applications across various sectors and transform existing ones. The specific requirements that these pose on the Cloud-Edge infrastructure, and how it is operated and managed, will differ between use cases.

CLOUD-EDGE USE CASES - WORKING GROUP SCOPE:

Use cases and applications that could take advantage of the continuum; 1) Mobility, Transport & Travel, 2) Energy, 3) Manufacturing & Industry 4.0/5.0, 4) Health, 5) Infrastructures, Smart Buildings & Cities, 6) Tourism & Cultural Heritage, 7) Agriculture & Environment, and 8) Media.

Initial roll-out of next generation use cases as part of a first industrial deployment with European wide scale, showcasing data processing in different sectors to verify functionality, high scalability, interoperability, portability, interconnectivity and compatibility.

8.1 Automative and the continuum

Context: Vehicles are becoming 'computers on wheels' with technology assistance for the drivers. Currently the assistance is often safety related. Fully automated tech. finds its way down the tech chain: cruise control, lane departure warnings, automatic crash signalling (OnStar in the US, Apple devices) to name a few.

Technology extends beyond the driver; computer-based maintenance, GPS-enabled theft electronic Vehicle Identification Numbers. An (e)SIM is commonplace in trucks, transmitting maintenance, wearage information to OEMs on behalf of hauliers that demand high uptimes using on demand service.

The industry is also changing *how* software is developed. Moving towards Software Defined Vehicle (SDV) architectures where features are updated continuously and uploaded over the air. Connectivity using cloud services offer new possibilities. Motivated by Telsa and Jenkins-style development, the SDV in the automotive sector spans the continuum from the cloud, edge and devices. Smart cities through roadside units for safety, road monitoring, autonomous driving exemplify a rich environment for the continuum.

Roadside Units (RSUs), as intermediatory storage and compute units, the automotive sector illustrates well the continuum. Vehicles store and upload data via RSUs an example of a working system is automated toll booths, transmitting and paying for the journey via IEEE 802.11p, WiFi with priority bands. Further developments will be cameras indicating VRUs, unforeseen icy roads or accident hot spots. RSUs demonstrate the use of *edge compute* as opposed to solely *edge devices*. Note, data sovereignty and privacy are key issues.

Challenges:

Figure 7 Connected Vehicles are in the continuum

Edge compute has traditionally been seen as a networking concept, primarily introduced to reduce latency. Groups of devices, vehicles in this case, sense data and need local processing, privacy-sensitive face & number plate removal. An achievable priority is a set of libraries to do the V2X, image processing, data anonymisation & secure sharing and storage.

R&D priorities:

- *Non-inter-operability between non-compliant standards*. An example is 3GPP and the IEEE. Parts of 5G for vehicular communication and a variant of IEEE 802.11p, named G5 where simultaneously chosen by different OEMs in the automative sector in Europe.

- This caused Cooperative Intelligent Transport Systems (C-ITS) systems and the CCAM EU frameworks for vehicle-to-infrastructure communication to fracture or significant uncertainty in directions to select. The impact on R&D was large, with indecision around which tech base to use in C-ITS and new areas emerging, multi-frequency antennas to be started. *Priority, be decisive and clear in future policy directions.*

8.2   Augmented Reality/Virtual Reality technologies

Challenges: Extended reality (XR) technologies, such as augmented reality (AR) and virtual reality (VR), are expected to transform everyday life fundamentally, and enable new use cases and applications in industry. Due to the high data throughput and low latencies required to deliver a seamless VR/AR/XR experience, these technologies are among the main use cases for 5G and edge computing technologies.

R&D priorities:

- *Consistency in Virtual Environments*: Develop algorithms to ensure seamless and consistent user experiences across decentralized networks.

- *Latency Reduction*: Deploy and reinforce telecom and network infrastructure to minimize latency for real-time interaction within VR environments.

- *AI Integration*: Integrate AI to dynamically adapt and optimize VR experiences based on user interaction and environmental changes.

- *Interoperability Standards*: Establish standards to ensure interoperability among diverse VR platforms and decentralized computing resources.

- *Secure Data Exchange*: Create secure protocols for spatial data exchange in decentralized VR applications to protect user privacy and data integrity.

- *Operational Datasets*: Develop open operational datasets for training and evaluating AI models within VR scenarios.

Potential impact: VR/AR/XR are enabling new use cases and applications, with the potential of bringing great value to industry and enterprises.

8.3 Cyberspace and physical space fusion

Challenges: Originating from Japan, the concept of "Society 5.0" envisions a connected cyberspace where AI surpasses human capabilities, feeding optimal outcomes back into the physical realm. Ensuring data privacy and security on the Cloud is paramount as AI systems process vast amounts of data. High latency can hinder performance, particularly in critical applications such as healthcare or autonomous vehicles, where real-time processing is essential. Additionally, AI systems must efficiently scale with increasing data volumes and user demand to maintain optimal performance. The computational power required for AI can be costly, especially with the utilization of large neural networks, thus affecting overall expenses. Interoperability is crucial as AI systems often need to integrate with various other technologies and data sources, necessitating seamless compatibility. Moreover, regulatory compliance, particularly regarding data protection regulations like GDPR in Europe, is vital for AI systems operating on the Cloud, emphasizing the importance of cross-border data flows and specialised legal expertise. Lastly, addressing ethical considerations surrounding AI's integration into society, alongside ensuring data quality and standardization, remains imperative to harness its full potential while mitigating risks and limitations.

R&D priorities:

- *Data Privacy and Security*: There are risks associated with data breaches and unauthorized access, which necessitate robust encryption and security protocols.

- *Latency and Performance*: Cloud infrastructure must be optimized to minimize latency and provide the necessary computational power.

- *Scalability*: Cloud platforms need to provide flexible and scalable resources to accommodate the growth of AI applications without compromising performance.

- *Cost*: Organizations must manage the cost of Cloud resources effectively to make AI integration economically viable.

- *Interoperability*: Ensuring interoperability between different Cloud services and AI models requires standardized protocols and interfaces.

- *Regulatory Compliance*: AI Governance platforms: Automate the identification of regulatory changes and translation into enforceable policies, Risk management and lifecycle governance.

- *Technical Expertise*: Training and recruiting talent are necessary to bridge this gap and drive integration forward.

- *Ethical Considerations*: Ensure that AI systems are transparent, explainable, and aligned with human values.

- *Data Quality and Standardization*: Ensure that shared data is of high quality and standardized for interoperability.

Potential impact: The convergence of cyberspace and physical space envisages a seamless integration, facilitating smart cities and environments where data exchange between sensors and cyberspace optimizes resources and enhances quality of life. Society 5.0 embraces AI-

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 69 of 80

© 2024-2026 NexusForum.EU

driven analysis, wherein AI not only processes data but also offers feedback and solutions, augmenting decision-making. This feedback loop, empowered by AI, is anticipated to spawn new value across sectors, fostering economic growth, job creation, and societal well-being.

© 2024-2026 NexusForum.EU

9 Disruptive impact initiatives

In addition to the previous sections and topics in this document, the NexusForum project have identified several topics of interest that could have a potentially disruptive impact on the cognitive computing continuum in the longer term. These are:

- Neuromorphic systems
- Space edge
- Integration of quantum computing infrastructure
- Quantum and classical computing fusion

These topics and potential synergies with the computing continuum are further described in the following sections.

9.1 Neuromorphic systems

Traditional digital computers are struggling to keep up with the demands of advanced technologies and applications, such as AI and Edge computing, as well as the optimisation of intricate systems. This is evident in simulations used in chemistry and pharmaceuticals to speed up the development of new medications and vaccines, in the process optimisation of complex production lines, as well as in the area of traffic and freight transport.

Neuromorphic computing, which aims to emulate the self-organizing and self-learning nature of the brain, offers a promising solution to this challenge. Despite its potential, neuromorphic hardware has not found its way into commercial AI data centres. One reason is due to insufficient opportunities for application-oriented testing of the hardware developments required for the highly complex computing technologies, as well as for a rapid implementation of the results in prototypes and small series. Another is the lack of standardized neuron models and common training techniques.

As an example, the EU-funded HYBRAIN[177] project aims to develop a new computing system that is inspired by the human brain. This system will be based on 'ultra-fast response' technologies, combining a number of highly innovative solutions based on integrating complementary technology platforms. Companies like SynSense and Innatera are designing neuromorphic hardware specifically for integration into consumer devices, for sensor-adjacent processing. They have deployed several audio inference use cases to Xylo Audio, and a bunch of vision inference use cases to Speck. Moreover, the first EU exascale supercomputer JUPITER will include a neuromorphic module.

Neuromorphic computing introduces a *new event-based paradigm* and new ways of developing and deploying AI applications. It is based on a different architecture than the commonly used von Neumann architecture, which means that existing software tools and solutions are generally not compatible with it. The event-based nature of neuromorphic computing systems will have new requirements on the computing continuum, since the communication and computing patterns will differ from those of traditional systems.

Increased efforts in *hardware-software codesign* can accelerate the seamless integration of neuromorphic computing capabilities in the Compute Continuum. This will require adapting existing software stacks and architecture patterns commonly used today and creating novel interfaces between the neuromorphic and digital computing domains.

---

[177] https://cordis.europa.eu/project/id/101046878, https://hybrain.eu/.

© 2024-2026 NexusForum.EU

The integration of neuromorphic hardware into data centres and at the edge could lead to more sustainable and energy-efficient AI processing. This could revolutionize the processing of sensor data at the edge, opening new possibilities for applications in wearables, smart home, and IoT devices. The development and improvement of neuromorphic software can lead to more efficient and powerful AI systems. It can enhance the overall learning performance for specific tasks, moving away from hardware benefits to understanding the potential application benefits of neuromorphic computing. It can also lead to improvements in neuroscience as researchers start to recreate our grey matter in electronics.

With its ultra-efficient, event-driven processing capabilities, neuromorphic hardware enables unprecedented power-performance gains for always-on sensing use cases. This could lead to significant advancements in various fields, including chemistry, pharmaceuticals, production lines, traffic and freight transport, and more. Other communities, such as ESA, are also exploring neuromorphic-oriented calls. Event-driven processing, edge computing, and GDPR compliance are essential considerations for successful integration.

9.2   Space Edge

The European Space Agency (ESA) has launched several relevant initiatives on the topic of edge computing and AI in space. For example, one of ESA's Phi Labs is exploring Cognitive Cloud Computing in Space (3CS),[178] and another one focusing on edge learning in space is anticipated.[179] Their Phi-sat programme performs experiments to deploy on-board AI on satellites for various earth observation tasks, such as filtering out high-value, for example cloud-free, images before they are sent back to earth.[180,181]

At the moment, it seems that both satellite integration and space edge in the computing continuum are firmly in scope for the SNS JU, but there are potential synergies and points of collaboration between the SNS projects, and the projects funded under CL4/DATA- or CL4/DIGITAL-EMERGING- calls. Beyond this, there are several other points that suggest a convergence and synergy:

- Edge Computing, with or without "Space" in front, is ubiquitous.
- Flexible service orchestration is also quite prominent in SNS JU.
- Virtualisation and Cloud Computing techniques (e.g., FaaS) overlap with Virtual Network Functions (VNFs).
- Data-driven AI is being considered, if not already adopted as a key enabler for 6G networks.

There are several ongoing projects and initiatives in this direction under the SNS-JU that could be particularly relevant to the computing continuum.

The SNS-JU RIA project 6G-NTN[182] (NTN project, using AI, Stream B, Communication Infrastructure Technologies and Devices) covers the complete integration of Terrestrial Network (TN) and Non-Terrestrial Network (NTN) in 6G (5G considers TN and NTN as two separate segments and does not try to cross-optimise between them). The NTN does not consider only satellites, but anything above the surface of the earth i.e. airplanes, drones, and similar airborne vehicles. There is also mention of space edge in some of its use cases:

---

[178] https://philab.esa.int/esa-explores-cognitive-computing-in-space-with-fdl-breakthrough-experiments/

[179] https://philab.esa.int/esa-and-ai-sweden-sign-letter-of-intent-for-first-pilot-of-esa-%cf%86-labnet/

[180] https://www.esa.int/Applications/Observing_the_Earth/Ph-sat

[181] https://www.esa.int/Applications/Observing_the_Earth/Phsat-2/New_satellite_demonstrates_the_power_of_AI_for_Earth_observation

[182] https://www.6g-ntn.eu/

- Public deliverable *"D2.1 Use Cases Definition"* (mention of space edge on page 13, page 15, page 16, page 61)[183]
- Public deliverable *"D3.1: Report on 3D multi layered NTN architecture"*, 1st version (description and assessment of the various components of the multi-layered NTN[184])

The 6G-NTN project already has space edge as one of its potential innovations, particularly relevant to the project use cases, UC3 Urban Air Mobility and UC4 Adaptation to PPDR or Temporary Events.

The projects answering to the newly closed SNS-JU call[185] HORIZON-JU-SNS-2024-STREAM-B-01-03 would preferably expand the work of projects like 6G-NTN. The call mentions for example: "*Disaggregation, and virtualisation considering the ground and non-terrestrial segments are in scope. It should enable integrated space and ground edge computing and in-space traffic decision procedures allowing a 'router in the space'*". There are also mentions of IoT-to-satellite connectivity.

9.3   Integration of quantum computing infrastructure

Quantum computing is emerging as a transformative technology with the potential to revolutionize various sectors, including cryptography, materials science, and complex system simulations. Globally, significant investments are being made to develop scalable quantum hardware and efficient quantum algorithms. Countries like the United States and China are leading the charge, aiming to achieve quantum supremacy and integrate quantum computing with existing HPC and cloud infrastructures.

In Europe, the focus is on building a robust quantum computing ecosystem that leverages existing strengths in HPC and fosters innovation across the continent. The European Union has launched several initiatives to support the development and integration of quantum computing technologies. These efforts aim to position Europe as a leader in the global quantum race, ensuring that European industries and researchers can fully exploit the capabilities of quantum computing. Europe is developing different types of quantum computers, including those based on superconducting qubits, trapped ions, and photonics, to explore various approaches and applications. Key initiatives include the establishment of European Quantum Excellence Centres, which aim to foster the development of an ecosystem of quantum programming facilities, application libraries, and a skilled workforce.

The current infrastructure for quantum computing (QC) is limited, making it difficult to fully leverage the capabilities of QC and integrate it with HPC and cloud services to enable efficient AI workloads. Quantum computing is a promising technology that could revolutionize various sectors. However, the lack of a robust infrastructure, including hardware and software, hinders its full potential.

The challenges include developing scalable quantum hardware, creating efficient quantum algorithms, and integrating QC with existing technologies like HPC and cloud services. Some relevant current initiatives include:

- HPCQC EU Project: High Performance Computer – Quantum Simulator hybrid.

---

[183] https://www.6g-ntn.eu/download/d2-1-use-case-report/?wpdmdl=2866&masterkey=gYhW0HmX3ZCCL6U6pyUC44YLR3-ifgCr20jZkviQOnpxxrHiOtv-V61zVlLhuYBtWaz7_ngTLvg1A79el2guA7I1VxQigS541ESPnDd0XB4
[184] https://www.6g-ntn.eu/download/d3-1-report-on-3d-multi-layered-ntn-architecture-1st-version/?wpdmdl=2870&masterkey=jaeYz8R8ZyqzKPzsuAKYsXkZS_cjiWBcx1f4PEz2UhPW_Zs8ctqVUUu0Bcl4YwiB-jrxWWBNVmvS5HNAuj_0_wFrH-Zd0QL2aOIpCAAVF9A
[185] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-ju-sns-2024-stream-b-01-03

- OpenSuperQ: A Quantum Computer for Europe.

- Quantum Flagship (and QUCATS): One of the most ambitious long-term research and innovation initiatives of the European Commission.

- Six EuroHPC sites selected to host first European quantum computers.[186]

- QuIC – Quantum Industry Consortium: QuIC is a pan-European non-profit association dedicated to the advancement of commercial quantum solutions and Europe's competitiveness in quantum technology on the global stage.

- QIA – Quantum Internet Alliance: QIA is a consortium of approx. 40 world-leading institutions working together to build a global Quantum Internet made in Europe.

- The European Quantum Communication Infrastructure (EuroQCI) Initiative.

- The QC4EO initiative from ESA exploring using HPC+QC workflows for a climate adaptation digital twin.[187]

The European Quantum Excellence Centres aim to foster the development of an ecosystem of quantum programming facilities, application libraries, and a skilled workforce.[188] They will serve as a one-stop-shop for industry, academia, and the wider quantum technology user community, accelerating the discovery of new quantum-oriented applications and fostering their knowledge and uptake.

The European Commission could fund projects focusing on addressing research challenges in quantum computing, the development of large-scale quantum computing testbeds, the creation of efficient Open Science quantum algorithms, and the integration of QC with HPC and cloud services. This could involve the use of the Modular Supercomputing architecture in the first EU exascale supercomputer JUPITER, which includes quantum and neuromorphic modules.

By funding these areas, the EC could significantly enhance Europe's computing capabilities, including quantum computing, leading to advancements in various sectors. This could foster innovation, create jobs, and strengthen Europe's position as a global leader in technology. It could also help address societal challenges, such as climate change and healthcare, by enabling more sophisticated data analysis and decision-making. It could also foster innovation, create jobs, and strengthen Europe's position as a global leader in technology.

9.4   Quantum and classical computing fusion

The fusion of quantum and classical computing represents a significant advancement in computational capabilities. Quantum computing uses qubits, which can process a richer set of possibilities compared to classical computing's binary bits. This makes quantum computing more efficient for certain types of problems, such as those involving exponential variables. The most promising algorithms are hybrid, combining quantum and classical approaches to leverage the strengths of both paradigms.

Challenges: The primary challenge lies in the inherent limitations of classical computing, which uses binary bits and struggles with problems involving exponential variables. Quantum computing, on the other hand, uses qubits and can process a richer set of possibilities, making it more efficient for certain types of problems. However, quantum computers require

---

[186] https://eurohpc-ju.europa.eu/selection-six-sites-host-first-european-quantum-computers-2022-10-04_en.
[187] https://eo4society.esa.int/projects/qc4eo-study/
[188] https://eurohpc-ju.europa.eu/european-quantum-excellence-centres-qecs-applications-science-and-industry_en

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Page 74 of 80   © 2024-2026 NexusForum.EU

specialised environments and operate at cryogenic temperatures, which makes them impractical for personal devices like laptops.

The solution to making quantum computing widely accessible is through cloud computing. Quantum calculations will be performed in data centres, and the results will be delivered through the cloud. This approach will allow the masses to benefit from quantum computing without the need for personal devices to handle the actual quantum processes. Hybrid algorithms, which integrate quantum and classical computing, are particularly promising. These algorithms can optimize the use of both computing paradigms, enhancing efficiency and performance. The fusion of Quantum Computing and Classical Computing in the cloud represents an exciting frontier in computing, promising to address problems currently beyond our reach and driving innovation and problem-solving in the future.

The convergence of quantum and classical computing in the cloud is expected to exponentially increase computational capabilities. This integration will enable software to determine the most efficient computing paradigm - classical, AI, or quantum - for different parts of a computation. Users will benefit from this combined power without being directly involved in the complex processes.

Appendix A: Open Consultation Process

Scope and objectives

The Open Consultation Process is designed and carried into effect within WP2, to ensure that the roadmap reflects a broad spectrum of insights from various stakeholders including researchers and industry experts. This process is structured to engage these stakeholders through direct engagements such as surveys, thematic forums, and interactive workshops. Each of these platforms is intended to gather substantial feedback that will be analysed to refine and adapt the roadmap accordingly.

Transparency and active communication are crucial throughout this process, aiming to build trust and ensure all contributors see how their feedback is analysed by the working groups and, when appropriate, incorporated in the roadmap. Regular updates and detailed reports will be disseminated to keep all parties informed and engaged.

The objectives also encompass the validation of research and technology priorities that have been identified, ensuring they are thoroughly vetted and endorsed by a diverse group of experts, as this validation is critical in confirming that the roadmap not only meets current needs but is also adaptable to future technological shifts and challenges.

Furthermore, the roadmap is designed with a view toward long-term sustainability. It includes mechanisms for ongoing collaboration and periodic updates, allowing it to evolve in response to new discoveries and technological advancements. The NexusForum consortium utilises this dynamic approach to ensure that the roadmap remains relevant and continues to guide the cognitive computing continuum towards strategic growth and innovation.

Stakeholder segmentation

The successful open consultations process hinges on the active participation and input from a diverse array of stakeholders. At the core of our stakeholders are academic researchers and experts from RTOs, who provide foundational knowledge and drive much of the pioneering research in cognitive computing. Industry experts from technology companies, ranging from startups to established multinational corporations, are equally vital, as they play a key role in addressing technological advancements, operational challenges, and the scalability of cognitive solutions. Their feedback is particularly relevant to sections of the roadmap dealing with collaboration between industry and researchers from academia and RTOs, and the transfer of technology from theoretical models to market-ready products.

The segmentation of these stakeholders is aligned with their area of expertise and relevance to specific roadmap topics. For instance, academic researchers are primarily involved in sections dealing with research challenges and new scientific directions, while industry experts focus on technological advancements and industry-academia partnerships.

Platforms selection and utilisation

The consortium has selected effective digital platforms that will be crucial for engaging stakeholders and managing the open consultation process. Several platforms have been chosen for their distinct functionalities and target audiences, ensuring comprehensive stakeholder engagement and efficient feedback management.

The consortium will utilise Whaller to create tailored networks for specific working groups, allowing for private discussions and collaboration in a secure environment. Whaller's ability to

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 76 of 80

© 2024-2026 NexusForum.EU

create closed or open spheres caters well to the varying needs of project's diverse stakeholder groups. EUSurvey will be employed specifically for structured survey dissemination and data collection, as this tool is integral for gathering quantitative and qualitative feedback from a broad audience, aiding in the systematic analysis of stakeholder input will be employed specifically for structured survey dissemination and data collection, as this tool is integral for gathering quantitative and qualitative feedback from a broad audience, aiding in the systematic analysis of stakeholder input.

Open consultation process structure

To effectively engage stakeholders in the co-creation of research roadmaps (T2.3) and policy recommendations (T3.2), a structured Open Consultation Process has been designed. This process involves several key steps (as shown in Figure 8): defining KPIs, elaborating a monitoring process, setting up a validation panel, managing callouts and communications, and systematically handling feedback.
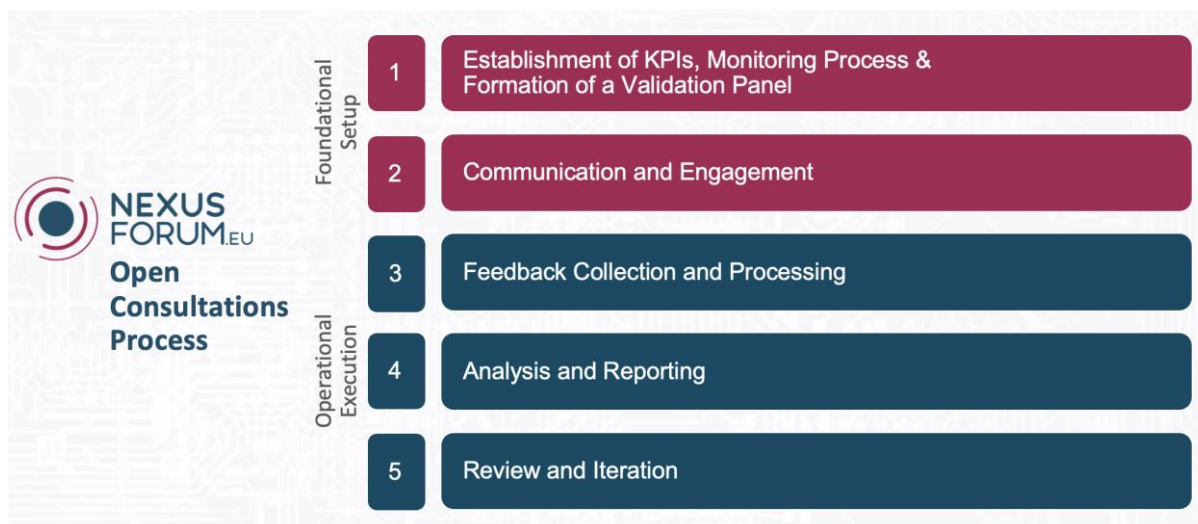

Figure 8: Foundational setup and operational execution steps of the open consultation process.

The five key steps of the Open Consultation Process that are outlined can be logically clustered into two main groups: **Foundational Setup** and **Operational Execution**, each encompassing specific activities that ensure the process is both inclusive and effective.

Foundational Setup involves laying the groundwork for the consultation. This begins with the **establishment of KPIs** which provide measurable goals related to stakeholder engagement, quality of feedback received, and the overall impact of the consultation outcomes. The development of a monitoring process follows, equipped with tools and procedures to track these KPIs in real-time, allowing for necessary adjustments to keep the consultation aligned with its objectives.

Simultaneously, a **validation panel** is formed within the NexusForum.EU framework. This panel, comprising consortium members (at least one representative per project partner), is tasked with overseeing the integrity and effectiveness of the consultation process. Their responsibilities include reviewing feedback, guiding the integration of inputs into the roadmap, and confirming that outcomes align with strategic objectives, as the aim of this setup ensures that there is a structured approach to validate the gathered insights.

Alongside these structural setups, the phase of **communication and engagement** takes place, and it involves launching callouts for participation using project platforms and leveraging partners' communication channels. A dedicated space on Whaller is established to serve as a

Co-funded by the European Union

Project funded by
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
State Secretariat for Education,
Research and Innovation SERI

Page 77 of 80   © 2024-2026 NexusForum.EU

central hub for discussions, document sharing, and updates, ensuring all stakeholders have a common platform for interaction.

Operational Execution focuses on the active phases of the consultation. It starts with **feedback collection and processing**, where inputs from stakeholders are gathered through structured surveys (EUSurveys), forums, and direct submissions. This feedback is then organised and analysed to extract actionable insights, ensuring that the stakeholders' sentiments and recommendations are accurately understood and considered.

Following the collection phase, **analysis and reporting** are conducted where detailed statistics on the feedback and consultation outcomes are generated. These statistics will help assess the effectiveness and reach of the engagement efforts. Reports are created to summarise the feedback, highlight trends, and outline necessary adjustments to the roadmap based on stakeholder inputs.

The final aspect of the Operational Execution is **review and iteration**. Regular review meetings with the validation panel are conducted to assess the process, discuss KPIs, and make necessary adjustments. This ensures that the roadmap remains dynamic and responsive to new information and stakeholder feedback, continuously refining and updating based on this iterative feedback integration.

Stakeholder feedback loops & timeline

Stakeholder feedback loops are critical components of the Open Consultation Process, ensuring that all contributions are not only gathered but also iteratively reviewed and, when appropriate, integrated into the roadmap. These feedback loops facilitate ongoing engagement, allowing stakeholders to see the evolution of the roadmap and understand how their input has been utilised. Stakeholders can continue to influence the roadmap by incorporating multiple rounds of feedback as new information and perspectives emerge, fostering a dynamic and adaptive planning environment.
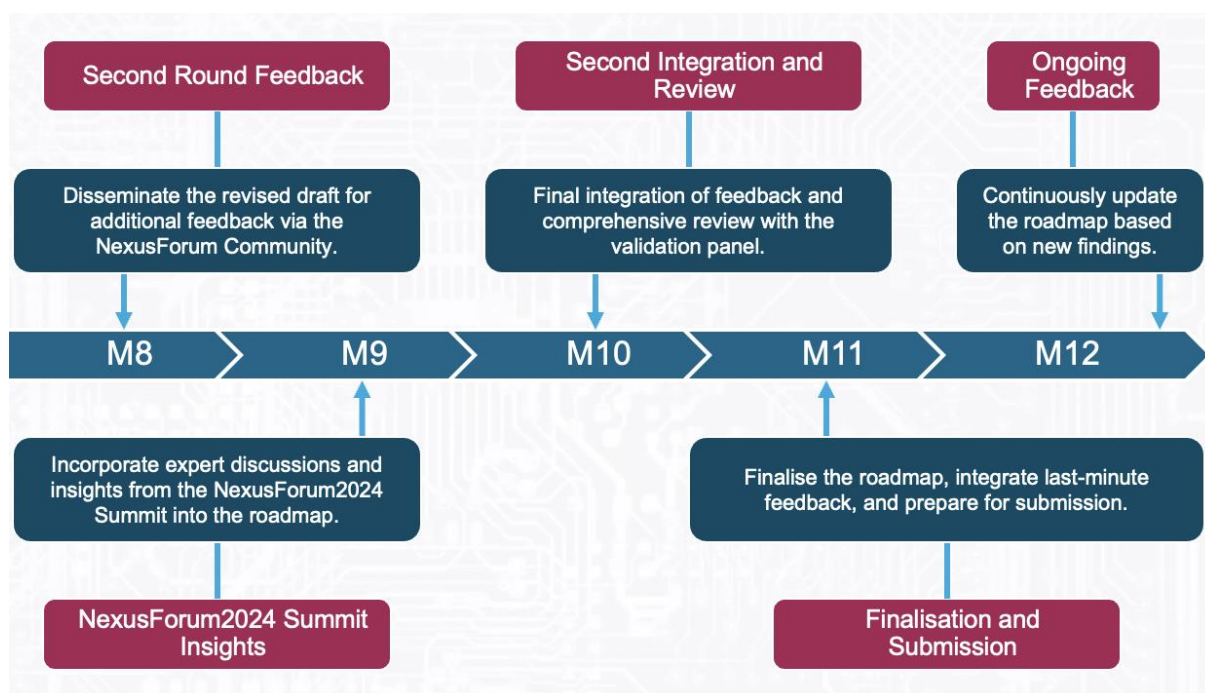

Figure 9: Stakeholder feedback loops & timeline.

© 2024-2026 NexusForum.EU

To ensure the timely and effective completion of the second roadmap iteration by M12, the stakeholder feedback loops have been strategically structured within the timeframe from M6 to M12 (see Figure 9). This **provisional schedule** incorporates a series of planned engagements and iterative reviews, including the integration of insights from the NexusForum2024 Summit at M9 (in September) and future workshops, both within the EU and Japan/South Korea, which are crucial for enhancing the roadmap with the latest expert discussions and technological trends.

The first preliminary round of feedback took place at the OpenContinuum final event, in June 2024, involving researchers actively participating in ongoing RIAs under the Horizon Europe programme. This information will be analysed and incorporated in the roadmap by the end of M7 (July) in preparation for the second round of feedback that will start in M8 (August).

In M8-M9, the revised draft is disseminated back to the stakeholders through platforms like Whaller and F6S. This second round of feedback seeks to refine specific sections of the roadmap, focusing particularly on areas highlighted during the initial feedback phase. The aim is to ensure that each section of the roadmap addresses the detailed concerns and suggestions of the community, preparing the draft for high-level expert validation.

The first significant incorporation of expert insights from the broader community occurs in M9 (September) during the **NexusForum2024 Summit**. This event will bring together leading experts and stakeholders in targeted domains, providing a unique opportunity to harness cutting-edge knowledge and strategic discussions directly into the roadmap. The insights garnered from this Summit are critical in ensuring that the roadmap reflects current research, and technology trends and aligns with future directions in the field.

Following the Summit, in M10, all the feedback and insights are analysed and eventually integrated into the roadmap. This version undergoes a comprehensive review with the validation panel, which includes representatives from each project partner. This process ensures that the roadmap is not only reflective of the broader stakeholder community but is also scrutinised for strategic alignment and coherence with project goals.

In M11, the near-final draft of the roadmap is circulated among all stakeholders for one last round of feedback. This final review process is crucial for capturing any remaining adjustments and ensuring that the roadmap is fully comprehensive, and consensus driven. By M12, the second version of the roadmap is finalised and prepared for submission. This final document encapsulates months of consultations, feedback, and expert input, ensuring a robust guide for the future of cognitive computing research and innovation.

Post-M12, a review cycle will be established to continuously update the roadmap. This ongoing process will accommodate new research findings, technological advancements, and evolving stakeholder feedback, maintaining the roadmap's relevance and utility in guiding strategic growth and innovation in cognitive computing.

Provisional open consultation KPIs and monitoring

To effectively monitor and evaluate Open Consultations, several KPIs have been identified/proposed. These KPIs include the **Stakeholder Engagement Rate**, which measures the percentage of invited stakeholders who actively participate in the consultation process. A target of **50% active participation** has been set to ensure broad and meaningful engagement. Another critical KPI is the **Feedback Volume**, which tracks the total number of feedback items collected through various channels, aiming for at least **200 pieces of substantial feedback** to guarantee a comprehensive range of insights. The **Feedback Quality Score** assesses the relevance, detail, and utility of the feedback received, with a target score of **4 out of 5** to ensure high-quality contributions that are relevant for improving the roadmap.

© 2024-2026 NexusForum.EU

Additionally, the **Stakeholder Satisfaction Rate** is monitored through post-engagement surveys, targeting an **80% positive response** to ensure the consultation process is meeting the expectations of participants. Lastly, **Report Timeliness** is tracked to ensure that all reports and updates are published according to the established timeline, aiming for **100% punctuality** to maintain schedule adherence and project momentum.

Regular review meetings will be scheduled to assess progress against these KPIs, allowing for immediate adjustments to the consultation strategy if targets are not being met.