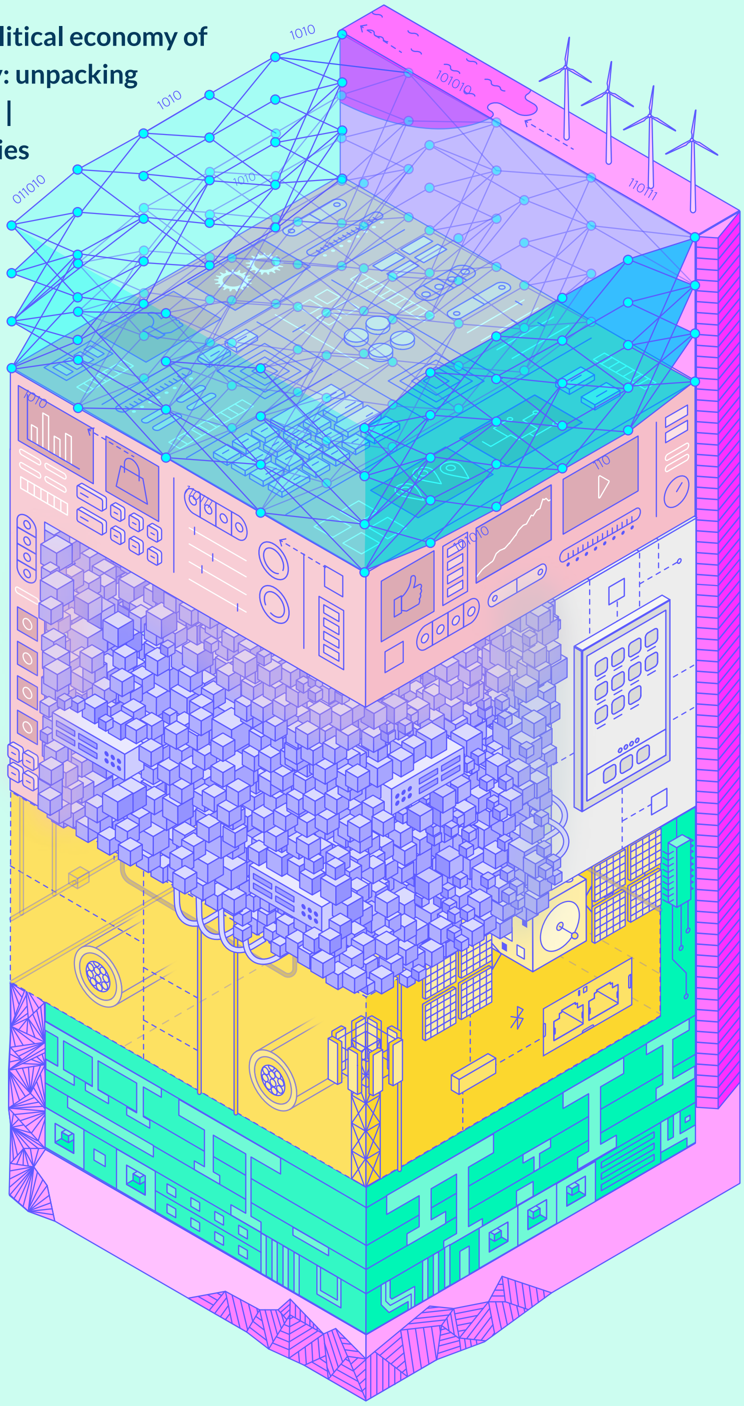
EuroStack – A European Alternative for Digital Sovereignty

Section 2 – The political economy of digital sovereignty: unpacking power in the stack | Annex A – Strategies of dominance among selected Big Tech



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EuroStack – A European Alternative for Digital Sovereignty

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Section 2 – **The political economy of digital sovereignty: unpacking power in the stack**

Strategies of value capture in the digital economy

Digital strategic autonomy, or "digital sovereignty," is a cornerstone of Europe's strategic vision for its future. Digital strategic autonomy consists of the capabilities, capacities, and control in the digital domain that are necessary to safeguard sovereignty.[21] Digital infrastructures – data centers, cloud platforms, semiconductors, software ecosystems, and AI – have reshaped global industries. The current economic landscape sees a concentration of power in the hands of a few dominant players that are not European – particularly in cloud infrastructure, semiconductors, and AI platforms. This power imbalance hampers Europe's ability to innovate, compete, and maintain control in the digital economy, as well as in its broader societal and democratic structures.

Reclaiming digital sovereignty requires Europe to address structural dependencies, tackle systemic bottlenecks and other control points, and leverage its regulatory and industrial strengths to build a resilient and competitive digital ecosystem. Bottlenecks – essential inputs with limited supply – expose vulnerabilities across the digital stack and are often exploited in geopolitics and geo-economics.

Market concentration and structural dependencies on technology giants extend beyond individual layers of the digital stack. Typically, dominant companies seek to extend their business across the stack through vertical integration, data monopolization, and control of key markets from digital advertising to semiconductor manufacturing and AI computing.[22] These strategies amplify the risks of market power abuse, the imposition of foreign regulatory norms, diminished accountability to safeguard democracy, reduced domestic job opportunities, and the exodus of top talent.

At the foundation of the digital stack, China exerts near-total control over the refining of certain rare earth elements (REEs), which are essential for manufacturing electronics, magnets, and other high-tech components. China accounts for approximately 90% of global REE refining capacity,[23] a dominance maintained through deliberate state policies and tightly integrated supply chains. Further up the stack, Taiwan Semiconductor Manufacturing Company (TSMC) dominates advanced chip production, controlling over 90% of the global market for cutting-edge semiconductors.[24]

By contrast, Europe produces less than 10% of the world's semiconductors and relies heavily on TSMC

21 Paul Timmers, "How Europe Aims to Achieve Strategic Autonomy for Semiconductors", Brookings Tech Stream, 9 August 2022, https://www.brookings.edu/techstream/how-europe-aims-to-achieve-strategic-autonomy-for-semiconductors/.

22 Fausto Gernone, "Moore's Death and the Rebirth of Vertical Monopolies", UCL IIPP (blog), 27 April 2023, https://medium.com/iipp-blog/moores-death-and-the-rebirth-of-vertical-monopolies-befa9ce5b892.

23 IEA, "Energy Technology Perspectives 2023 – Analysis", IEA, 12 January 2023, https://www.iea.org/reports/energy-technology-perspectives-2023.

24 The Economist, "Taiwan's Dominance of the Chip Industry Makes It More Important", 6 March 2023, https://www.economist.com/special-report/2023/03/06/taiwans-dominance-of-the-chip-industry-makes-it-more-important.

and South Korea's Samsung for advanced chips.[25] This dependency creates a significant strategic vulnerability, especially in the face of geopolitical tensions, particularly amid geopolitical tensions – such as those between China and Taiwan – or during disruptions to global supply chains, as seen during the COVID-19 pandemic. These supply chain shocks severely impacted industries like automotive, consumer electronics, and telecommunications. However, one key strength Europe possesses is its dominance in the machines that make chips, with ASML leading the global market in advanced lithography equipment essential for semiconductor manufacturing, giving Europe a critical foothold in the semiconductor value chain.

Many global tech companies have perfected the concept of "ecosystem power," integrating several products seamlessly into cohesive offerings, including cloud infrastructure, hardware, software, and user interfaces.[26] Central to this dominance is their "platform play,"[27] a strategy that leverages programmability, software, APIs, and infrastructure services to create powerful ecosystems. This model allows a small, highly specialized (and often expensive) team of experts to build and maintain a platform, enabling vast networks of developers and tech workers to create applications for end users. By leveraging dominance in one layer of the digital stack, these companies extend their dominance to others, dictating their terms for downstream applications, extracting rents through fees or commissions, and capturing valuable data streams. This entrenches market power, raises barriers to entry, and fosters dependency, reshaping competition across the digital stack.[28]

These companies, typically based in the United States, also benefit from robust venture capital ecosystems and public markets that reward innovation and scale. NVIDIA, with its market capitalization of approximately $3 trillion in 2025, exemplifies this advantage. The company has aggressively reinvested in research, development, and strategic acquisitions to consolidate its leadership in AI and Graphics Processing Units (GPU) technologies. Sovereign wealth funds, such as Saudi Arabia's Public Investment Fund (PIF), have further reshaped the AI and semiconductor landscapes by backing transformative initiatives like SoftBank's Vision Fund, which channels vast resources into AI and semiconductor startups. MGX, an Emirati investment firm specializingin AI, has also emerged as a key player in AI and data centers ventures, entering partnerships with Big Tech companies such as Microsoft, and financial giants such as BlackRock and SoftBank.[29] These financial networks enable dominant firms to acquire promising startups, further consolidating their power.

A similar pattern is evident in China. Both China[30] and, more recently, the United States[31] have introduced large industrial policy programs, investing hundreds of billions of dollars in the digital sector. These programs designate a broad range of digital technologies as strategic for economic and national security, mandating national control over critical technologies.[32] Global technology giants – including U.S. heavyweights such as Amazon,

25 European Commission, "A Chips Act for Europe".

26 Cristina Caffarra, Annabelle Gawer, and Michael Jacobides, "Mapping Antitrust onto Digital Ecosystems", CPI Antitrust Chronicle, 25 October 2024.

27 Annabelle Gawer, "Digital Platforms and Ecosystems: Remarks on the Dominant Organizational Forms of the Digital Age", Innovation 24, no. 1 (2 January 2022): 110–24, https://doi.org/10.1080/14479338.2021.1965888.

28 Vili Lehdonvirta, Cloud Empires: How Digital Platforms Are Overtaking the State and How We Can Regain Control (Cambridge, Massachusetts London, England: The MIT Press, 2022).

29 See: Hart, J. P. and C. (2024, September 17). BlackRock, Microsoft Partner on Massive New AI Infrastructure Fund. WSJ. https://www.wsj.com/tech/ai/blackrock-global-infrastructure-partners-microsoft-mgx-launch-ai-partnership-1d00e09f and "Announcing The Stargate Project", accessed 29 January 2025, https://openai.com/index/announcing-the-stargate-project/.

30 García-Herrero, A. and R. Schindowski (2024) "Unpacking China's industrial policy and its implications for Europe", Working Paper 11/2024, Bruegel

31 Aurelia Glass and Karla Walter, "How Biden's American-Style Industrial Policy Will Create Quality Jobs", Center for American Progress (blog), 27 October 2022, https://www.americanprogress.org/article/how-bidens-american-style-industrial-policy-will-create-quality-jobs/.

32 Alessandro Gili and Davide Tentori, "The Comeback of Industrial Policy. The Next Geopolitical Great Game" (ISPI, n.d.), accessed 11 January 2025.

Microsoft, Google, Apple, Meta, NVIDIA, Tesla/SpaceX, and Musk's associated ventures, as well as Chinese powerhouses like Huawei,[33] Alibaba, Tencent, and ByteDance – actively pursue integrated ecosystems that span critical infrastructure, platforms, and services.[34] Rather than simply offering discrete products, they embed their services deeply into essential layers of the digital economy – from cloud computing and data centers to software, operating systems, chips, AI models, mobile platforms, fulfillment logistics, advertising networks, and social media communities.

By controlling "stacks" of interdependent technologies, these companies generate powerful lock-in effects. Firms like Amazon, Microsoft, and Google integrate cloud, AI, and productivity tools, ensuring steady revenue streams while discouraging customers from switching due to high migration costs and complexity. Apple's similarly closed ecosystem tightly couples hardware, software, and its App Store, generating high user loyalty while capturing revenue from third-party developers. Meanwhile, Meta's social and virtual reality (VR) platforms rely on user data and open-source AI frameworks to encourage developers to build within its orbit, and NVIDIA's hardware-software alignment in GPUs fosters a similar kind of dependency.

Tesla has revolutionized electric vehicles by creating an advanced software ecosystem and AI-powered autopilot, while SpaceX leads global satellite communications through Starlink, now operating over 60% of active satellites.[35] Meanwhile, Musk's broader ventures also play into this strategy: xAI enhances Tesla's autonomous driving capabilities and explores broader AI applications, leveraging data from X, which he aims to transform into a unified hub for communication, payments, and AI services.

In China, well-funded government policies, including government-backed venture capital,[36] support firms like Huawei, Alibaba, Tencent, and ByteDance to replicate and refine strategies of infrastructural dominance. By leveraging their market power in specific domains – such as telecommunications, e-commerce, social networks, or video-sharing – these firms expand into critical layers like cloud computing, AI, and other foundational technologies.

Taken together, this model of infrastructural integration amplifies the power and resilience of a few dominant players, undermining domestic competitiveness, complicating regulatory oversight, and shaping information and commerce landscapes in ways that raise serious concerns about fairness, consumer choice, and democratic governance. Furthermore, in both China and the United States, demand from defense and security sectors significantly drives technological advancement. In contrast, the EU's decentralized defense policies and fragmented markets leave it without a comparable mechanism to support its industrial strategies.

Dominance is often fueled through data monopolization. Consumer-facing platforms collect vast amounts of data, which feed AI models. User data is commodified to predict and influence behavior.[37] Acting both as an input and as an output for many digital products, data creates feedback loops that entrench the dominance of existing players. For instance, Google's extensive data collection not only helps the company build better products, but it fuels advertising algorithms that dominate the digital advertising market, capturing

33 Xiaoying Dong, Mengling Yan, and Yanni Hu, Huawei: From Catching Up To Leading (Singapore: Springer Nature, 2023), https://doi.org/10.1007/978-981-19-4078-1.

34 Michael G. Jacobides, "How to Compete When Industries Digitize and Collide: An Ecosystem Development Framework", California Management Review 64, no. 3 (May 2022): 99–123, https://doi.org/10.1177/00081256221083352.

35 Debra Werner, "Want to Challenge Starlink in the Satcom Market?", SpaceNews, 16 September 2024, https://spacenews.com/want-to-challenge-starlink-in-the-satcom-market/.

36 Martin Beraja et al., "Government as Venture Capitalists in AI" (Cambridge, MA: National Bureau of Economic Research, July 2024), https://doi.org/10.3386/w32701.

37 This practice is called "surveillance capitalism" by Shoshana Zuboff, "The Age of Surveillance Capitalism: The Fight for a Human Future at the New Frontier of Power", Yale Law Journal 129, no. 5 (2020): 1460–1515, https://doi.org/10.26522/brocked.v29i2.849.

approximately 39% of global digital ad revenues in 2023. Meta holds an additional 18%.[38] These advertising revenues reinforce the financial strength of these companies, which in turn finances their expansion into digital ecosystems.

This consolidation has profound societal consequences. In their quest to increase their data harvest, platforms often amplify polarizing content to maximize engagement, creating fertile ground for fake news, conspiracy theories, and extremist ideologies. Algorithmic prioritization of sensational content exacerbates social divisions, undermines democratic discourse, and supports the rise of populism, which exploits these dynamics to spread misinformation and erode institutional trust.[39] Regulatory measures aimed at countering these effects include enforcing algorithmic transparency, limiting data monopolies, regulating targeted advertising, and curbing addictive design practices.[40]

If Europe fails to create the EuroStack and establish digital sovereignty, the global digital economy and its value capture mechanisms are likely to become even more concentrated and dominated by non-European players. Over the next decade, the consequences of inaction would be severe. Without the EuroStack initiative, Europe risks becoming a "digital colony," where critical technologies, data, and digital services are almost entirely controlled by external powers. In this scenario, transformative technologies such as IoT and edge computing would be dominated by non-European ecosystems, reducing Europe to a passive consumer rather than an innovator. The lack of European alternatives in cloud services and AI platforms would severely limit the ability of EU companies to compete globally in data-driven industries. This digital dependency will have profound implications for Europe's economic sovereignty, potentially constraining policy choices and leaving the continent vulnerable to economic coercion through control of vital digital infrastructure.

The absence of a robust European digital ecosystem will likely result in significant economic losses, including the erosion of high-skilled jobs and diminished value creation within the EU. The data generated by European citizens and businesses will increasingly be processed and monetized outside Europe, leading to a massive transfer of wealth and strategic assets to foreign entities. This scenario not only threatens Europe's economic prosperity but also its ability to uphold its values of privacy, transparency, and democratic governance in the digital realm.

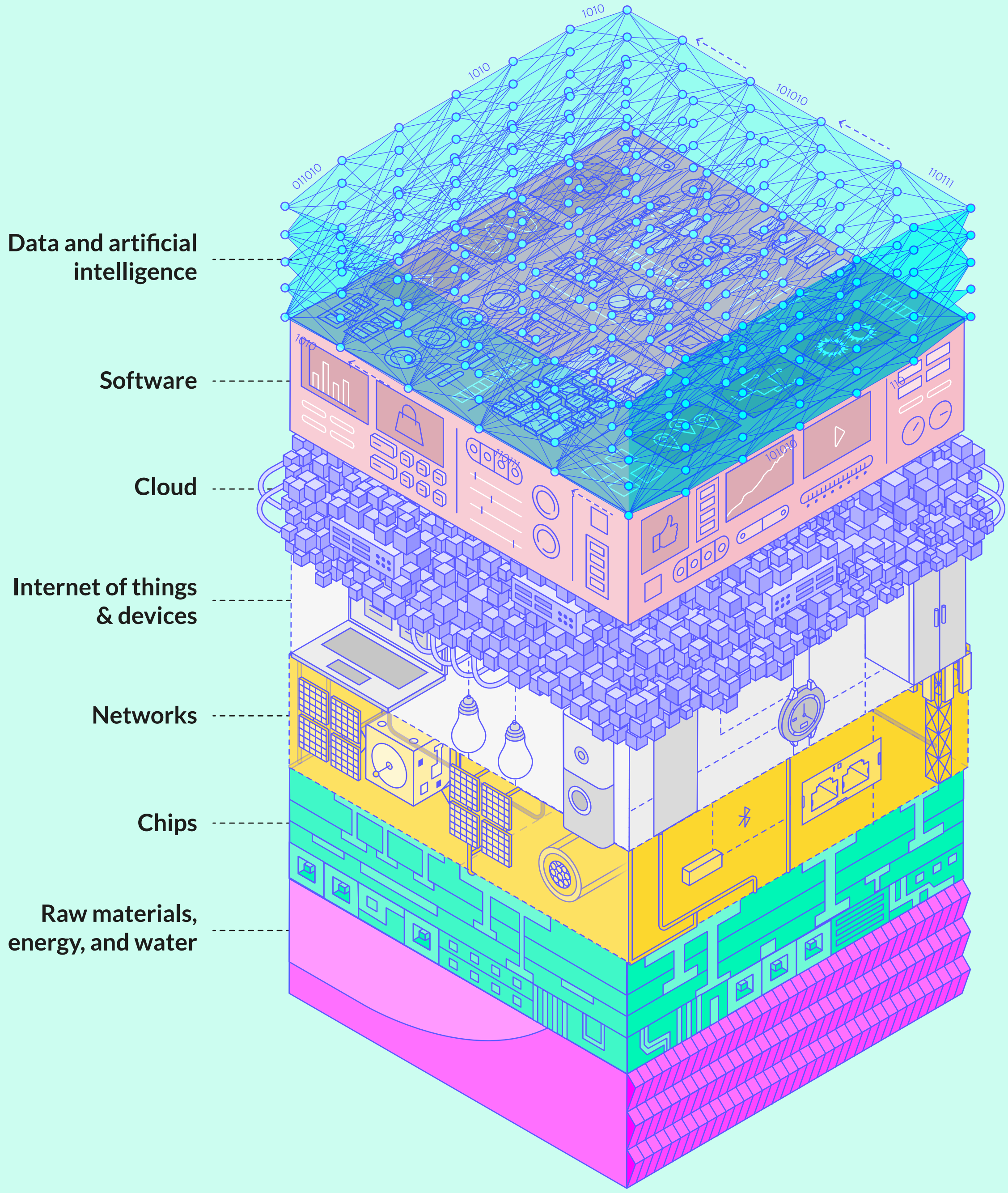
38 Statista, "Digital Ad Revenue Share by Company 2023", 3 December 2024, https://www.statista.com/statistics/290629/digital-ad-revenue-share-of-major-ad-selling-companies-worldwide/.

39 Steven Livingston, "The Rise of Right-Wing Populism: Diagnosing the Disinformation Age", Media@LSE (blog), 8 November 2023, https://blogs.lse.ac.uk/medialse/2023/11/08/the-rise-of-right-wing-populism-diagnosing-the-disinformation-age/.

40 European Parliament, "Addictive Design of Online Services and Consumer Protection in the EU Single Market – Tuesday, 12 December 2023", 12 December 2023, https://www.europarl.europa.eu/doceo/document/TA-9-2023-0459_EN.html.

The political economy of digital sovereignty

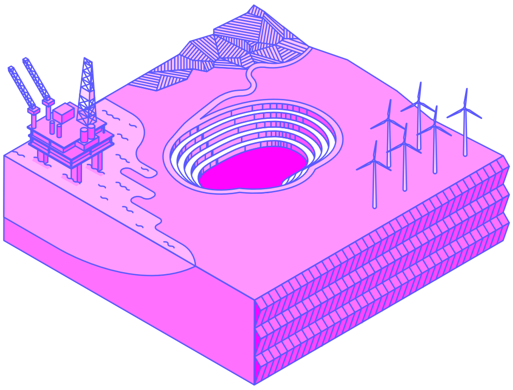
Exploring the tech stack



The separate layers explained

Raw materials, energy and water

The hidden backbone of technology

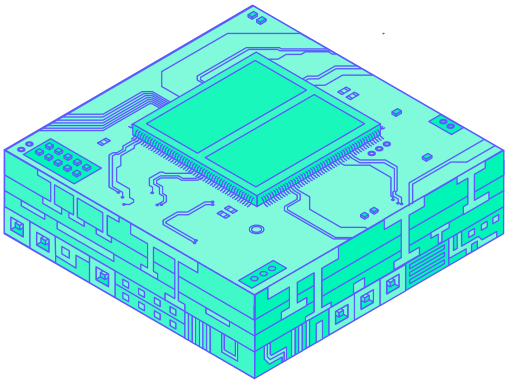


This foundational layer comprises essential resources – such as rare earth elements, energy sources, and skilled labor – that form the backbone of all digital infrastructure.

Key segments:
All layers

Chips

The brain of the stack

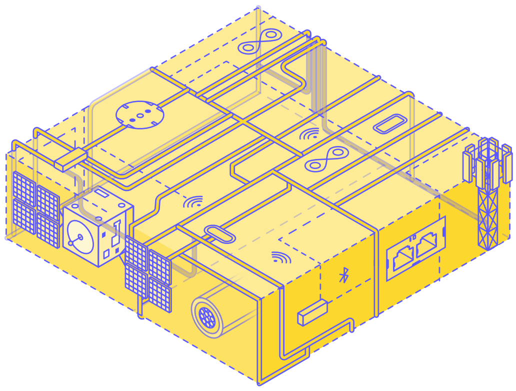


Processors and memory technologies, essential for powering digital infrastructure and ensuring secure supply chains, GPUs, and emerging quantum technology.

Key segments:
Foundry, design, equiament

Networks

The lifelines of connectivity

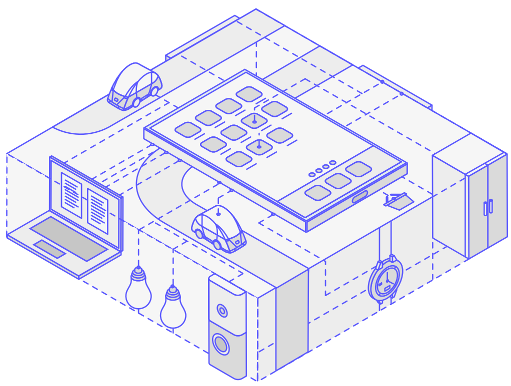


This layer is comprised of physical and digital infrastructures – such as cell towers, fiber-optic networks, undersea cables, and the public core of the internet – that connect Europe to the global digital ecosystem.

Key segments:
TMC equiament, mobile networks, satellites, submarine communication cables

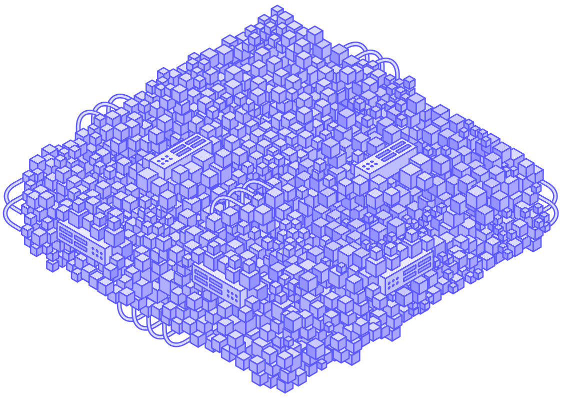
Internet of things & devices

The connective tissue of the digital ecosystem



From smartphones and laptops to IoT devices, this layer enables real-time information processing and data collection.

Key segments:
amartaaones, laatoas, smart aome devices, wearables, industrial & automotive IoT

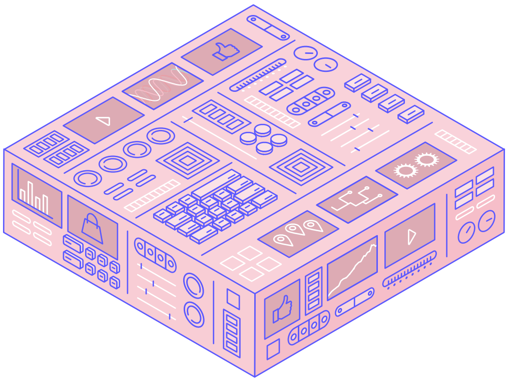


Cloud

The operational core of the digital economy

This layer includes secure data storage and computational power, with distributed computing infrastructures that are essential for ensuring data sovereignty and autonomy.

Key segments:
Data centers, cloud services

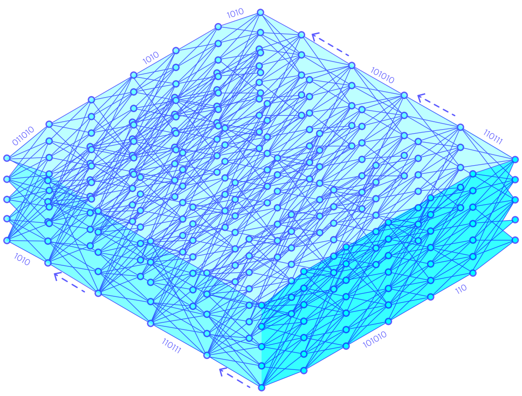


Software

The command center of platforms and applications

This layer includes operating systems, applications, authentication and cybersecurity frameworks that drive digital interactions.

Key segments:
OS, online platforms, programs



Data and artificial intelligence

Catalysts for innovation and strategic autonomy

This layer includes secure data storage and computational power, along with distributed computing infrastructures that are central to maintaining data sovereignty and autonomy.

Key segments:
AI, data

The evolving dynamics of the tech stack

The current stack – the computational framework that forms the backbone of the global digital supply chain – is not a fixed, static structure. Instead, it represents a dynamic and contested space where technology, strategic interests, and power intersect. Major tech companies are reshaping the stack through vertical integration, merging hardware, software, and cloud infrastructure into unified ecosystems. At the same time, governments worldwide are competing to control the technologies that underpin economic power and geopolitical influence. Today, the stack is a living, evolving system, with every layer – hardware, cloud computing, AI, edge computing, and quantum technologies – being continuously transformed by relentless innovation and strategic ambitions of both governments and large companies.

Vertical integration is particularly evident in the AI sector, though it is not confined to it. The surge in generative AI has driven demand for Nvidia's advanced GPUs, particularly the H100, catapulting the company to a trillion-dollar valuation. This surge in demand has also prompted companies like Microsoft, Meta, OpenAI, Amazon, and Google to develop custom AI processors, signaling a shift away from dependence on external suppliers. For example, Google's Axion chip and Amazon's Trainium3 are enabling these firms to improve performance, reduce costs, and maintain control over AI workloads.[41] As AI applications proliferate across industries, AI-specific chips are expected to account for a growing share of global semiconductors revenue.

Infrastructure is also evolving rapidly to support the AI boom. Microsoft, in partnership with asset managers like BlackRock, is building AI-dedicated data centers powered by renewable energy and exploring the use of micro-nuclear reactors to meet the growing energy demands of advanced AI systems. Amazon is experimenting with on-site energy generation to reduce dependency on external grids. Musk's xAI, powered by its Colossus data center with 100,000 NVIDIA GPUs, has taken aggressive steps to scale its infrastructure, doubling chip capacity and straining Nvidia's supply chain.[42] These moves highlight how innovation in infrastructure is not just about enhancing efficiency but also about integrating environmental sustainability into business strategies while consolidating market power. The stack is currently dominated by centralization, as illustrated by OpenAI and Microsoft's collaboration on custom AI supercomputers, which further consolidates chip design and manufacturing under a few global players. Without decisive action to enhance its own capabilities, this centralization risks deepening Europe's dependency on non-European systems, particularly in critical sectors like AI and cloud infrastructure.

The evolution of the tech stack is as much a geopolitical phenomenon as it is a technological one. Countries across the globe are prioritizing control over critical technologies to secure economic competitiveness and national security. The U.S.-China rivalry for technological dominance has emerged as one of the defining contests of the 21st century, reshaping global supply chains and international alliances.

The United States has escalated its efforts to curb China's advances in semiconductors, AI, and quantum computing. In October 2022, the Biden administration imposed severe export controls to block Chinese firms from accessing advanced chips and manufacturing tools like the extreme ultraviolet (EUV) lithography machines made by Dutch firm ASML. These measures are part of a broader U.S. strategy to limit China's technological rise, pressuring allies such as the Netherlands and Japan to restrict key exports.

41 Gernone, "Moore's Death and the Rebirth of Vertical Monopolies".

42 Stephen Morris and Tabby Kinder, "Elon Musk Plans to Expand Colossus AI Supercomputer Tenfold – FT", Financial Times, 4 December 2024, sec. xAI, https://www.ft.com/content/9c0516cf-dd12-4665-aa22-712de854fe2f.

The United States has also targeted Huawei, a global leader in 5G, citing national security concerns. These actions have significantly disrupted Huawei's supply chain. At the same time, Washington is investing heavily in AI and quantum technologies through initiatives like the CHIPS and Science Act, which allocates billions to strengthen domestic semiconductor production and R&D.

China is countering with a two-pronged strategy: ramping up domestic production and leveraging its dominance in critical raw materials. Beijing has committed over €140 billion under its Made in China 2025 plan to achieve self-sufficiency in advanced technologies. Despite restrictions, China's Semiconductor Manufacturing International Corporation has developed 7-nanometer chips, showcasing resilience, though it still faces significant technical limitations. Additionally, China has restricted exports of rare earth elements like gallium and germanium – essential for semiconductors and other advanced technologies – using these resources as leverage in the global supply chain.

Europe finds itself in a pivotal but precarious position within this geopolitical rivalry. ASML, the world's only producer of EUV lithography machines, is under pressure from the United States to limit sales to China, despite its economic interests – 14% of ASML's 2022 revenue came from China.[43] Meanwhile, the European Union is advancing its digital sovereignty with the €43 billion European Chips Act, aiming to double its share of global production of cutting-edge and sustainable semiconductors by 2030. Complementary initiatives like EuroStack underscore Europe's commitment to building a secure, independent digital infrastructure aligned with democratic values.

However, challenges remain. The semiconductor supply chain is highly complex, involving numerous countries and intricate processes, which complicates the enforcement of export controls. Additionally, Europe's economic dependencies on China further make full decoupling difficult. As the United States seeks to maintain dominance and China accelerates its self-sufficiency goals, Europe has the opportunity to assert its leadership by investing in innovation, protecting strategic industries, and charting a path toward autonomous yet interconnected digital sovereignty.

The stakes are clear: this tech rivalry will shape the future of digital capitalism, influencing global power dynamics for decades to come. However, escalating trade wars fueled by these technological tensions threaten to deepen economic fragmentation, disrupt supply chains, and undermine the collaborative frameworks needed to address global challenges. This, in turn, casts uncertainty over the path to stability and innovation, leaving all parties at risk.

Key paradigm shifts are transforming the technological landscape, including decentralization through edge cloud computing, advancements in quantum technologies, and the deep integration of the physical and digital realms. Decentralization is emerging as a countertrend to traditional centralized paradigms. The rise of edge cloud computing and next-generation networks is reshaping how data is processed and managed. Europe, leveraging its strengths in industrial IoT, federated cloud systems, and data sovereignty-oriented regulatory frameworks, is well-positioned to take the lead in this space.

Initiatives such as the Important Projects of Common European Interest in Cloud Infrastructure and Services (IPCEI-CIS) are paving the way for decentralized, federated infrastructures capable of processing data closer to its source. This approach enhances resilience, reduces latency, and bolsters security. Edge computing has moved beyond theoretical discussions and is now being actively deployed in sectors such as autonomous driving, smart factories, and healthcare, placing Europe at the forefront of these transformative technologies. However, blockchain technology, which underpins

43 Adam Levine, "The U.S. Has 2 Choices on China Chip Policy. Neither Are Good for Stocks.", barrons, accessed 13 January 2025, https://www.barrons.com/articles/chip-stocks-us-china-trade-policy-78acc6e4.

much of the current decentralization movement and the so-called web 3.0 paradigm, remains dominated by U.S. players. Europe has yet to reclaim its footing in this critical domain, presenting a challenge to its broader decentralization ambitions.

The cutting edge of the stack's transformation lies in quantum, photonics, and neuromorphic technologies which promise to disrupt traditional computing and communication paradigms. Quantum processors, such as IBM's 127-qubit Eagle and Pascal's 100-qubit quantum computer,[44] may be advancing encryption and simulation capabilities. Meanwhile, European hubs in Germany and the Netherlands are leading innovations in photonics, which uses light for data processing and transmission. Photonics offers significant advantages in speed and energy efficiency over traditional semiconductors, positioning Europe as a frontrunner in sustainable technology innovation.

The profound convergence of the physical and digital worlds is also driving the development of integrated ecosystems that combine AI, IoT, robotics, and AR/VR technologies. Examples include Amazon's warehouse robotics, Apple's Vision Pro AR headset, and Bosch's industrial IoT systems. These innovations blur the boundaries between real and virtual environments. Major players such as Meta (AR/VR) and NVIDIA (robotics) are investing heavily in this paradigm shift.[45] Europe's established strengths in areas like industrial IoT and robotics offers opportunities to lead in this domain, though competition from China and the United States remains intense.

The stack has become a battleground for economic power and digital sovereignty. Big Tech firms are consolidating control through bespoke innovation and vertical integration, while Europe's initiatives focus on decentralization, resilience, and sustainability. The future stack will evolve as a dynamic interplay of centralized and decentralized systems, shaped by technological breakthroughs and geopolitical priorities. For Europe, this transformation presents both challenges and opportunities. The growing centralization of AI and cloud infrastructure by non-European players highlights vulnerabilities in Europe's digital sovereignty. Defining the future stack is not just about technology – it is about shaping the systems that will define economic, societal, and political power for decades to come.

44 insideHPC, "Pasqal 100-Qubit Quantum Computer Shipped to Jülich Supercomputing Centre", High-Performance Computing News Analysis (blog), 2 December 2024, https://insidehpc.com/2024/12/pasqal-100-qubit-quantum-computer-shipped-to-julich-supercomputing-centre/.

45 Michael Acton and Cristina Criddle, "Nvidia Bets on Robotics to Drive Future Growth", Financial Times, 29 December 2024.

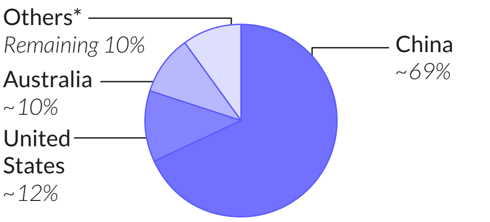
The geopolitical dimension

Key countries and leading firms in each stack layer

	KEY COUNTRIES	KEY FIRMS
Data and artificial intelligence	US, China	*OpenAI, Microsoft, Google, Meta, Anthropic, XAI, Amazon, Baidu, Tencent, Alibaba, DeepSeek*
Software	US, China, Germany	*Microsoft, Apple, Alphabet, Meta, Amazon, Salesforce, SAP, ByteDance, Tencent*
Cloud	US, China	*Amazon, Microsoft, Alphabet, Alibaba*
Internet of things & devices	US, China, Korea, Germany	*Amazon, Google, Apple, Samsung, Huawei, Bosch, Siemens, Xiaomi*
Networks	US, China, Europe, Japan	*Huawei, Nokia, Ericsson, ZTE, SpaceX, NEC*
Chips	Taiwan, Korea, US, Netherlands	*TSMC, Samsung, Intel, NVIDIA, AMD, ASML*
Raw materials, energy, and water	US, China, Russia	*Chinese government (through SOEs e.g., China Rare Earth Group), ExxonMobil, Gazprom*

FACTS

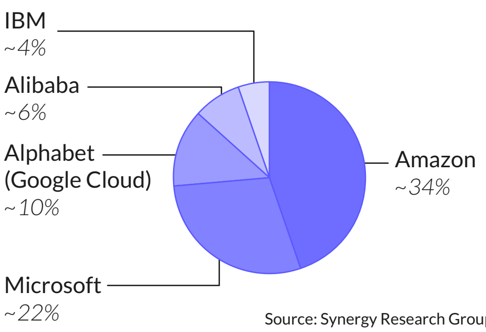
Global rare earth elements market
Market share by percentage



*Including Russia and Myanmar

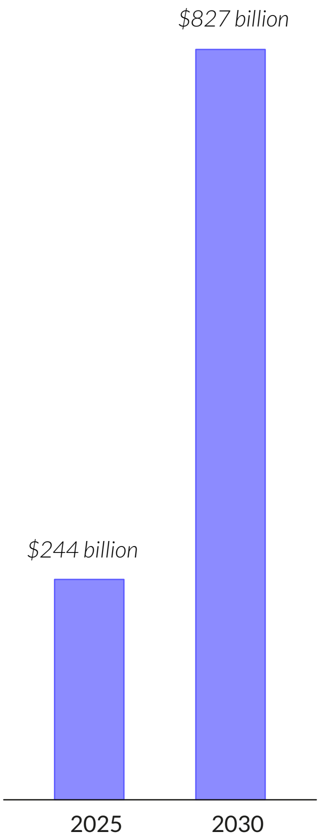
Source: U.S. Geological Survey

Cloud infrastructure market,
Market share by percentage



Source: Synergy Research Group

The global AI market
Estimated value
(in billion U.S. dollars)



Source: Statista

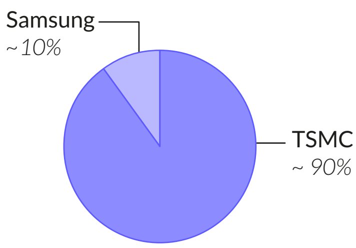
Emerging trends

Quantum communication networks are being developed, with **China leading** in satellite-based quantum communications.

RAN technology

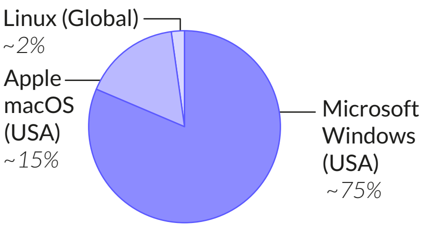
Open RAN technology providers are **gaining traction**, including Rakuten Symphony, Parallel Wireless, and Ericsson.

Advanced nodes manufacturing market
Market share by percentage

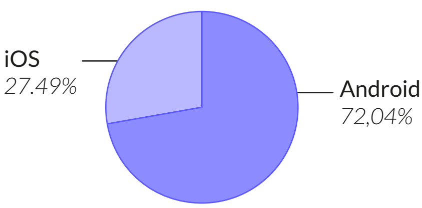


Source: Counterpoint Research

OS desktop market
Market share by percentage

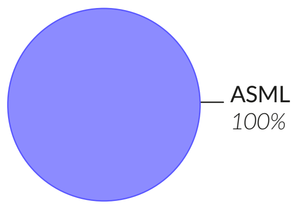


Global mobile operating system
Market share by percentage



Source: StatCounter

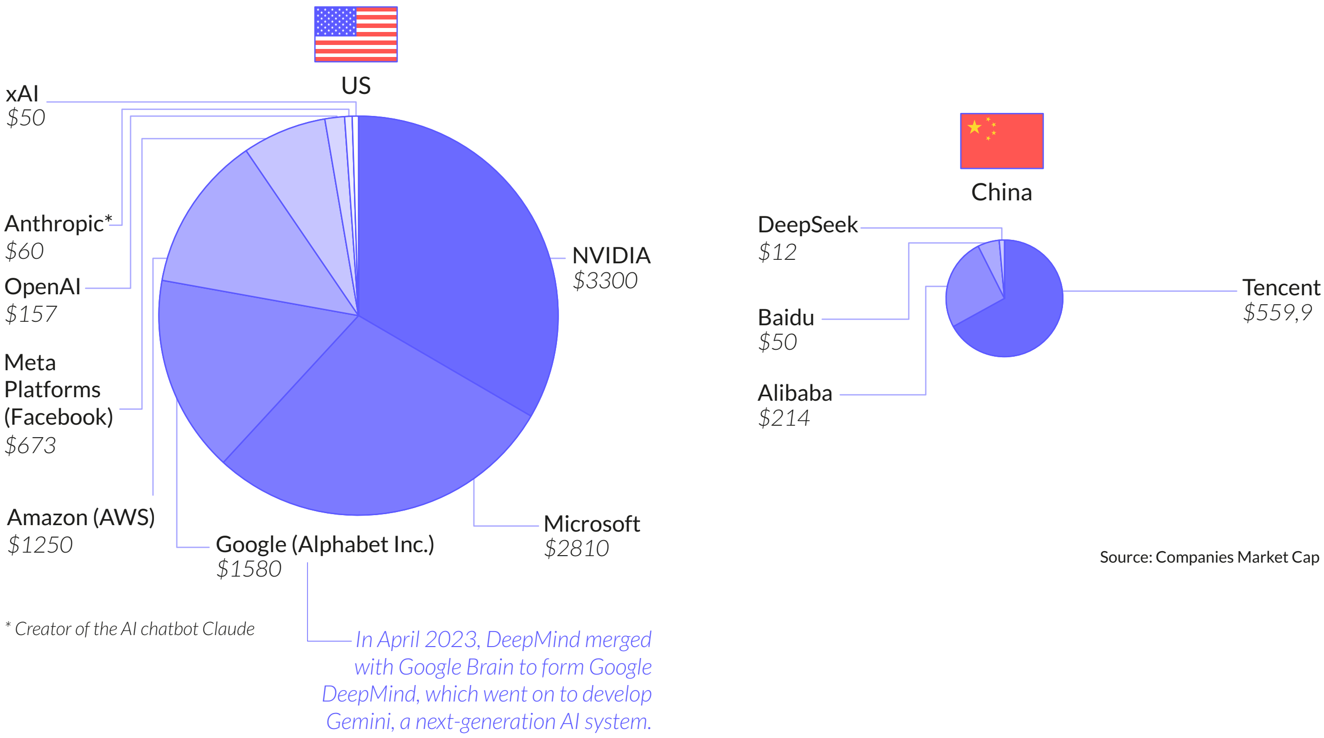
EUV lithography equipment market
Market share by percentage



Source: Semiconductor Industry Association

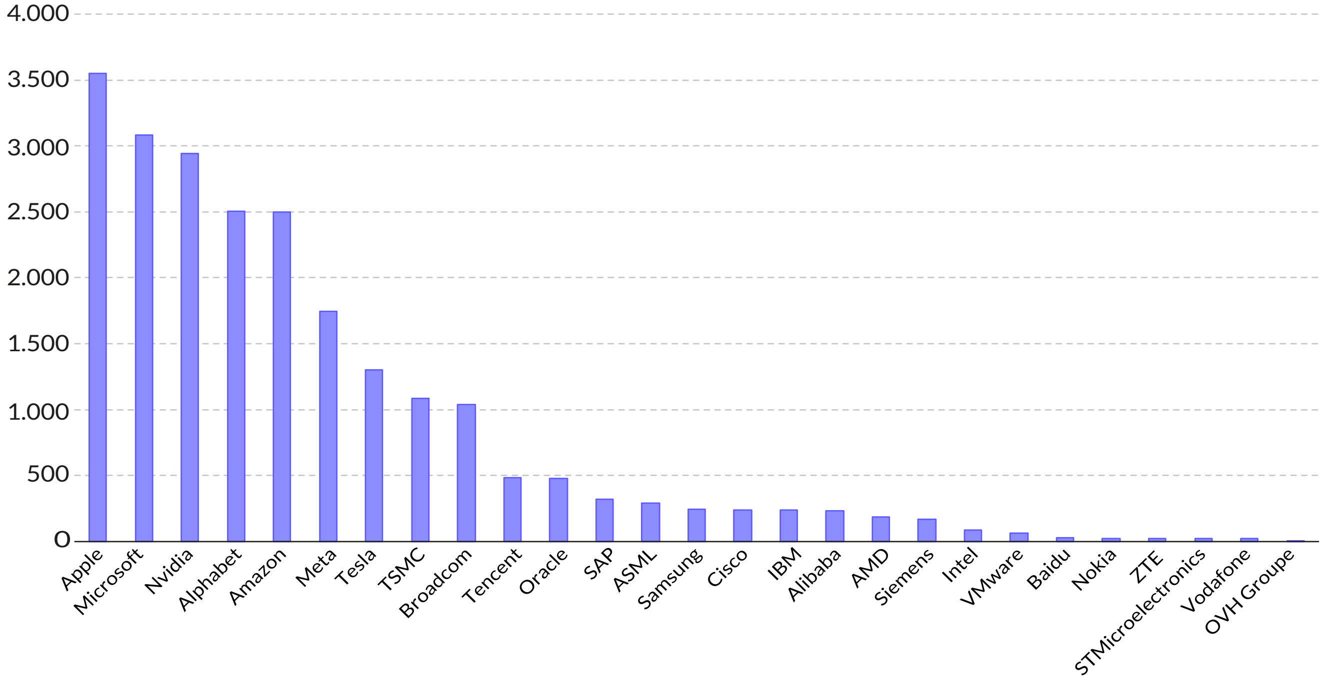
FACTS

Key AI companies by market capitalization and valuations, 2024
(in billion U.S. dollars)

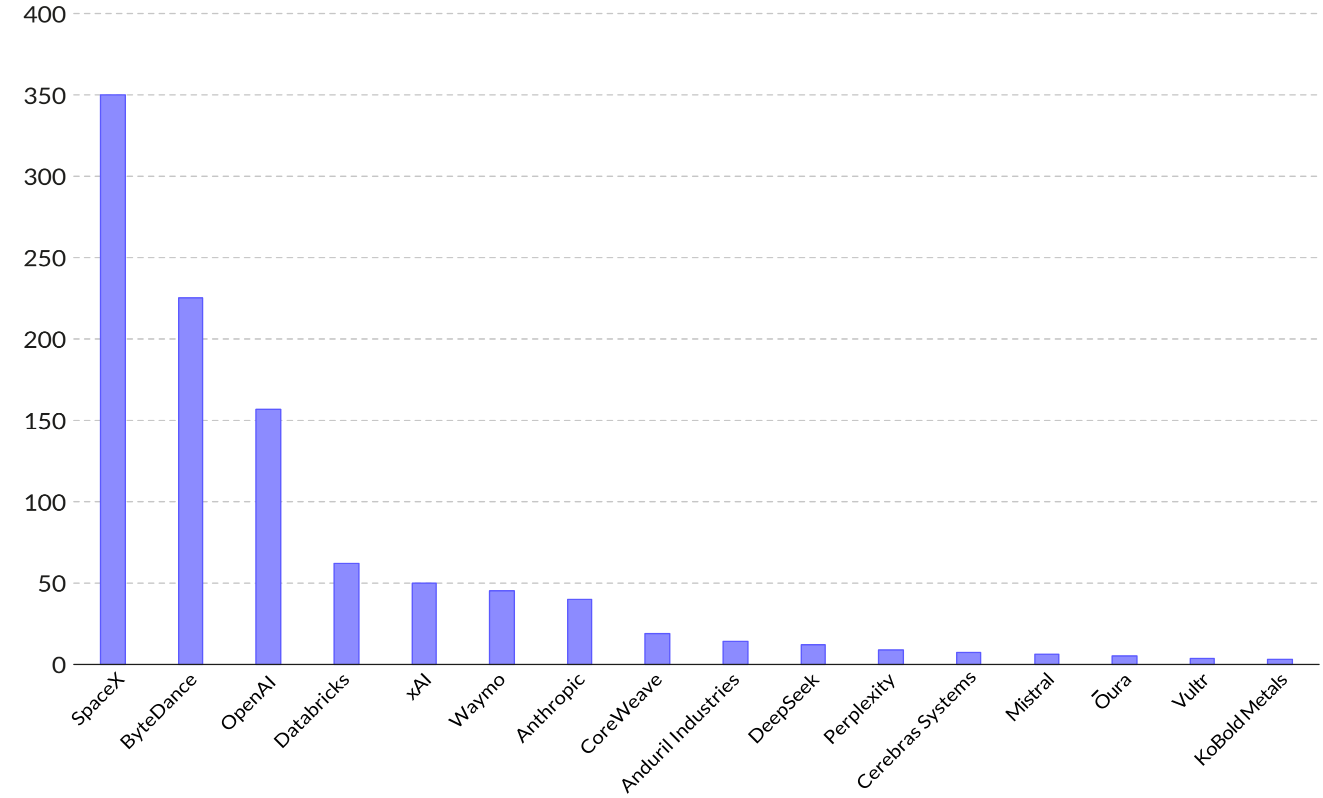


Source: Companies Market Cap

Market capitalization of key public companies in the digital sector, February 2025
in billion U.S. dollars



Market valuation of key private companies in the digital sector, 2024
in billion U.S. dollars



Source: Statista, Nasdaq, Wall Street Journal, Foundation Capital, Crunchbase, The Guardian, NY Times, Financial Times, TechCrunch, CNBC

Raw materials, energy and water: The hidden backbone of technology

The digital stack fundamentally depends on critical raw materials such as REEs, lithium, and cobalt. These materials are essential for manufacturing the key components of modern digital infrastructure, including semiconductors, batteries, displays, and high-performance magnets. However, their supply chains are largely controlled by foreign actors, particularly China. China dominates REE refining, accounting for over 90% of global capacity.[46] This dominance, achieved through state-backed policies and strategic acquisitions, extends to key battery materials like lithium and cobalt, where China's influence is reinforced by its investments in the Democratic Republic of Congo (DRC). Companies like China Northern Rare Earth Group and China Minmetals Corporation lead the sector, giving China unparalleled leverage, including the power to impose export restrictions during geopolitical disputes.

Europe remains heavily reliant on imports of critical raw materials. Over 68% of its cobalt and 78% of its lithium are imported, leaving the continent vulnerable to geopolitical risks and supply chain disruptions.[47] While countries like Sweden and Portugal, as well as Serbia – geographically close but outside the EU – possess promising reserves, large-scale extraction has yet to materialize. Notably, Serbia holds an estimated 1.2 million tons of lithium, representing a potential opportunity for reducing Europe's reliance on imports if sustainable extraction practices are developed and implemented. Europe's vulnerability is further exacerbated by its limited refining capacity. Addressing resource dependency requires not only greater access to raw materials but also technological innovation. For instance, germanium – one of the resources China has restricted for export – can be derived from zinc, as demonstrated by Europe's Nyrstar. An industrial policy is needed to further stimulate such technological innovation in resources.

The European Union has launched ambitious initiatives to reduce these dependencies. The Critical Raw Materials Act aims to secure 15% of Europe's raw material needs through recycling and ensure 10% of critical materials are sourced domestically by 2030.[48] Initiatives like the European Raw Materials Alliance (ERMA) are fostering partnerships with resource-rich regions such as Australia and Latin America while promoting investment in advanced recycling technologies. Recycling innovations offer a promising path forward. Companies like Germany's Aurubis and Belgium's Umicore, leaders in electronic waste recycling, and Norway's Hydrovolt, which specializes in battery recycling, demonstrate the potential of circular economies to reclaim valuable materials. However, scaling these efforts remains a challenge, requiring substantial investments and alignment with sustainability goals.

The digital economy's reliance on energy is also intensifying, growing energy demands add another layer of complexity, particularly with the rapid proliferation of AI models, whose training requires enormous computational resources. According to the International Energy Agency, data centers account for 2–4% of global electricity consumption, with localized impacts even higher.[49] For example, in Ireland, data centers consume over 20% of the country's electricity. These figures are likely to increase, as U.S. tech giants are investing heavily in Europe's data economy.[50] While these investments create opportunities, they also pose challenges, as many projects explore energy-intensive solutions, including nuclear power, which clash with Europe's

46 IEA, "Critical Minerals Market Review 2023 – Analysis", IEA, 11 July 2023, https://www.iea.org/reports/critical-minerals-market-review-2023.

47 Samuel Carrara et al., "Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU – A Foresight Study", 16 March 2023, https://doi.org/10.2760/386650.

48 Council of the European Union, "Critical Raw Materials Act", Consilium, 18 March 2024, https://www.consilium.europa.eu/en/press/press-releases/2024/03/18/strategic-autonomy-council-gives-its-final-approval-on-the-critical-raw-materials-act/.

49 IEA, "What the Data Centre and AI Boom Could Mean for the Energy Sector – Analysis", IEA, 18 October 2024, https://www.iea.org/commentaries/what-the-data-centre-and-ai-boom-could-mean-for-the-energy-sector.

50 United Nations Conference on Trade and Development, "Digital Economy Report 2024", 2024, https://unctad.org/system/files/official-document/der2024_en.pdf.

renewable energy priorities. The widespread use of renewable energy certificates by major providers often masks the true environmental cost, underscoring the need for stricter transparency and oversight.

Europe's energy landscape is evolving. Renewable sources like wind, solar, and hydropower are expanding, with leaders such as Sweden and Finland attracting energy-intensive industries due to their clean energy production. However, countries like Germany and Poland face challenges in balancing their reliance on coal and natural gas with the integration of renewables. The 2022 energy crisis, triggered by Russian supply disruptions, accelerated Europe's transition to renewables but also exposed its energy vulnerabilities. Rising energy prices increased operational costs for businesses, potentially dampening investment in the region. To address these challenges, Europe must prioritize energy-efficient, renewables-based solutions for AI-centric infrastructure. Innovations like Finland's LUMI supercomputer, powered entirely by hydropower from Vattenfall, provide a model for sustainable high-performance computing. Transparent emissions reporting and stricter oversight of renewable energy certificates are critical to ensuring alignment with Europe's carbon neutrality goals.

The security and resilience of the electricity grids are essential prerequisites for digital sovereignty and strategic autonomy. However, the security of ICT systems and supervisory control and data acquisition components, which are critical for managing power grids, has received relatively little attention in this context. These components must undergo comprehensive 360° risk assessments to address vulnerabilities. Such assessments typically focus on the following risk categories:

- **Geopolitical:** Disruptions in supply chains, competitive distortions as tools of hybrid warfare, anticipated trade restrictions, impacts on economic security, and related threats.
- **Strategic:** Dependence on foreign economies and technologies, loss of sovereignty, reduced market diversity, and external influence on standards.
- **Technical:** Data manipulation, targeted infiltrations (e.g., "backdoors"), and concealed "kill switches" that could compromise grid integrity.

Water is another critical resource, especially for cooling HPC systems. In 2023, Google's hyperscale data centers consumed an average of 2.1 million liters of water daily for cooling purposes.[51] This demand poses significant long-term risks, particularly as more than half of the global population is projected to live in water-stressed regions by 2050, including drought-prone areas such as Southern Europe. While advances in water recycling and desalination technologies hold promise, their adoption across Europe remains inconsistent. Strengthening these systems is vital to mitigate the environmental impact of expanding digital infrastructure.

Europe's digital sovereignty hinges on scaling its mining, refining, and recycling capabilities, all while adhering to sustainability goals. Partnerships with resource-rich regions and investments in advanced recycling technologies can reduce reliance on imports. Equally important is the integration of renewable energy sources and efficient water systems into AI and data center operations, which is essential for meeting climate targets and maintaining global competitiveness.

Chips: The brain of the stack

The forces shaping semiconductor dominance

Semiconductors form the backbone of the digital age, encompassing components ranging from basic resistors and sensors to memory chips and microprocessors. While early microprocessors were designed for general-purpose computing, they have

51 Mary Zhang, "Data Center Water Usage: A Comprehensive Guide", Dgtl Infra, 17 January 2024, https://dgtlinfra.com/data-center-water-usage/.

since evolved into specialized processors engineered for applications like AI, HPC, and machine learning (ML). Today's chips span a broad spectrum, from general-purpose central processing units used in PCs and servers to specialized GPUs and task-specific processors, such as Tensor Processing Units (TPUs), optimized for AI and HPC workloads. With increasing demands for efficiency, scalability, and energy optimization in cloud environments, the global microprocessor market has become a critical enabler of technological innovation. The global semiconductor market is estimated to grow from over €600 billion in 2024 to over €1 trillion by 2030.[52]

The semiconductor industry is shaped by powerful economic forces that concentrate control among a handful of dominant players, while relying on highly intricate and globalized supply chains.[53] The manufacturing stage of semiconductors is characterized by significant economies of scale that require billions of euros in investment and a massive concentration of tacit knowledge and talent, all of which creates formidable barriers for new entrants. Asian foundries, particularly those in Taiwan and South Korea, dominate advanced chip manufacturing, producing chips at cutting-edge process nodes like 5nm and 3nm. TSMC alone commands over 50% of the global semiconductor market and 90% of advanced chip production. Companies like TSMC and Samsung leverage their scale to reduce per-unit costs, ensuring efficiency while reinforcing their market dominance. The industry's rapid technological progress continues to be driven by "Moore's law," which remains a foundational principle of advancement.

Another critical factor is the network effect in chip design, where established architectures like x86 (used by Intel and AMD) and ARM gain dominance through widespread adoption and robust developer ecosystems. ARM's architecture, owned by Japan's SoftBank, underpins many custom chip designs, including Amazon Web Services (AWS's) Graviton and Google's TPUs. These network effects not only spur innovation but also lock developers into specific ecosystems, further consolidating market control.

Co-specialization plays an important role in the chips industry. Intel's integrated design-manufacturing exemplifies the traditional model based on the co-specialization between design and production, allowing seamless optimization of chip performance and cost efficiency. More recently, new business models harness the specialization between chip design and end use.[54] NVIDIA, for example, controls over 80% of the chips specialized for AI – so-called GPUs – and provides a programming platform tightly coupled with its chips, enhancing performance while fostering ecosystem dependence. The company generated €26.3 billion in data center revenue in the second quarter of the 2024 calendar year.[55] Similarly, cloud providers like AWS, Google Cloud, and Microsoft Azure increasingly integrate chip design and cloud-specific applications, creating proprietary processors tailored to their platforms. Innovations like AWS's Graviton processors, Google's TPUs, and NVIDIA's proprietary GPU architectures exemplify this trend, optimizing performance and energy efficiency while locking customers into their ecosystems. NVIDIA CUDA further illustrates this model by providing a programming platform tightly coupled with NVIDIA's GPUs, enhancing performance while fostering ecosystem dependence.

These economic dynamics often create tension within the industry, influencing its trajectory. Specialization fosters the development of narrow-purpose chips tailored to specific applications, but this clashes with the benefits of standardization, which supports network effects by enabling broad applicability across platforms. Similarly, the tailored processes required for specialized designs

52 PwC, "State of the Semiconductor Industry", PwC, 28 November 2024, https://www.pwc.com/gx/en/industries/technology/state-of-the-semicon-industry.html.

53 Miller, C. (2022). Chip War: The Fight for the World's Most Critical Technology. Scribner.

54 Gernone, "Moore's Death and the Rebirth of Vertical Monopolies".

55 Statista, "Data Center/AI Chip Revenue of Nvidia, AMD, and Intel 2024", 29 August 2024, https://www.statista.com/statistics/1425087/data-center-segment-revenue-nvidia-amd-intel/.

conflict with the economies of scale that favor the high-volume production of standardized chips. These competing forces underscore the inherent complexity of the semiconductor industry.[56]

Europe's path to semiconductor resilience

Europe plays a relatively modest role in the semiconductor industry, accounting for just 10% of global production and possessing limited capacity for advanced chip manufacturing. The continent relies heavily on foreign suppliers for leading-edge chips.[57] As noted earlier, this reliance exposes the region to geopolitical risks.

However, Europe is not without strategic assets. The region holds approximately 25% of the global market for semiconductor equipment, with key players such as ASML, Bosch, and STMicroelectronics driving the industry forward.[58] The Netherlands-based ASML, a global leader in the production of semiconductor equipment, holds a critical position in the semiconductor ecosystem. ASML's extreme ultraviolet (EUV) lithography technology is indispensable for manufacturing advanced chips, a monopoly that gives giving Europe leverage in the global value chain. Nevertheless, ASML's dominance is constrained by U.S. export controls, imposed for national security and potentially economic reasons.[59] Moreover, Europe lacks the downstream production capacity to capitalize on this advantage, particularly in areas like HPC and AI-specific chips.

To address these vulnerabilities, Europe has taken decisive action. The European Chips Act, with its €43 billion investment plan, aims to double Europe's share of global advanced semiconductor production to 20% by 2030 and leverage strengths in specialized equipment and areas like automotive and industrial electronics. This initiative aligns with global trends: the U.S. CHIPS Act allocates €51 billion to domestic semiconductor production, while China is investing €140 billion over five years to achieve greater self-sufficiency in the sector. Nevertheless, Europe's contribution to the semiconductor industry remains uneven. While companies like STMicroelectronics, NXP Semiconductors, and Infineon excel in automotive and industrial electronics, they have limited presence in sectors driving the next wave of digital innovation. Furthermore, despite significant investments, Europe's semiconductor industry faces challenges in securing subsidies, diversifying production, and attracting talent. These obstacles are exemplified by the delays and uncertainties surrounding Intel's planned factory in Magdeburg.[60]

Initiatives like SiPearl's Rhea processor and the Barcelona Supercomputing Center's investment in open-source RISC-V architecture signal a shift in Europe's approach to reducing its dependence on proprietary technologies like ARM. RISC-V's flexibility and free licensing can enable Europe to develop tailored software ecosystems for AI, advanced manufacturing, and high-performance computing, fostering innovation while reducing reliance on foreign intellectual property. The RISC-V is projected to grow at a compound annual growth rate (CAGR) of 33.1%, reaching €2.6 billion by 2027.[61] Another promising area is photonic chips, which use light to achieve faster processing speeds and lower energy consumption. The Spanish Institute of Photonic Sciences (ICFO), in collaboration with institutions

56 W. Edward Steinmueller, "The Economics of Flexible Integrated Circuit Manufacturing Technology", Review of Industrial Organization 7, no. 3/4 (1992): 327–49.

57 European Commission, "European Chips Act: Staff Working Document | Shaping Europe's Digital Future", 12 May 2022, https://digital-strategy.ec.europa.eu/en/library/european-chips-act-staff-working-document.

58 Credence Research, "Semiconductor Equipment Market Size, Growth and Forecast 2032", 7 October 2024, https://www.credenceresearch.com/report/semiconductor-equipment-market.

59 Reuters, "ASML CEO Says US Desire to Restrict Exports to China 'Economically Motivated'", Reuters, 4 September 2024, sec. Technology, https://www.reuters.com/technology/asml-ceo-says-us-motivation-restricting-equipment-exports-china-is-economically-2024-09-04/.

60 Politico, "The EU's Chips Plan Implodes as Intel Pauses Investments", POLITICO, 17 September 2024, https://www.politico.eu/article/intel-germany-chips-plant-competitiveness-eu-ambition/.

61 BCC Publishing, "RISC-V Technology Market Size, Share & Growth Analysis Report", 1 December 2022, https://www.bccresearch.com/market-research/semiconductor-manufacturing/global-risc-v-technology-market.html.

from Ireland, the Netherlands, Finland, Belgium, Portugal, Poland, Austria, Italy, and France, is leading a €380 million project to advance this technology. These efforts showcase Europe's ability to lead in next-generation semiconductor technologies.

Networks: The lifelines of connectivity

Networks serve as the backbone of Europe's digital infrastructure, connecting devices, services, and systems across telecommunications and cloud environments. The public core of the internet, including the domain name management system (DNS) and Internet Exchange Points (IPX), is located in this layer. The rise of 5G and the shift toward standalone 5G networks – which integrate 5G radio and core systems – along with the increasing role of private networks supported by satellite systems and undersea cables, are driving a significant transformation. These networks enable low-latency, high-speed, and redundant connections that are critical for cloud platforms as well as for emerging technologies such as autonomous vehicles, industrial automation, and smart cities. Virtualization is now a defining feature of these networks, as they increasingly rely on cloud services, blurring the traditional distinctions between traditional telecommunications providers and cloud providers.

The concept of network sovereignty – or strategic autonomy in the network layer – has emerged as a pressing priority for Europe, influencing its competitiveness, security, and resilience. This issue is particularly evident in areas such as network equipment, undersea cables, and satellite systems, but may also become more prominent in DNS. Globally, the communications equipment market is dominated by a handful of players, including Huawei, Ericsson, and Nokia, followed by ZTE, Cisco, Ciena and Samsung.[62] European manufacturers, particularly Ericsson and Nokia, excel in technological innovation, such as 6G research and pre-standardization. However, these firms face intense competition from Chinese vendors, whose state-backed support enables aggressive pricing strategies and rapid global market penetration. Europe's fragmented telecom market, with hundreds of mobile operators compared to the much more concentrated markets in the United States and China, further complicates its ability to compete.[63] Market fragmentation, including inconsistent security requirements across member states, limits economies of scale and reduces investment efficiency, constraining the sector's capacity for innovation and the deployment of advanced networks.[64]

The telecom ecosystem is shaped by the interplay of equipment manufacturers, telecom operators (telcos), cloud providers, and value-added service providers such as entertainment and e-commerce platforms. European telcos, including Deutsche Telekom, Telefónica, and Vodafone, maintain large global footprints, particularly in the United States and Latin America. Despite this, European telcos face significant financial constraints. Average revenue per user in Europe is far lower than in other regions, which limits the resources available for investing in advanced networks. These financial constraints contribute to delays in the rollout and adoption of 5G, leaving Europe trailing behind the United States and China in this critical area.

Dominant foreign cloud and platform providers are playing an increasingly influential role in the network layer, providing virtualized services critical for 5G while increasingly competing with telcos. Their proprietary virtualized network solutions enable them to control critical parts of the network layer. Additionally, several platform providers, such as Alphabet and Meta, have become significant players in the telecom backbone, investing heavily in undersea cables and low-Earth orbit satellite

62 2023 data as reported in Mario Draghi, "The Future of European Competitiveness – A Competitiveness Strategy for Europe".

63 Mario Draghi, 69.

64 ETNO, "ETNO – Future of Electronic Communications Networks in Europe – Fact-Pack" (ETNO, September 2023), https://etno.eu/library/reports/116-future-of-electronic-communications-networks-in-europe.html.

networks. Companies like SpaceX and its Starlink service dominate satellite communications, raising further concerns about critical dependencies In the undersea cable business, limited and highly concentrated repair capacity represents an additional vulnerability. The EU has initiated coordinated measures to enhance the protection of undersea cables,[65] while the European Space Agency is working to develop satellite launch capacities.[66] However, it remains unclear whether these efforts will achieve the strategic autonomy that Europe aspires to in the network domain.

The EU must remain vigilant in safeguarding its strategic autonomy in the evolution of the public core of the internet, including critical elements like DNS management, undersea cables, and satellite networks. Discussions on proposals such as new intellectual property (IP) frameworks at the International Telecommunication Union (ITU) underscore the risks of influence from major powers, which could undermine European interests. Emerging technologies like AI and blockchain are set to transform domain name management, potentially shifting the balance of control. To protect its digital sovereignty, the EU must actively engage in these developments, ensuring its values and priorities remain central to shaping the global digital landscape.

Security concerns add another dimension to the set of challenges facing Europe's network layer. The reliance on Chinese equipment has prompted the European Commission to issue a 5G Security Recommendation,[67] prompting several operators to remove Huawei and ZTE equipment from their networks. However, adoption of these measures has been uneven. Large telcos such as Deutsche Telekom and Telefónica have been slower to replace Chinese components.

Ensuring digital sovereignty in 6G will require a comprehensive network security architecture capable of isolating security concerns (e.g., for core-of-government information) while learning lessons from the 5G security challenges. Such an approach must also adapt to emerging business models and regulatory frameworks.[68] This principle extends to potential new internet designs such as SCION.[69]

The security risks extend beyond 5G hardware to include undersea cables and – increasingly – satellite connections and AI-driven network management. These risks are not limited to cyber threats but also encompass physical sabotage – such as cutting undersea communications cables in the Baltic Sea, arson attacks on 5G base stations, hybrid warfare, and geopolitical disruption. Climate-related risks such as the 2024 Boris flooding, which disrupted electricity and telecom networks, further exacerbate these vulnerabilities, given the high interdependence of these systems. Addressing these evolving threats will require the integration of cybersecurity and defense policies into telecom strategies, along with cross-sectoral cooperation to enhance resilience.[70] The rise of Open Radio Access Network (OpenRAN) technologies offers a potential pathway for Europe to reduce dependencies and strengthen its position. OpenRAN decouples hardware and software in the access (radio) network, allowing telcos to source components from multiple vendors and fostering competition. Countries such as Canada have successfully replaced Chinese equipment with OpenRAN solutions, highlighting its potential as a secure and cost-effective alternative. For Europe,

65 European Commission, "Commission Recommendation on the Security and Resilience of Submarine Cable Infrastructures | Shaping Europe's Digital Future", 21 February 2024, https://digital-strategy.ec.europa.eu/en/library/recommendation-security-and-resilience-submarine-cable-infrastructures.

66 Ariane 6 overview. (n.d.). Esa.Int. Retrieved 3 February 2025, from https://www.esa.int/Enabling_Support/Space_Transportation/Launch_vehicles/Ariane_6_overview.

67 European Commission, "COMMISSION RECOMMENDATION (EU) 2019/ 534 – of 26 March 2019 – Cybersecurity of 5G Networks", Official Journal L, no. 88/42 (26 March 2019): 6.

68 Paul Timmers, "There Will Be No Global 6G Unless We Resolve Sovereignty Concerns in 5G Governance', Nature Electronics 2020 3:1 3, no. 1 (24 January 2020): 10–12, https://doi.org/10.1038/s41928-020-0366-3.

69 For more information, see SCION's website: https://www.scion.org.

70 Richard Feasey et al., "Ideas for the Future of European Telecommunications Regulations | CERRE" (CERRE, 12 September 2024); Georg Serentschy, "Digital Networks Resilience and Security, Policy Implications and Mitigation Measures – Summary", 13 January 2024.

OpenRAN presents an opportunity to promote domestic innovation and diversify supply chains.

Europe's strengths in 5G and 6G research and development, as well as pre-standardization, provide a solid foundation for future competitiveness if adoption is accelerated. Supported by leading academic institutions and research organizations, European manufacturers are well-positioned to shape the next generation of network technologies. Initiatives like the announced Digital Networks Act (DNA) may address market fragmentation, enhance security, and facilitate telco consolidation, fostering a more competitive telecom sector while safeguarding consumer interests. Revising competition policies to prioritize public interests such as security and sustainability could further bolster the industry.[71]

Finally, integrating advanced technologies into telecom infrastructure is essential for Europe's resilience. Quantum cryptography, including quantum key distribution (QKD) and post-quantum cryptography (PQC), will be critical for securing next-generation networks against emerging cyber threats. Additionally, the telecom sector's heavy reliance on electricity highlights the need for closer integration of energy and network strategies to ensure both resilience and sustainability, as previously discussed. Europe has an opportunity to redefine its telecom sector. Through strategic investments in 6G, OpenRAN, and quantum technologies, alongside policies that foster innovation, adoption, and consolidation, Europe can build a robust and secure network layer that safeguards its digital sovereignty while driving competitiveness and economic growth.

71 Feasey et al., "Ideas for the Future of European Telecommunications Regulations | CERRE".

IoT: The connective tissue of the digital ecosystem

The internet of things bridges the physical and digital worlds by embedding sensors, processors, and connectivity into objects, enabling real-time data exchange and automation across a broad range of sectors. Connected devices consist of self-contained equipment connected to digital communication networks, including heart monitors, other medtech devices, and mobile phones. This discussion excludes more complex equipment such as connected e-vehicles. The number of IoT devices is forecast to grow from 18 billion in 2024 to 39 billion by 2033.[72] IoT-generated data is projected to generate over 79.4 zettabytes of data annually by 2025.[73] IoT global markets are projected to reach €1.3 trillion in value by 2030.[74] High-growth areas include healthcare (projected to contribute €60 billion in IoT-driven growth by 2030) and industrial manufacturing, where IoT plays a critical role.

The transformative potential of IoT spans key industrial sectors such as manufacturing (e.g., smart factories), agri-food, smart energy, mobility, healthcare and environmental management. For instance, IoT enhances grid efficiency by enabling real-time data analysis and decision-making.[75] IoT technical systems often rely on orchestration software, which facilitates the identification, authentication, and connection of IoT devices while aggregating the data they generate, typically within a cloud-based service.

72 Transforma, "Current IoT Forecast Highlights – Transforma Insights", 9 December 2024, https://transformainsights.com/research/forecast/highlights.

73 Statista, "IoT Devices Installed Base Worldwide 2015–2025", 27 November 2016, https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/.

74 Transforma Insights, "Global IoT Market to Grow to $1.5trn Annual Revenue by 2030 | IoT Now News & Reports", IoT Now News – How to Run an IoT Enabled Business (blog), 20 May 2020, https://www.iot-now.com/2020/05/20/102937-global-iot-market-to-grow-to-1-5trn-annual-revenue-by-2030/.

75 Sunkari Pradeep et al., "Analysis and Functioning of Smart Grid for Enhancing Energy Efficiency Using OptimizationTechniques with IoT", in 2023 IEEE 5th International Conference on Cybernetics, Cognition and Machine Learning Applications (ICCCMLA), 2023, 316–21, https://doi.org/10.1109/ICCCMLA58983.2023.10346767.

Smart factories (Industry 4.0) that integrate IoT, AI/ML and 5G, are poised to enhance productivity and efficiency. By fostering AI-driven industrial innovation, Europe can strengthen its manufacturing base while promoting ethical and trustworthy AI applications. While Industry 4.0 focuses on automation, interconnectivity, and data exchange in manufacturing technologies, Industry 5.0 represents the next evolutionary step in industrial development (see Box 1: Advanced manufacturing and robotics). Industry 5.0 emphasizes collaboration between humans and machines, aiming to combine the speed and precision of automation with human creativity, critical thinking, and problem-solving skills.

Companies like Bosch and Siemens are at the forefront of deploying industrial IoT for industrial efficiency, scalability and trustworthiness. Their initiatives demonstrate how integrating IoT with AI and data analytics can lead to significant improvements in operational performance, resource management, and energy consumption. Overall, Germany's industrial IoT (IIoT) market is projected to grow at an annual rate of 10.54% from 2024 to 2029, reaching €12.5 billion by 2029.[76] Germany's industrial IoT capabilities are bolstered by robust market growth, active academic research, and strong public-private partnerships. The strategy of Bosch and Siemens reflects a commitment to fostering open ecosystems and trustworthiness (e.g., in the Charter of Trust) that support widespread adoption of IoT technologies across various industries.

Europe, home to two of the world's top three telecom vendors, has a strong foundation in 5G and 6G, enabling IoT adoption at greater scale and with increased reconfigurability.

The EU's Next Generation Internet of Things initiative highlights IoT's transformational role in the digitalization of the economy, society, and environment.[77] As connected devices proliferate, IoT integrates data, computing, and connectivity, enabling intelligent systems that collect, process, and act on information in real time. Trusted IoT and edge computing platforms, along with effective orchestration mechanisms, are widely recognized as essential for this next phase of digitalization. The European Commission, through Horizon Europe, is funding research and innovation to advance joint digital technology initiatives, AI and robotics partnerships, and programs such as sector-specific data spaces and cloud-edge federations. The Digitizing European Industry initiative prioritizes ecosystem development, interoperability, technology integration, and standardization.[78] Large-scale pilots and Technology and Experimentation Facilities target key sectors including agriculture, energy, manufacturing, mobility, healthcare, and smart communities, advancing Europe's IoT innovation.

Open-source initiatives, such as RIOT OS[79] for low-power IoT devices and the EEBus Initiative[80] for smart home and energy communication, exemplify efforts to foster collaboration, reduce reliance on proprietary platforms, and build a resilient IoT ecosystem. Meshtastic[81] is an open-source, community-driven project using inexpensive LoRa radios to create long-range, off-grid communication platforms in areas without reliable infrastructure. Arduino another leading open-source initiative, offers microcontroller boards widely used in IoT projects to connect sensors, actuators, and other components. Companies like Lithuania/Poland-based Cogniteq commercialize these technologies

76 Statista, "Industrial IoT – Germany | Statista Market Forecast", June 2024, https://www.statista.com/outlook/tmo/internet-of-things/industrial-iot/germany.

77 European Commission, "The next Generation Internet of Things | Shaping Europe's Digital Future", 29 November 2024, https://digital-strategy.ec.europa.eu/en/policies/next-generation-internet-things.

78 European Commission, "The Digitising European Industry Initiative in a Nutshell | Shaping Europe's Digital Future", 16 March 2018, https://digital-strategy.ec.europa.eu/en/library/digitising-european-industry-initiative-nutshell.

79 "RIOT – The Friendly Operating System for the Internet of Things", accessed 11 January 2025, https://www.riot-os.org/.

80 "Eebus – Homepage", EEBus – Empowering the digitalisation of Energy transition, accessed 11 January 2025, https://www.eebus.org/.

81 "Meshtastic – Introduction", accessed 11 January 2025, https://meshtastic.org/docs/introduction/.

to expand their application in IoT ecosystems.[82] FIWARE defines open standards for IoT, data management, and Big Data, enabling businesses to build scalable, interoperable, and sustainable solutions free from vendor lock-in.[83] Libelium, a standout European IoT company focuses on applying IoT solutions to enhance productivity and reduce costs while minimizing environmental impact.[84]

Challenges for Europe in IoT and connected devices.

Tightly integrated IoT ecosystems: While being strong in industrial IoT, Europe faces significant challenges in consumer IoT and connected devices, where global tech giants like Apple, Google, Huawei, and Samsung dominate and Chinese companies increasingly enter medtech. These companies often leverage vertically integrated ecosystems that combine hardware, software, and cloud services, allowing them to set de facto global standards and capture significant market value. Smartphone operating systems are increasingly the backbone of their IoT strategies.

Cybersecurity has become a critical issue as IoT and connected devices massively expand what is called the cyber-attack surface. The EU's Cybersecurity Resilience Act will be pivotal in shaping IoT's security regulatory environment. This is expected to drive demand for integrated hardware and software security, and data minimization (see also the data layer).

Data governance, privacy and ethical use all pose challenges in the IoT and connected devices landscape. Especially in the consumer world, massive amounts of data are collected by the vendors that pursue integrated digital ecosystems (for more context, see the data layer). Despite the robust personal data protection framework provided by GDPR, severe privacy infringements continue to occur. With IoT becoming more pervasive in homes, there is a growing need for stronger assurances, such as voluntary certification and trust-labeling mechanisms. This challenge could also present an opportunity for competitive differentiation, particularly if EU vendors are supported in applying data protection laws and ethical standards efficiently.

Standards: Standardization is closely tied to the challenges discussed above. Europe faces strong competition from Chinese companies in international standardization, particularly through initiatives like the oneM2M industry collaboration.[85] The EU currently holds a limited share of leadership roles in IoT standardization. Despite initiatives like Alliance for AI, IoT and Edge Continuum Innovation (AIOTI) and StandICT.eu, Europe's influence in global IoT standards remains constrained, emphasizing the need for further engagement.[86] Unless Europe adopts a more proactive stance on technical interoperability and responsible international IoT governance – addressing critical issues like security and privacy – it risks encountering challenges akin to the 5G security debacle, including potential import bans and fragmented markets.[87]

82 "Building IoT Ecosystems with Open-Source Tools | Cogniteq", 20 August 2024, https://www.cogniteq.com/blog/building-iot-ecosystems-open-source-tools.

83 European Commission, "FIWARE – a European Success Story | Shaping Europe's Digital Future", 30 March 2017, https://digital-strategy.ec.europa.eu/en/news/fiware-european-success-story.

84 Susana Asin, "We were pioneers in providing IoT services", Go Aragón (blog), 28 September 2022, https://www.goaragon.eu/alicia-asin-ceo-of-libelium-iot-we-were-pioneers-in-providing-iot-services/.

85 "oneM2M Sets Standards For The Internet Of Things & M2M", accessed 11 January 2025, https://www.onem2m.org/.

86 https://standict.eu/news/iot-standards-landscape-report?utm_source=chatgpt.com

87 The White House, "FACT SHEET: Protecting America from Connected Vehicle Technology from Countries of Concern", The White House, 23 September 2024, https://www.whitehouse.gov/briefing-room/statements-releases/2024/09/23/fact-sheet-protecting-america-from-connected-vehicle-technology-from-countries-of-concern/.

Box 1 – Advanced manufacturing and robotics: resilience and strategic autonomy

Advanced manufacturing and robotics are integral to Europe's competitive advantage, driving key industries such as automotive, aerospace, and industrial machinery. Europe's leadership in precision engineering – exemplified by Germany's automotive sector and its complex industrial products – reinforces its potential as a global manufacturing hub. Recent disruptions in global supply chains have underscored the critical importance of maintaining a robust manufacturing base to ensure resilience and strategic autonomy. In the realm of advanced manufacturing and robotics, Industry 5.0 promises to revolutionize production by enabling seamless human-robot collaboration. Cobots, or collaborative robots, will work alongside humans to integrate creativity and problem-solving with the precision and efficiency of machines. Robotics systems are set to become increasingly intelligent and adaptive, harnessing advanced AI, machine learning, edge computing, and 5G networks to enable real-time decision-making and autonomous operations. This technological progress will support highly flexible and customizable production lines, facilitating mass customization without compromising efficiency. Industry 5.0 robotics will also focus on optimizing energy use, reducing waste, and incorporating innovations like bionic design and soft robotics, which allow for the safe and efficient handling of delicate objects. Augmented reality will further enhance human-robot interaction, offering intuitive visualization and control over processes.

This sector also includes specialized materials, such as advanced composites and alloys, supplied by leading European firms like BASF and ArcelorMittal. However, the reliance on global sources for raw materials exposes the sector to geopolitical risks. The integration of industrial IoT, which links sensors and machines to digital systems, enables the creation of responsive and intelligent manufacturing ecosystems. European companies such as Siemens are at the forefront of developing digital twins and industrial metaverses, transforming factory processes through virtual planning and resource management.

Robotics and factory automation represent additional areas of European strength. Swiss ABB Robotics is a global leader but faces intense competition from Japanese firms such as Fanuc and Yaskawa Electric. While the integration of AI-driven software for process automation remains an emerging field, companies like Romanian UiPath demonstrate Europe's potential. Nonetheless, the sector's reliance on U.S.-based cloud providers for real-time analytics and automation poses a strategic vulnerability.

Cloud infrastructure: The operational core of the digital economy

Cloud infrastructure has evolved far beyond its initial role as a tool for data storage or application hosting; it has become the critical backbone of the digital economy. Functioning as the "power grid" of this new economy, it provides a foundational production environment that transforms industries, public services, and operational models into tightly integrated ecosystems.[88] This shift has cemented the dominance of a few global tech giants, granting them extraordinary influence over critical digital infrastructure. The Draghi Report (September 2024) underscores the essential role of cloud infrastructure in safeguarding Europe's competitiveness and

88 BEREC, "Draft BEREC Report on Cloud and Edge Computing Services", 12 March 2024, https://www.berec.europa.eu/en/document-categories/berec/reports/draft-berec-report-on-cloud-and-edge-computing-services.

strategic autonomy. The report frames cloud not merely as a component of a digital strategy but as a holistic enabler of the broader economy. It highlights the region's shortcomings in cloud technology provisioning and adoption, which have deepened its reliance on foreign providers and weakened its data sovereignty. To address this, the report advocates for a unified strategy through a proposed New EU Cloud and AI Development Act. This initiative emphasizes high-performance computing, AI, and quantum technologies, alongside harmonized standards and procurement processes. [89]

Recent data highlights the growing reliance on cloud services. In 2023, European spending on public cloud services was projected to reach €139 billion, with forecasts suggesting growth to €285 billion by 2027.[90] Thirty percent of companies now store 41–60% of their data in the cloud, while 22% rely on the cloud for more than 60% of their data storage.[91] Despite the adoption of multi-cloud strategies to mitigate risks, these efforts have not significantly disrupted the dominance of leading cloud providers. AWS, Microsoft Azure, and Google Cloud collectively control nearly 70% of the global Infrastructure-as-a-Service (IaaS) market, with AWS holding 31%, Azure 24%, and Google Cloud 11% as of Q4 2024.[92] In contrast, European cloud service providers (CSPs) have experienced a steady decline in market share, dropping from 26% in 2017 to just 10% today – a trend expected to reach a point of no return within three to five years, around 2030.

As of 2021, EU cloud providers held less than 16% of the market, with Deutsche Telekom – the largest – capturing only 2%.[93] Most European providers concentrate on basic IaaS offerings and often rely on reselling platform-as-a-service (PaaS) solutions from dominant U.S. providers like Amazon, Microsoft, and Google, limiting their competitiveness. Non-EU providers such as IBM, Oracle, and Alibaba Cloud also hold portions of the market but lack the scale to challenge the U.S. giants. European firms like OVHcloud, IONOS, and Aruba Cloud face significant challenges in competing due to constraints in resource capacity, portfolio breadth, and innovation speed.

In response, some European providers have begun challenging unfair market practices. For instance, in July 2024, the Cloud Infrastructure Services Providers in Europe (CISPE) and Microsoft resolved a dispute over licensing practices, with Microsoft committing to enhance Azure Stack hyperconverged infrastructure (HCI) – the hybrid, multi-tenant version of the public Azure cloud stack – for European providers as part of the settlement. While this agreement aims to level the playing field in the European cloud market, major providers like Google and AWS were not included, and new complaints continue to raise concerns about persistent inequities. If Microsoft fails to meet its commitments within nine months, CISPE reserves the right to refile its case.[94] However, without proactive measures and a comprehensive industrial plan to protect, strengthen, and expand the size, capacity, and competitiveness of individual European providers, they are unlikely to be seen as viable alternatives by end users.

In the software-as-a-service (SaaS) market, businesses are increasingly relying on tailored applications. Recent data reveals that organizations used an average of 130 SaaS applications as of 2022, reflecting the growing specialization of tools designed to boost productivity and efficiency. Some

89 Mario Draghi, "The Future of European Competitiveness – A Competitiveness Strategy for Europe".

90 https://www.idc.com/getdoc.jsp?containerId=prEUR151144823&utm_source=chatgpt.com

91 IDC, "Worldwide Quarterly Enterprise Infrastructure Tracker: Buyer and Cloud Deployment", IDC: The premier global market intelligence company, 2024, https://www.idc.com/getdoc.jsp?containerId=IDC_P31615.

92 Synergy Research Group, "Cloud Market Gets Its Mojo Back; AI Helps Push Q4 Increase in Cloud Spending to New Highs".

93 Digitalisation World, "European Cloud Providers Double in Size but Lose Market Share", Digitalisation World, 28 September 2021, https://digitalisationworld.com/news/62320/european-cloud-providers-double-in-size-but-lose-market-share.

94 Ben Maynard, "CISPE and Microsoft Agree Settlement in Fair Software Licensing Case", accessed 11 January 2025, https://cispe.cloud/cispe-and-microsoft-agree-settlement-in-fair-software-licensing-case/.

companies now depend on over 100 applications to address diverse operational needs. Despite its fragmented nature, the SaaS market remains deeply integrated into the ecosystems of dominant IaaS providers, further reinforcing their control over the digital stack. To counteract this dependency, the open-source software ecosystem (explored in the next chapter) presents a strategic alternative to Big Tech's proprietary solutions. However, substantial private investment is required to support re-engineering programs – an undertaking complicated by the uncertainty surrounding their business benefits.

The dual influence of cloud providers

Leading cloud providers dominate the digital economy by integrating physical infrastructure with advanced software platforms, creating tightly interconnected ecosystems. This integration streamlines processes for software development teams by offering seamless hardware/software compatibility and powerful CI/CD (Continuous Integration/Continuous Deployment) tools. Computational infrastructures – comprising the cloud and end devices – function not as products but as production environments for digital services.[95] At the same time, business decision-makers are incentivized to choose these global platforms for their reliability and widespread adoption, often overlooking smaller local providers perceived as less scalable or reliable. Whether organizations avoid big cloud providers due to trust concerns, bypass smaller providers for scalability reasons, adopt off-the-shelf solutions, or re-engineer applications for cloud migration, the influence and control of Big Tech in the market remain substantial.

At the physical and computational layer, providers like AWS and Google offer the raw computational power for high-demand workloads, including AI. Leading cloud providers do not rely on standard commercial computing technologies (e.g., computer servers, storage servers, or network routers). Instead, they design custom hardware to optimize costs and performance while reducing dependencies on third-party suppliers. The rapid growth of AI technology has, however, created significant dependencies even for Big Tech, particularly on single-source chip suppliers like NVIDIA, due to a lack of viable alternatives. This reliance has spurred a new industrial strategy, focusing on the development of proprietary technologies encompassing both software stacks and chips to protect margins and retain customer loyalty.

Building on the foundational computing infrastructure, the software and platform layer transforms how ordinary businesses operate daily. These platforms are one-stop-shop solutions offering application development tools, integrated marketplaces, and advanced machine learning capabilities. For example, services like Google's TensorFlow and AWS's SageMaker provide not just the underlying computing power, but also pre-configured development environments, specialized software libraries, and automated workflows. As a result, businesses increasingly rely on cloud providers to create and deploy applications for tasks ranging from sales forecasting to customer service chatbots, embedding their most essential operations directly into the provider's ecosystem. This deep integration leads to significant dependency, as migrating away from these platforms would require not only transferring data but also rebuilding the core architecture of applications. Additionally, customers are reliant on the willingness of platform providers to maintain "baseline security-by-default," further entrenching this dependence.[96]

This model of end-to-end integration across the technology stack, from software applications (SaaS) to software frameworks (PaaS), down to IaaS, has reinforced Big Tech's market positioning and amplified its influence across industries. These include healthcare, finance, manufacturing, and

95 Agathe Balayn and Seda Gürses, "Misguided: AI Regulation Needs a Shift in Focus," Internet Policy Review 13, no. 3, September 30, 2024, https://policyreview.info/articles/news/misguided-ai-regulation-needs-shift/1796

96 See: "Security By Default – Homepage", accessed 12 January 2025, https://securitybydefault.org/.

automotive, where the exponentially increasing volume of data has created a pressing need for more integrated, auto-scalable, and cloud-native platforms to support predictive analytics, diagnostics, and operational optimization. Notable examples include Volkswagen's partnership with Microsoft to streamline production data and Renault's collaboration with Google Cloud to develop Software-Defined Vehicles. These alliances underscore the growing reliance on centralized cloud providers.

Partnerships between major telecom providers and Big Tech cloud platforms have driven the market's evolution. Rising operational costs and increasing competition have led telecoms to focus on cloud-based value-added services, forming strategic alliances to avoid costly proprietary infrastructure investments. Examples include Deutsche Telekom and Google, Telecom Italia and Google, and Orange and Microsoft with Bleu. These partnerships have deeply tied European businesses to Big Tech platforms, making it challenging to untangle dependencies due to significant business and technical barriers.

The physical infrastructure of the cloud

The rapid expansion of cloud computing and AI technologies highlights the critical role of physical infrastructure in shaping Europe's digital future. Data centers, HPC clusters, and their energy and cooling systems, long-distance and undersea cables and soon even satellite systems (Starlink of Musk's SpaceX, Kuiper of Amazon) enable these advancements but also expose Europe to critical dependencies, sustainability challenges, and geopolitical risks.

Global investment in data centers has surged, with private U.S. spending increasing from €1.8 billion in 2014 to €17.8 billion in 2023. The United States now hosts one-third of the world's data centers. Within Europe, HPC clusters such as those under the EuroHPC Joint Undertaking aim to provide sustainable and sovereign alternatives.[97]

97 "EuroHPC JU – Homepage", 19 December 2024, https://eurohpc-ju.europa.eu/index_en.

For example, Finland's LUMI supercomputer, powered by hydropower from Sweden's Vattenfall, demonstrates the potential for green computing. Expanding EuroHPC into a public alternative for computing power could enhance European autonomy, drive innovation, and align with climate goals. However, the significant power demands of AI computing, the rapid obsolescence of AI technologies, and the private sector's dominance in developing foundational models and inference networks underscore the need for sustainable, long-term investment strategies supported by appropriate governance models. The HPC market will reach approximately €85.56 billion by 2030, with a CAGR of 7.5% from 2023 to 2030.[98] The performance of the world's fastest supercomputers has grown by a factor of 626 since 2010, with compute requirements increasing at an even faster pace.[99] Europe's success in this field is evident, with three of the world's top 10 supercomputers – a remarkable leap from having none in 2016.[100]

The concentration of data centers in a few countries,[101] coupled with competition to attract infrastructure, often results in tax breaks, weakened privacy or environmental standards, and a lack of inclusive growth.[102] This dynamic creates a "race to the bottom," undermining job creation, trade, and long-term economic growth.[103]

98 Grand View Research, "High Performance Computing Market Worth $87.31 Billion By 2030", accessed 11 January 2025, https://www.grandviewresearch.com/press-release/global-high-performance-computing-hpc-market.

99 Jaime Sevilla et al., "Compute Trends Across Three Eras of Machine Learning", 2022, https://doi.org/10.48550/ARXIV.2202.05924.

100 TOP500, "November 2024 | TOP500", 64th edition of the TOP500, November 2024, https://top500.org/lists/top500/2024/11/.

101 Jukka Ruohonen, Geospatial Insights on the EuroHPC Supercomputing Ecosystem, 2024, https://doi.org/10.31219/osf.io/z94f2.

102 Enrico Letta, "Enrico Letta's Report on the Future of the Single Market – European Commission".

103 I. Papadakis and M. Savona, "The Uneven Geography of Digital Infrastructure: Does It Matter?", November 2024, https://leap.luiss.it/publication-research/publications/i-papadakis-m-savona-the-uneven-geography-of-digital-infrastructure-does-it-matter/.

Sustainability is a pressing concern. Data centers, driven by IoT data growth and AI applications, face mounting environmental pressures, with cooling systems accounting for up to 40% of energy consumption in some facilities. From 2015 to 2020, data center energy use in Europe rose by 10%, and by 2022, these facilities consumed 2.7% of Europe's electricity,[104] including almost 20% of Ireland's national consumption.[105] Google's hyperscale data centers used an average of 2.1 million liters of water daily in 2023 for cooling.[106] The widespread use of renewable energy certificates often obscures true environmental costs, highlighting the need for stricter transparency standards. The rapid expansion of data centers in Europe has also prompted calls for micro-nuclear plants (i.e., small modular reactors or SMRs) to meet future AI computing demands. However, these advancements also intersect with Europe's ongoing taxonomy debate, which seeks to define the environmental sustainability of emerging technologies and energy sources. The inclusion of nuclear energy and quantum computing under „green" or „sustainable" classifications has sparked contention among policymakers, reflecting broader concerns about balancing innovation with ecological and social objectives.[107] Green computing standards, emphasizing renewable energy, efficient cooling, and reduced water use, are essential to align data center growth with carbon neutrality targets.

Although still years away from widespread adoption, quantum computing holds the potential to address power demands in data centers by enabling highly efficient algorithms for specific classes of problems. These efficiency gains stem from algorithmic advancements, reduced hardware needs, and the use of enhanced machine learning and AI technologies.

European challenges and opportunities in cloud and edge infrastructure

European cloud service providers are making significant investments in infrastructure and services that emphasize data sovereignty and compliance with EU regulatory standards. By aligning their offerings with European data protection regulations, such as GDPR, and operating entirely within European territory, these providers ensure their services remain insulated from non-European jurisdictions, including the implications of legislation like the U.S. CLOUD Act.

France's OVHcloud positions itself as a secure alternative to non-European providers by emphasizing GDPR compliance and interoperability. Outscale, in partnership with Docaposte and Dassault, launched NumSpot as a sovereign cloud focused on public administration and defense services. Scaleway has shifted its business model from traditional data centers to exclusively public cloud services, pursuing growth through acquisitions.

In Italy, Aruba Cloud combines retail and enterprise cloud offerings with leading trust services (e.g., digital identity) and proprietary European data centers powered by renewable energy. Germany's IONOS, the largest European CSP with over €6 billion in revenue, plans to expand across Europe. StackIT, a subsidiary of Germany's Schwarz Group, has followed Amazon's AWS model by opening its IT infrastructure as a cloud platform, with the goal of becoming the largest EU CSP. Hetzner focuses on cost-effective bare-metal servers, while Leaseweb, based in the Netherlands, offers a diverse portfolio similar to that of IONOS and Aruba.

Most European CSPs operate on a relatively small scale. Only a few, such as IONOS and OVHcloud have a market capitalization exceeding €1 billion. Others,

104 Directorate-General for Energy, "Commission Adopts EU-Wide Scheme for Rating Sustainability of Data Centres – European Commission", accessed 12 January 2025, https://energy.ec.europa.eu/news/commission-adopts-eu-wide-scheme-rating-sustainability-data-centres-2024-03-15_en.

105 European Commission. Joint Research Centre., Energy Consumption in Data Centres and Broadband Communication Networks in the EU. (LU: Publications Office, 2024), https://data.europa.eu/doi/10.2760/706491.

106 Zhang, "Data Center Water Usage".

107 Martina Pilloni, "The Nuclear Debate and Energy Taxonomy in the European Union | Heinrich-Böll-Stiftung | Tel Aviv – Israel", 22 March 2022, https://il.boell.org/en/2023/03/30/nuclear-debate-and-energy-taxonomy-european-union, https://il.boell.org/en/2023/03/30/nuclear-debate-and-energy-taxonomy-european-union.

like Aruba and Leaseweb, generate revenues in the range of €3–5 million. While Scaleway and a handful of other providers surpass €100 million in revenue, the majority remain below €50 million, with many generating less than €20 million. This fragmented industry is further overshadowed by large European telecom providers offering cloud services based on U.S. hyperscalers like Microsoft Azure, Google Cloud, or Amazon AWS.

Deutsche Telekom and TIM have deepened partnerships with U.S. tech giants like Microsoft and Google to develop cloud and edge solutions. At the same time, proprietary tech vendors like the U.S.-based VMware (now part of Broadcom) have doubled their efforts in Europe to present themselves as providers of "sovereign cloud" solutions, similar to some of the hyperscalers. The European cloud market has also become a focal point for substantial investments by global technology giants, highlighting both opportunities and challenges for the region's digital sovereignty.

In Germany, AWS announced a €17.8 billion investment through 2040, including €7.8 billion for its European "sovereign cloud" in Brandenburg. In France, Microsoft committed €4 billion to expand AI capabilities, including advanced cloud infrastructure and GPU deployment. Meanwhile, in Spain, Oracle plans to invest $1 billion in AI and cloud computing, while AWS has committed €15.7 billion to data centers in Aragon over the next decade. A clearer definition of "sovereign cloud" is needed to counter the trend toward "sovereign-washing."

While these collaborations address immediate market needs, they increase reliance on foreign providers subject to U.S. legislation, such as the CLOUD Act. This law allows U.S. authorities to access data stored by American companies, regardless of its physical location, raising significant concerns about data sovereignty and security in Europe. These dependencies, along with compliance and regulatory challenges[108] expose critical infrastructure to external legal jurisdictions and undermine Europe's strategic autonomy, particularly in sensitive sectors such as government, aerospace, and defense.

The market control of cloud providers is partially addressed by the Digital Markets Act (DMA). The DMA is intended to ensure fair competition and reduce gatekeeper dominance. Under its provisions, companies identified as gatekeepers must adhere to specific obligations and limitations, such as ensuring fair access to their platforms, preventing self-preferencing, and promoting interoperability between different services. While it is too early to fully assess the effectiveness of this regulatory framework, it alone is unlikely to close the competitiveness gap faced by vertically disintegrated European cloud providers.

To address these structural weaknesses, Europe has launched several ambitious policy initiatives.[109] Gaia-X, initiated by Germany and France in 2019, was presented as a key component of Europe's strategy to reduce dependence on global hyperscalers and regain digital sovereignty. Designed as a federated cloud infrastructure built on shared European standards, Gaia-X has focused on addressing market fragmentation by fostering interoperability and trust. While it has succeeded in raising considerable awareness, establishing a collaborative framework, and launching several pilot projects, its reliance on non-European hyperscalers by many participants has caused confusion about its role in achieving digital sovereignty. Additionally, its broad scope, its tendency to overlook the cloud infrastructure layer, and its slow progress have raised concerns about its ability to deliver tangible results.[110] However, other initiatives

108 Dhruv Seth, Madhavi Najana, and Piyush Ranjan, "Compliance and Regulatory Challenges in Cloud Computing: A Sector-Wise Analysis", International Journal of Global Innovations and Solutions (IJGIS), 1 June 2024, https://doi.org/10.21428/e90189c8.68b5dea5.

109 European Commission, "Cloud Computing | Shaping Europe's Digital Future", 2022, https://digital-strategy.ec.europa.eu/en/policies/cloud-computing.

110 Francesco Bonfiglio, XI. Why Europe's Cloud Ambitions Have Failed, 15 October 2024, https://ainowinstitute.org/publication/xi-why-europes-cloud-ambitions-have-failed.

such as 8ra[111] and the IPCEI-CIS have the potential to build on Gaia-X's achievements with a clearer focus on EU strategic autonomy.

The new Important Project of Common European Interest on Next-Generation Cloud Infrastructure and Services (IPCEI-CIS), approved in 2023 with €3 billion in funding (half of which comes from private co-investments), has taken a different approach. Focused on open-source innovation, it aims to create the first interoperable, openly accessible cloud-edge computing continuum in Europe. Backed by over 100 companies and research institutions across 12 EU member states, the initiative provides €1.2 billion in state aid and is expected to leverage an additional €1.4 billion in private investments. The goal is to develop a decentralized, vendor-neutral platform that integrates data centers, public clouds, and edge computing, emphasizing multi-cloud interoperability, application portability, and low-latency solutions for critical sectors like energy, mobility, manufacturing, and tourism. The IPCEI-CIS initiative currently focuses on software and services but has yet to expand into hardware or infrastructure investments, leaving room for growth in the development of a federated and decentralized European cloud-edge infrastructure, an opportunity that initiatives like 8ra.com might effectively address.

Recognizing these gaps, the European Commission is planning new waves of IPCEIs to address infrastructure development and establish a commercial offering. However, the average timeline for such projects – three to five years from inception to delivery – risks delaying tangible results until 2030, by which time EU CSPs may have lost significant market share. To address scalability challenges, these new IPCEIs will support the development of a large-scale federated edge computing infrastructure and distributed AI services.[112] These efforts aim to amplify the impact of "made in Europe" edge cloud technologies developed under IPCEI-CIS, driving innovation and competitiveness across the EU.

The initiative's decentralized software infrastructure will reduce technological dependencies and lock-in effects while fostering innovative, data-driven business models in areas like artificial intelligence and industrial internet of things. By leveraging decentralization and federation, Europe can transform its heterogeneity into a strategic advantage, interconnecting European cloud providers into a diverse but scalable computing continuum. This approach promotes the emergence of "proximity cloud" service providers across the EU with strong local roots and a sense of social responsibility.

Software: The command center of platforms and applications

The software layer is central to digital infrastructure, encompassing operating systems, application platforms, and algorithmic frameworks. It orchestrates the execution of applications and services that use the functions and facilities of these systems, platforms, and frameworks. This includes common building-block functions such as identity and access management, electronic payments, transactions, and document delivery. In essence, software "runs the world." Yet, Europe lacks a comprehensive industrial strategy for software. U.S. companies dominate the foundational tools underpinning modern economies and societies, leaving Europe's digital sovereignty heavily contested.

Operating systems for desktops, mobile devices, and embedded systems are monopolized by three U.S. companies – Microsoft, Apple, and Google – which collectively over 90% of the European market. Microsoft Windows powers more than 70%

111 See: "8ra – Homepage", 8ra, accessed 11 January 2025, https://www.8ra.com/.

112 Joint European Forum for IPCEIs, "Opinion of the Joint European Forum for Important Projects of Common European Interest", 27 November 2024, https://competition-policy.ec.europa.eu/document/download/3d01ea9f-2c29-4f83-a66f-44f2e345c015_en?filename=JEF-IPCEI_Opinion%20of%20the%20high-level%20meeting_27%20November%202024.pdf.

of desktops,[113] Google's Android commands 72% of Europe's mobile market, and Apple's iOS dominates high-value segments.[114] Although open-source Linux has a global impact in servers, cloud environments, and the internet's core infrastructure, its adoption in consumer-facing systems remains limited. Efforts to develop Linux-based national operating systems have struggled to achieve scale, yet Linux's flexibility, security, and alignment with European values make it a critical asset for enhancing digital strategic autonomy.

Application platforms present a mixed picture. Europe is home to global leaders like SAP and Dassault Systèmes in enterprise software and industrial tools, with SAP leading the global Enterprise Resource Planning software market, holding a 6.2% share in 2023.[115] However, even these platforms depend on foreign-controlled operating systems and middleware, limiting their potential to function as fully sovereign alternatives. Moreover, in many key applications – such as office productivity, messaging, collaboration – the dominance of U.S. companies is uncontested. However, open-source platforms developed by the private sector (Nextcloud) or through a public-private partnership (openDesk, La Suite Numérique) represent a good model to build European alternatives.

Similarly, Europe's track record in developing and adopting common services is uneven. Secure eID and secure authentication methods for accessing government services digitally have been successful in countries like Estonia and Belgium, but their adoption in Germany remains limited. Nonetheless, the EU's long-term investments across the internal market, such as the EU Connecting Europe Facility (CEF) funding, demonstrate that common services can evolve into scalable digital infrastructures. Notable examples include e-invoicing based on the Pan-European Public Procurement OnLine (PEPPOL) system – now becoming mandatory in an increasing number of EU countries – as well as services for business reporting, document delivery, and translation. These services, along with e-signatures and timestamping, benefit from EU-wide legal recognition under regulations like the eIDAS2 Regulation.[116]

Despite their open-source nature, algorithmic frameworks such as TensorFlow and PyTorch, remain tethered to U.S.-based ecosystems. These frameworks shape developer communities, align innovation with proprietary platforms like Google Cloud or Meta's AI infrastructure, and reinforce dependencies on foreign systems.[117] The structural integration of operating systems, application platforms, and algorithmic frameworks creates high switching costs, further entrenching dependency and lock-in. Consequently, much of the value generated by these systems flows out of Europe, diminishing its influence over global standards and eroding tax revenues that could otherwise fuel local innovation.

Applications represent what end users interact with in their daily use of mobile phones, laptops, or professional equipment. They cover a huge range of use cases, from personal navigation to inventory management, from health monitoring to traffic control systems. Europe is home to several prominent companies, such as Spotify and SAP, yet their market capitalization is generally lower than that of foreign competitors. Over the years, entrepreneurial EU application startups have often achieved global expansion. However, this capitalization is frequently provided by foreign investors and larger international companies.

113 StatCounter, "Desktop Operating System Market Share Europe", November 2024, https://gs.statcounter.com/os-market-share/desktop/europe?utm_source=chatgpt.com.

114 Statista, "Mobile OS Market Share Europe 2010-2023", 7 March 2024, https://www.statista.com/statistics/639928/market-share-mobile-operating-systems-eu/?utm_source=chatgpt.com.

115 Albert Pang, Misho Markovski, and Ristik Marija, "Top 10 ERP Software Vendors, Market Size and Market Forecast 2023-2028", Apps Run the World, 10 June 2024, https://www.appsruntheworld.com/top-10-erp-software-vendors-and-market-forecast/.

116 European Commission, "eGovernment and Digital Public Services | Shaping Europe's Digital Future", 28 November 2024, https://digital-strategy.ec.europa.eu/en/policies/egovernment.

117 Amba Kak, Sarah Myers West, Meredith Whittaker, "Make No Mistake – AI Is Owned by Big Tech", MIT Technology Review, 5 December 2023, https://www.technologyreview.com/2023/12/05/1084393/make-no-mistake-ai-is-owned-by-big-tech/.

Europe's role in software

Beneath the surface of external dominance lies an "invisible" European strength: a long-standing presence in open-source software (OSS) and open standards that form the backbone of critical digital infrastructures. From Linux and Python to core internet protocols, Europe has made significant contributions to open source initiatives. European companies like SAP have long been global leaders in business systems, and Europe also shows promise in AI software, embedded security, and cybersecurity forensics – though on a smaller scale compared to the United States or China.

Open-source software, which constitutes 70-90% of modern codebases, serves as a cornerstone of software development and offers a promising pathway to strengthening Europe's digital sovereignty.[118] OSS enables decentralized, interoperable online services that can serve as alternatives to today's centralized and surveillance-based platforms. Beyond its technical advantages, OSS aligns with Europe's vision of transparency, collaboration, and interoperability. Public investments in OSS have yielded impressive returns: A 2021 European Commission study found that €1 billion invested in OSS could generate up to €95 billion in economic impact.[119] Thus, OSS is not only a technological enabler but also a strategic economic driver, capable of fostering innovation, reducing dependencies, and strengthening Europe's global competitiveness. By leveraging and investing in OSS, Europe can accelerate its digital sovereignty agenda while cultivating an open and sustainable technological landscape.[120]

However, the sustainability and governance of Europe's OSS ecosystem need bolstering. Funding remains fragmented, and reliance on non-European platforms like GitHub compromises sovereignty. Public procurement often favors proprietary solutions over open-source alternatives, while Big Tech companies strategically exploit OSS to entrench their dominance.[121] These companies acquire platforms such as GitHub, integrate proprietary code into open environments (e.g., Android or Chromium), and profit from community-driven innovations without adequately contributing in return. The European Commission's Open-Source Software Strategy has laid the groundwork for addressing these challenges, advocating for equal treatment of OSS in procurement and promoting a level playing field. Additionally, efforts such as the Open-Source Observatory (OSOR) and the Interoperable Europe Act underscore Europe's dedication to open-source integration.

The success of these initiatives depends on sustained investment, effective governance, and alignment with market realities to counteract the dominance of proprietary solutions. Power dynamics within open-source settings are often obscured, with some actors disproportionately reaping the benefits. For instance, Microsoft, once a vocal opponent of open-source,[122] has dramatically shifted its stance over the years, culminating in its acquisition of open-source platform GitHub.

Big Tech companies increasingly take advantage of open-source communities by sharing portions of their code while keeping their core business proprietary. This approach allows them to benefit from cost-effective, high-quality feedback and improvements, leveraging the community's

118 Jameson Perlow, "A Summary of Census II: Open Source Software Application Libraries the World Depends On", Linux Foundation, 7 March 2022, https://www.linuxfoundation.org/blog/blog/a-summary-of-census-ii-open-source-software-application-libraries-the-world-depends-on.

119 OpenForum Europe and Fraunhofer ISI, "Open Source Study", OpenForum Europe, 2021, https://openforumeurope.org/open-source-impact-study/.

120 Content and Technology European Commission: Directorate-General for Communications Networks et al., The Impact of Open Source Software and Hardware on Technological Independence, Competitiveness and Innovation in the EU Economy – Final Study Report (Publications Office, 2021), https://doi.org/10.2759/430161.

121 Alice Pannier, "How Big Tech Is Shaping the Global Open Source Ecosystem | SovereignEdge.EU", SovereignEdge (blog), 22 May 2023, https://sovereignedge.eu/blog/how-big-tech-is-shaping-the-global-open-source-ecosystem/.

122 Then Microsoft CEO Steve Balmer famously declared that "Linux is a cancer that attaches itself in an intellectual property sense to everything it touches." See: Thomas C. Greene, "Ballmer: 'Linux Is a Cancer'", The Register, 2 June 2001, https://www.theregister.com/2001/06/02/ballmer_linux_is_a_cancer/.

collaborative efforts for their gain. For example, Google's management of Android and Chromium, which integrates proprietary components and features into an open environment, helps the company entrench its dominance in key markets while shaping browser development and web standards.[123] Amazon's forking of Elasticsearch enabled it to avoid contributing to the original project while profiting from its functionality, raising concerns about the sustainability of open-source initiatives. Oracle's contentious stewardship of Java – particularly its legal disputes over Java APIs in Android – illustrates the conflicts that arise when proprietary interests intersect with widely adopted open-source technologies. This trend is also evident in the emergence of so-called open AI models, where foundational research and tools are released as open source, yet the resulting implementations are frequently embedded into proprietary platforms, reinforcing control by dominant players.[124]

These practices underscore the need for policies that protect the integrity and accessibility of the digital commons, ensuring open-source principles are not diluted by corporate interests. To counter this trend, Europe must build robust, independent open-source ecosystems that prioritize decentralization, interoperability, and alignment with its regulatory and ethical standards.

Successful examples already exist. Europeana institutionalizes data sharing in cultural heritage, and the European Open Science Cloud provides a trusted, sovereign framework for open science. Initiatives like Decidim thrive not only because they are open source but also because they are supported by long-term institutional backing, ensuring sustained growth.[125] Future opportunities include investing in Linux-based systems for public administration, leveraging open-source solutions in key sectors like healthcare and smart cities, and championing federated AI models. Decentralized networks based on open protocols can offer privacy-first, transparent alternatives in messaging and social media, while regulatory tools such as the Digital Markets Act, Digital Services Act, Media Freedom Act, and the Interoperable Europe Act help ensure that competition and innovation can flourish within a trusted, pluralistic digital ecosystem. Initiatives such as the EDIC offer a pathway for building open-source solutions in areas of public interest, from access to public services to key intermediation technologies.

Aligning digital commons with industrial strategies and leveraging public institutions as strategic supporters and early adopters can consolidate these gains. Europe has the opportunity to scale funding for OSS-based AI projects, digital infrastructure consortia, and common services for eID and e-invoicing. However, Europe's public institutions currently lack the capabilities to fully understand and address critical dependencies within the digital stack. Institutions like the proposed Sovereign Tech Agency and initiatives such as FOSSEPS and bug bounty programs represent important steps forward. The German Sovereign Tech Agency[126] is a promising model for funding the maintenance of digital commons while strategically driving their development. Nonetheless, the related Sovereign Tech Fund highlights the challenge of limited resources, with a total allocation of only €11.5 million for 2023. This modest budget underscores the need for more substantial financial commitments to ensure the sustainability and impact of open-source software. In the 2024 German Federal budget, €17 million was allocated to the Sovereign Tech Fund. To reduce reliance on external partners and safeguard Europe's technological independence, public

123 David McCabe and Nico Grant, "What's Next for Google's Search Monopoly", The New York Times, 21 December 2024, sec. Technology, https://www.nytimes.com/2024/12/20/technology/google-antitrust-case-chrome.html.

124 David Gray Widder, Meredith Whittaker, and Sarah Myers West, "Why 'Open' AI Systems Are Actually Closed, and Why This Matters", Nature 635, no. 8040 (November 2024): 827–33, https://doi.org/10.1038/s41586-024-08141-1.

125 See: "Decidim, Free Open-Source Democracy – Homepage", n.d., https://decidim.org/.

126 See: "Sovereign Tech Agency – Home", 6 December 2024, https://www.sovereign.tech/.

institutions must ensure long-term support and governance for open-source ecosystems.

In contrast, the French Ministry of Public Transformation and Civil Service has launched an ambitious free Software and Digital Commons action plan, spearheaded by the newly established Free Software Unit within the Interministerial Directorate for Digital Affairs (DINUM). This initiative aims to promote the adoption of free software and digital commons across public administration, encourage the release and publication of source codes, and enhance the state's appeal as a digital employer by recognizing public contributions to open-source projects.

Using agile methodologies, the French government is developing collaborative products such as La Suite and Albert AI. Currently, La Suite is actively utilized by approximately 300,000 public servants on a daily basis. The ambitious goal is to scale these solutions to serve millions while fostering the reuse of their modular building blocks – each representing an active open-source community – within the private sector as well. This initiative exemplifies the critical role of public administrations as orchestrators of open-source ecosystems,[127] and early adopters of digital commons,[128] creating a robust foundation for innovation and collaboration in both the public and private sectors. This approach, in which governments act as lead users for public innovation, demonstrates that success is not solely dependent on investment but also on adopting a product-driven methodology. Agile methodologies enable the capture of new users and use cases, emphasizing the importance of channeling resources through digital commons communities and public incubators to foster innovation and scalability. However, caution is required when referencing "digital assets." These assets must represent active communities with strong user bases – such as Matrix or Firefox – or risk becoming irrelevant without the foundational support of vibrant ecosystems. Building and sustaining these communities is essential for ensuring meaningful impact and long-term success.

Smart public procurement and sustained investment are key to ensuring that Europe's software ecosystem becomes a foundation of its digital sovereignty, transforming open source and digital commons into lasting strategic assets that underpin Europe's influence, resilience, and global competitiveness.

127 "Action Plan for Free Software and Digital Commons", Direction interministérielle du numérique, accessed 12 January 2025, https://code.gouv.fr/en/action-plan-for-free-software-and-digital-commons/.

128 See: "Mission Société Numérique – Homepage", accessed 12 January 2025, https://societenumerique.gouv.fr.

Box 2 – **Digital Public Infrastructure, a foundation for citizen-centric digital services**

Digital Public Infrastructure (DPI) is vital to modern governance, connecting citizens to public institutions through digital identity systems, secure payments, and interoperable data platforms. These systems drive inclusivity, accessibility, and efficiency while reflecting Europe's regulatory values. However, to fully unlock DPI's potential, Europe must reduce dependencies and ensure privacy, transparency, and interoperability.

At the core of Digital Public Infrastructure (DPI) are digital identity systems, exemplified by the European Digital Identity Wallet (EUDI Wallet). While national models like Estonia's e-ID, Germany's Online-Ausweisfunktion, FranceConnect, Denmark's MitID, Italy's SPID, and Finland's Suomi.fi have streamlined access to services, they remain nationally isolated and based on legacy architectures. The EUDI Wallet, established under the eIDAS 2.0 Regulation which entered into force in May 2024, aims to provide EU citizens with secure and interoperable digital identities. Member states are actively developing wallets through initiatives like Germany's Funke Competition, while the European Commission's common EU Toolbox ensures uniform implementation standards. By 2027, all EU member states must issue or certify at least one EUDI Wallet, with pilot projects currently testing functionality and user acceptance. Positioned to become a cornerstone of Europe's digital identity framework, the EUDI Wallet has also sparked discussions about aligning with Europe's digital sovereignty goals. Concerns include potential reliance on proprietary systems and the importance of robust security and privacy safeguards. Addressing these issues through privacy-first standards will be critical to its long-term success as a secure and trusted solution for EU citizens.

Secure payments are a key pillar, with Italy's PagoPA enabling seamless citizen-administration transactions. The proposed Digital Euro, led by the European Central Bank, has the potential to unify digital payment systems within a secure, interoperable framework, especially when integrated with solutions like the EUDIW.

Data platforms ensure secure, interoperable ecosystems. Examples like Estonia's X-Road, Finland's Suomi.fi Data Exchange Layer, and Spain's SARA enhance public service delivery. France's API Platform and Germany's GovData portal promote open data sharing, improving transparency and collaboration. Platforms such as AuroraAI in Finland and Decidim Barcelona highlight Europe's leadership in citizen-centric innovation.

Despite these successes, Europe's DPI remains heavily reliant on foreign cloud infrastructure. Critical DPI components – such as digital identities, payments, and data exchanges – must be based on EuroStack digital infrastructure ensuring alignment with EU regulations.

To accelerate adoption, DPI must demonstrate clear benefits to citizens. For example, the COVID-19 pandemic showed how digital contact tracing apps, linked to national digital IDs, enabled cross-border interoperability and increased trust in digital services. Integrating DPI into everyday interactions – such as healthcare, tax systems, and public administration – will further drive uptake.

The digital transformation of public administration is a critical priority for European governments seeking to enhance service delivery, reduce costs, and improve overall efficiency. At the forefront of this transformation is Government Process Automation (GPA) as a cross-border approach that leverages technology and shares process knowledge to streamline and optimize administrative workflows.

Data and artificial intelligence: Catalysts for innovation and strategic autonomy

Data is the backbone of the digital economy, driving innovation across industries. However, much of this data – particularly industrial and urban data – is extracted and monetized by non-European platforms. While Europe generates a significant portion of global industrial data,[129] much of it is processed and monetized by foreign entities. This reliance on U.S. and Chinese cloud providers not only limits Europe's economic gains but also raises concerns about data sovereignty and security.

To counter the dominance of extractive data practices and proprietary ecosystems, Europe is advancing an ambitious data sovereignty framework. The European Union's data strategy aims to establish a unified data ecosystem that enhances competitiveness, protects citizens, and ensures data sovereignty, supported by strong legislation such as the GDPR. Far from being a limitation, the GDPR has become a global benchmark for data protection, inspiring similar legal frameworks worldwide. However, challenges remain in its effective implementation and in addressing power imbalances in an opaque data marketplace where privacy and rights are frequently violated, often in contravention of European laws.

A significant shortcoming of the EU's strategy is its inability to develop robust, independent data infrastructures, leaving it reliant on major Big Tech companies for cloud and data processing services. This dependency undermines Europe's autonomy within the digital economy. While initiatives like the Data Governance Act and the Data Act (effective January 2024) aim to democratize data access and foster innovation, the lack of independent infrastructure perpetuates asymmetries of power in the global data economy.[130] To achieve true sovereignty and competitiveness, Europe must pair its legislative leadership with tangible advancements in independent, energy-efficient, and secure data infrastructure.

Key efforts include the development of Common European Data Spaces,[131] intended to enable secure and interoperable data sharing across sectors such as health, energy, and agriculture. These data spaces are presented as tools to foster innovation and economic growth, yet doubts persist regarding the speed of their implementation and their ability to scale sufficiently to serve as viable alternatives to extractive global data platforms.

Standards form a critical aspect of the rapidly evolving data landscape. The EU's Data Act, Data Governance Act, and Open Data Directive aim to harmonize frameworks for IoT-generated data sharing and reuse, as does the Cyber Resilience Act for the cybersecurity of IoT solutions. However, harmonized implementation and the minimization of bureaucratic obstacles are not guaranteed.

Industrial data, critical for sectors like manufacturing, energy, and mobility, is one of Europe's most valuable assets. Initiatives such as Catena-X,[132] Manufacturing-X,[133] and EONA-X[134] exemplify progress in industrial data ecosystems, demonstrating the potential of industrial data spaces to reduce inefficiencies and drive competitiveness in Europe's industrial heartlands, These initiatives aim to lower barriers, foster trust, and drive adoption and competitiveness for European providers.

In addition to industrial data, urban data holds strategic significance, with many cities advancing

129 European Commission, "Data Act: Measures for a Fair and Innovative Data Economy", Text, 23 February 2022, https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1113.

130 Miguel Otero Iglesias and Agustín González-Agote, "The Future Data Economy – Competitive, Fair, Safe" (IE CGC, April 2024).

131 European Commission, "Common European Data Spaces | Shaping Europe's Digital Future", accessed 12 January 2025, https://digital-strategy.ec.europa.eu/en/policies/data-spaces.

132 See: "Catena-X Your Automotive Network – Homepage", accessed 12 January 2025, https://catena-x.net/de/.

133 See: Germany's Federal Ministry for Economic Affairs and Climate Action and Federal Ministry of Education and Research, "Manufacturing-X", accessed 12 January 2025, https://www.plattform-i40.de/IP/Navigation/EN/Manufacturing-X/Manufacturing-X.html.

134 See: "Eona-X, Homepage", accessed 12 January 2025, https://eona-x.eu/.

the development of urban digital twins – virtual replicas of physical urban environments that integrate real-time data into simulations to support decision-making.[135] These platforms leverage open data and real-time integrations to enable informed, data-driven decisions, enhance transparency, and foster collaborative urban planning. European cities are at the forefront of this field, generating massive volumes of data through smart city technologies like IoT sensors for traffic management, energy optimization, and public services. The SynchroniCity project, funded under Horizon 2020, is an example of a pan-European initiative creating frameworks for smart cities to share data in consistent formats. It involves cities like Milan, Helsinki, and Eindhoven, where data-sharing platforms are enabling innovations in mobility, waste management, and energy efficiency.

Amsterdam, a leader in smart city development, has implemented an open urban data platform that empowers citizens and local businesses while maintaining strong data governance.[136] By prioritizing data sovereignty and interoperability, these projects showcase how urban data spaces can enhance livability and collective empowerment. In Barcelona, the DECODE project and Decidim platform have empowered citizens to take control of their data, repurposing it as a public good for urban planning and participatory democracy.[137] These experiments have been subsequently replicated globally and extended to AI through the Cities for Digital Rights Coalition.[138] Similarly, Hamburg has used mobility data to enhance public services while safeguarding data privacy. Portugal, Estonia, Slovakia and Ukraine have drawn attention for their high growth in open data maturity scores.[139] These examples highlight how cities can leverage data governance to benefit communities.[140]

Gaps in European data infrastructure

Despite these promising examples, Europe's data infrastructure remains underdeveloped. To close these gaps, Europe must accelerate investment in sovereign data infrastructure. Decentralized and edge computing technologies, which process data locally, are critical for ensuring compliance with EU regulations and enhancing data security. For example, edge computing can support real-time decision-making in manufacturing and smart cities while minimizing the dependence on data data transfer to centralized foreign platforms. An illustrative example of decentralized sovereign data management is Inrupt, founded by Sir Tim Berners-Lee, the creator of the World Wide Web. Inrupt advances data sovereignty through the Solid protocol, enabling individuals to control personal data via decentralized "Pods." Collaboration efforts like the Athumi initiative with the Flanders government empower citizens to manage data securely, fostering innovation in public and private services.[141] In healthcare, Inrupt's pilot with the United Kingdom's NHS allows patients to control access to their medical records, enhancing privacy and care. Similarly, its work with the BBC demonstrates how user-controlled data can transform digital experiences. These efforts align with Europe's vision for a trusted, interoperable data commons.

135 OECD, Smart City Data Governance: Challenges and the Way Forward, OECD Urban Studies (OECD, 2023), https://doi.org/10.1787/e57ce301-en.

136 Jutta Ravelli, "City Data: A Treasure Full of Data about the City", Amsterdam Smart City, 15 August 2017, https://amsterdamsmartcity.com/updates/news/city-data-a-treasure-full-of-data-about-the-city.

137 Fernando Monge et al., "A New Data Deal: The Case of Barcelona", IIPP WP, no. 2022/02 (18 February 2022).

138 See: "Cities for Digital Rights – Homepage", accessed 12 January 2025, https://citiesfordigitalrights.org/.

139 European Data Portal et al., Open Data Best Practices in Europe: Estonia, Slovenia and Ukraine (Publications Office of the European Union, 2022), https://data.europa.eu/doi/10.2830/277405; Publications Office of the European Union et al., 2023 Open Data Best Practices in Europe (Publications Office of the European Union, 2024), https://data.europa.eu/doi/10.2830/68229.

140 Francesca Bria, "Governing Urban Data for the Public Interest", 26 October 2023, https://thenew.institute/en/media/the-new-hanse-final-report-out-now.

141 Inrupt, "Flanders Government Strengthens a Trusted Data Economy", accessed 12 January 2025, https://www.inrupt.com/case-study/flanders-strengthens-trusted-data-economy.

The EU's emphasis on FAIR data principles – making data findable, accessible, interoperable and reusable – is supported by organizations like MyData Global, Finland's SITRA, and Project Liberty, which champion human-centric data governance. While these efforts align with the EU's vision for data sovereignty, they face significant practical hurdles, including aligning diverse stakeholders and addressing technical and legal interoperability challenges. The risk of fragmentation, both within the EU and globally, remains a major barrier. Structural challenges persist as well. Initiatives such as the Interoperable Europe Act,[142] which prioritizes and promotes open standards and open source for cross-border digital services and public administrations, and the Open Data Directive, which promotes the reuse of high-value public datasets, hold promise but require substantial political and technical coordination to succeed. Europe's vision for ethical and inclusive data governance hinges on overcoming these barriers and ensuring frameworks gain public and private sector buy-in while remaining globally competitive.

Policymakers and organizations must transform data from a tool of exploitation into a shared resource for societal progress. By addressing monopolistic practices and unethical product design while improving infrastructure and policies, Europe has a unique opportunity to create a fairer and more sustainable data economy. With regulatory frameworks already recognized as global benchmarks, Europe is well-positioned to lead the implementation of an interoperable data commons ecosystem, setting a global standard for ethical and collaborative data governance.

142 EU, "Regulation (EU) 2024/903 of the European Parliament and of the Council of 13 March 2024 Laying down Measures for a High Level of Public Sector Interoperability across the Union (Interoperable Europe Act)" (2024), http://data.europa.eu/eli/reg/2024/903/oj/eng.

Artificial intelligence: Opportunities and challenges for the EuroStack initiative

AI is a transformative technology capable of analyzing vast amounts of structured and unstructured data while dynamically adapting to new conditions without requiring reprogramming. By revolutionizing how information is processed and synthesized, AI has the potential to reshape the digital industry, creating new markets and potentially displacing established products. For instance, the success of generative models such as OpenAI's ChatGPT has introduced the possibility of challenging the previously unassailable online search market. Furthermore, the versatility of general-purpose foundation models promises to drive transformation across the economy, influencing sectors as diverse as healthcare, manufacturing, food production, and autonomous systems.

The prospect of far-reaching market shifts has spurred massive investments. In 2023, private AI investment reached €62.5 billion in the United States, €7.3 billion in China, and €9 billion across the European Union and the United Kingdom.[143] The resulting expansion of the industry is extraordinary. Valued at €234 billion in 2025, the global AI market is projected to grow at a CAGR of 27.67% through 2030, underscoring its central role in the modern economy.[144]

In this digital gold rush, new players are seeking to establish themselves in the AI-powered economy, while existing tech giants work to defend their market positions by integrating AI into their products and shaping the technology's development to their advantage. However, because the development and training of AI models rely heavily on other elements of the digital stack, incumbents with dominant

143 Nestor Maslej, et al., "AI Index Report 2024 – Artificial Intelligence Index" (Stanford: AI Index Steering Committee, Institute for Human-Centered AI, April 2024), https://aiindex.stanford.edu/report/.

144 Statista, "Artificial Intelligence – Global", accessed 12 January 2025, https://www.statista.com/outlook/tmo/artificial-intelligence/worldwide.

positions in related markets enjoy a significant competitive edge.[145]

As AI models grow increasingly complex, computational power – referred to as "compute" – has become the primary input. For instance, OpenAI's ChatGPT-3.5, with 175 billion parameters, was succeeded by ChatGPT-4, which incorporates 1.75 trillion parameters at an estimated training cost of $100 million.[146] This exponential demand for computational power is creating a significant bottleneck, as the market is dominated by U.S. cloud providers such as AWS, Google Cloud, and Microsoft Azure. Even well-funded firms face constraints in accessing high-performance compute. For example, the Emirati AI holding company G42, despite its vast financial resources, entered in a €1.5 billion partnership with Microsoft in 2024 to expand its AI infrastructure.[147] In turn, data centers source specialized chips, primarily from NVIDIA, or design proprietary hardware while also developing software to optimize performance and enable additional software layers by third parties.

In January 2025, OpenAI announced the Stargate Project, a joint venture in partnership with SoftBank, Oracle, and MGX aiming to invest $500 billion over the next four years to build advanced AI infrastructure in the United States. The project will commence with an immediate deployment of $100 billion, focusing on constructing state-of-the-art data centers and energy facilities to support the next generation of AI models. The Stargate Project aims to overcome current bottlenecks in AI development, ensuring that the United States remains at the forefront of technological innovation.[148]

Initiatives like Microsoft's Founders Hub, Google Cloud for Y Combinator startups, and Northern Data's AI accelerator program aim to ease access to AI resources by offering free or subsidized GPU clusters. For example, Microsoft's Founders Hub, launched in February 2022, offers up to $150,000 in Azure credits over four years, while Google Cloud provides Y Combinator startups with access to subsidized NVIDIA H100 GPU clusters. These programs, however, risk fostering dependency on Big Tech infrastructure, potentially hindering the emergence of an independent AI ecosystem. Moreover, by offering these resources, Big Tech firms gain valuable insights into startup activities, enabling them to influence the direction of AI innovation to align with their strategic interests. While such programs may provide short-term benefits, AI developers remain heavily reliant on a small group of suppliers. Nearly all AI startups, including OpenAI, Anthropic, and the French firm Mistral, depend on U.S.-based cloud infrastructure.[149] In 2023, Alphabet CEO Sundar Pichai revealed that over 70% of generative AI startups rely on Google Cloud.[150]

While AI models are typically characterized by high setup and training costs, Europe-originated Stable Diffusion offers a compelling alternative. Developed through academic research at Munich's Ludwig Maximilian University and Heidelberg University, in collaboration with the open-source community, it democratizes access to advanced image creation.[151] The open-source nature of Stable Diffusion, supported by the CompVis group, Stability AI, and EleutherAI, fosters transparency and community-

145 Fausto Gernone and David Teece, "Competing in the Age of AI: Firm Capabilities and Antitrust Considerations", in Artificial Intelligence and Competition Policy (Concurrences, 2024).

146 Olena Zherebetska, "100 ChatGPT Statistics to Know in 2025 & Its Future Trends", Intelliarts, accessed 12 January 2025, https://intelliarts.com/blog/chatgpt-statistics/.

147 "Microsoft, UAE's AI Firm G42 to Set up Two New Centres in Abu Dhabi", Reuters, 17 September 2024, sec. Technology, https://www.reuters.com/technology/microsoft-uaes-ai-firm-g42-set-up-two-new-centres-abu-dhabi-2024-09-17/.

148 "Announcing The Stargate Project".

149 The German startup Aleph Alpha is a notable exception in this regard, boasting to be technologically independent of US Big Tech. See: Georgia Butler, "Aleph Alpha and Cerebras Systems to Develop Sovereign AI Solutions", Data Center Dynamics, 17 May 2024, https://www.datacenterdynamics.com/en/news/aleph-alpha-and-cerebras-systems-to-develop-sovereign-ai-solutions/.

150 Johan Moreno, "70% Of Generative AI Startups Rely On Google Cloud, AI Capabilities", Forbes, 2023, https://www.forbes.com/sites/johanmoreno/2023/07/25/70-of-generative-ai-startups-rely-on-google-cloud-ai-capabilities-says-alphabet-ceo-sundar-pichai/.

151 See: Stability AI, "Stable Diffusion Launch Announcement", 10 August 2024, https://stability.ai/news/stable-diffusion-announcement.

driven development. Additionally, online developer communities are refining methods to set up bespoke AI models locally, running on users' machines using open-source frameworks such as Meta's Llama. While these developments hint at a future in which AI resources are more affordable and accessible, the scale and reliability required by organizations currently demand substantial investment.

DeepSeek, a Chinese startup founded in 2023, claims to have overcome the barrier of exorbitant training costs of generative AI. DeepSeek's flagship model, DeepSeek-R1, delivers performance comparable to OpenAI's ChatGPT but at a fraction of the development cost. Notably, DeepSeek trained its model using approximately 2,000 Nvidia H800 GPUs over 55 days, incurring a cost of around $5.6 million – significantly less than the estimated $100 million spent on training models like ChatGPT-4.[152] Since the energy consumption of AI datacenters is proportional to the computational requirements, these advancements indicate that overall power demand for AI might be less than expected.[153] This efficiency has been achieved through innovative training methods and the utilization of less advanced hardware. The open-source nature of DeepSeek-R1 has further accelerated its adoption, leading it to surpass ChatGPT as the top free app on the iOS App Store in the United States. Moreover, other Chinese firms, such as Zhipu AI and Bytedance have launched AI video-generation tools to rival OpenAI's Sora, while Baichuan, Zhipu AI, Moonshot AI and MiniMax have been celebrated by investors as China's new "AI Tigers."[154] The recent accomplishments of Chinese AI models has highlighted the geopolitical dimension of the AI race, provoking strong reactions in the media and markets regarding the U.S.' narrower-than-expected technological lead.[155]

Access to data, alongside computational power and talent, is a critical factor shaping the AI landscape. Frontier AI models are highly data-intensive, often trained on massive datasets scraped from the internet.[156] This practice raises ethical and legal concerns surrounding copyright and ownership, particularly as internet data becomes increasingly enclosed. Resources that were once freely available are now being monetized, with platforms like Reddit limiting access to their valuable data. As a result, AI firms are increasingly competing for data acquisition through exclusive licensing agreements or outright purchases. For instance, Elon Musk's xAI leverages proprietary user content from X (formerly Twitter) to train its models, underscoring the strategic importance of data ownership and governance in the AI race.[157] This trend toward data exclusivity not only raises barriers to entry for smaller players but also consolidates power among those who control these critical resources.

Europe's AI ecosystem

Despite these challenges, Europe has made progress in building an AI ecosystem aligned with its values. European firms have concentrated on specialized markets, leveraging AI to address domain-specific needs. Mistral, a Paris-based AI company, has emerged as a key player in open-weight language models, prioritizing efficiency and adaptability for European languages and regulatory environments. Its models, such as Mistral 7B and Mixtral, are

152 James Vincent, "The DeepSeek Panic Reveals an AI World Ready to Blow", The Guardian, 28 January 2025, sec. Opinion, https://www.theguardian.com/commentisfree/2025/jan/28/deepseek-r1-ai-world-chinese-chatbot-tech-world-western.

153 Ian Johnston, Malcolm Moore, and Laura Pitel, "DeepSeek Threat Exposes Guesswork on AI Power Demand, Says IEA", Financial Times, 29 January 2025, sec. Artificial intelligence, https://www.ft.com/content/0cc897c2-e12d-4143-81ff-e56c5381a5a1.

154 Ben Jiang, "China's 4 New 'AI Tigers' Emerge as Investor Favourites", South China Morning Post, 19 April 2024, https://www.scmp.com/tech/big-tech/article/3259499/chinas-four-new-ai-tigers-baichuan-zhipu-ai-moonshot-ai-and-minimax-emerge-investor-favourites.

155 Dan Milmo et al., "'Sputnik Moment': $1tn Wiped off US Stocks after Chinese Firm Unveils AI Chatbot", The Guardian, 28 January 2025, sec. Technology, https://www.theguardian.com/business/2025/jan/27/tech-shares-asia-europe-fall-china-ai-deepseek.

156 Pablo Villalobos et al., "Will We Run out of Data? Limits of LLM Scaling Based on Human-Generated Data" (arXiv, 4 June 2024), https://doi.org/10.48550/arXiv.2211.04325.

157 Courtney Radsch, "Dismantling AI Data Monopolies Before It's Too Late | TechPolicy.Press", Tech Policy Press, 9 October 2024, https://techpolicy.press/dismantling-ai-data-monopolies-before-its-too-late.

designed to provide high-performance alternatives to closed-source offerings, supporting applications in business automation, translation, and multilingual content generation. Meanwhile, iGenius, an Italian AI company, focuses on developing enterprise AI solutions tailored for highly regulated industries such as finance, healthcare, and government. By incorporating explainable AI and compliance-driven architectures, iGenius aims to bridge the gap between cutting-edge machine learning and the stringent regulatory requirements that govern sensitive data environments. Another notable area of strength lies in industrial AI applications, with companies like Bosch and Siemens integrating AI into manufacturing, robotics, and predictive maintenance, reinforcing Europe's leadership in industrial automation and AI-powered efficiency.

Europe's reliance on foreign semiconductors and computational infrastructure highlights critical vulnerabilities in its AI ecosystem. Efforts are underway to address these challenges and strengthen digital sovereignty.[158] Aleph Alpha has partnered with Cerebras Systems to deploy sovereign AI solutions using advanced supercomputers housed in HPE-built data centers in Berlin. This partnership aims to promote AI transparency and develop solutions that operate independently of U.S. Big Tech while complying with European data protection regulations.

Recently, Aleph Alpha has shifted its focus from developing its own LLMs to supporting other organizations in deploying existing AI models. This shift is exemplified by the launch of PhariaAI, an end-to-end platform designed to help enterprises and governments integrate AI solutions effectively. European HPC clusters such as LUMI in Finland and Leonardo in Italy provide cutting-edge public computational capacity for training and deploying AI models. Meanwhile, Mistral AI collaborates with providers like CoreWeave and Scaleway to diversify its computing resources, reducing dependence on non-European platforms. However, what secures Mistral's ability to train its own models is its partnership with Microsoft. This collaboration allows Mistral to benefit from Microsoft's cloud resources for research and provides access to Microsoft's customer base. In exchange, Microsoft gains exclusive access to some of Mistral's models, a move aimed at reducing its reliance on OpenAI. While this partnership ensures Mistral's short-term viability, it raises concerns about its openness and long-term commitment to European sovereignty.

Future European initiatives like the recently announced new IPCEI on AI and edge computing could further solidify a sovereign AI ecosystem[159] empowered by a large European network of green public compute. To lead in sustainable and ethical AI deployment, Europe must prioritize green computing and generativity.[160] Optimizing data center design for energy efficiency, transitioning to renewable energy, and adopting advanced cooling systems to reduce water consumption are essential measures.[161] Developing energy-efficient AI models can further reduce electricity use while maintaining performance, aligning with Europe's climate goals, and minimizing the environmental impact of its AI ecosystem. The challenge for Europe is to pursue these sustainability goals while remaining competitive and innovative, thus ensuring that it leads in green AI without ceding ground to global rivals.

Europe is advancing its AI capabilities through targeted investments, infrastructure development, and strategic partnerships. A flagship initiative, the AI Factories, aims to integrate computing power, vast datasets, and skilled talent to train large models for

158 See, for example: "OpenGPT-X", accessed 12 January 2025, https://opengpt-x.de/en/.

159 Margrethe Vestager, "Statement by EVP Margrethe Vestager at the Joint European Forum for IPCEI", IEU Monitoring, n.d., https://ieu-monitoring.com/editorial/joint-european-forum-for-ipcei-statement-by-evp-margrethe-vestager/478623?utm_source=ieu-portal.

160 Fieke Jansen and Michelle Thorne, "IV. Predatory Delay and Other Myths of 'Sustainable AI'", AI Now Institute (blog), 15 October 2024, https://ainowinstitute.org/publication/predatory-delay-and-other-myths-of-sustainable-ai.

161 IEA, "Electricity 2024 – Analysis", IEA, 24 January 2024, https://www.iea.org/reports/electricity-2024.

sectors like healthcare, energy, and manufacturing. These factories leverage EuroHPC, Europe's HPC infrastructure, to enhance competitiveness in advanced AI applications.[162]

However, Europe's scale of investment – €750 million – remains modest compared to the enormous spending by Big Tech, such as Microsoft and OpenAI's $100 billion data center projects. Competing directly with such vast expenditures would neither be sustainable nor strategically prudent for the EU.

Instead, Europe can turn its relative vulnerability in computing resources into an opportunity by leveraging its collective purchasing power and expansive public compute network to shape global industry standards[163] – a concept referred to as conditional computing.[164] For instance, rather than relying on NVIDIA GPUs, which are locked into the proprietary CUDA ecosystem, Europe could prioritize GPUs developed through open-source initiatives, promoting transparency, interoperability, and sovereignty over critical technologies.

The European Union is intensifying its investment in AI to enhance competitiveness and uphold ethical standards. Through the InvestEU program, €26.2 billion has been earmarked as an EU budget guarantee, with the aim of mobilizing over €372 billion in public and private investments across various sectors, including AI. Private sector engagement is also on the rise. For instance, German AI startup Aleph Alpha has secured over $500 million in a Series B funding round,[165] while Mistral and DeepL have also attracted significant investment. Although private investments signal growing confidence, Europe's AI funding still trails its global competitors. In 2023, generative AI investments in Europe amounted to just $2.4 billion, compared to $22.4 billion in the United States. However, European funding is growing at a faster pace. Europe's approach reflects its unique emphasis on aligning technological progress with ethical, regulatory, and sustainability principles. While the strategy is sound, scaling these efforts to match the transformative potential of AI requires bolder investments, improved coordination among member states, and more streamlined pathways for public-private partnerships. Without addressing these gaps, Europe risks losing control over sovereign AI capabilities and its own development model, even as it upholds its commendable commitment to ethical and accountable AI. Initiatives like the AI Factories are still in their early stages, and their success will depend on overcoming structural barriers such as fragmented data ecosystems, limited cross-border collaboration, insufficient investments, and restricted access to local computational resources compared to global hyperscalers.

AI's societal and economic benefits will be maximized, and risks minimized, if its deployment in businesses and public sector agencies is decided collaboratively by workers and managers. Encouraging co-determination of technological changes in the workplace can help ensure a fair digital transition for all workers and unlock AI's potential to enhance productivity and efficiency. Public policy has a role to play in fostering this collaborative approach. Particular attention should also be paid to SMEs. AI deployment will be more effective if it has an overarching "directionality" – a sense of purpose in which businesses, workers, and citizens view AI as part of a broader social project aimed at achieving collective goals.

162 EuroHPC JU, "Selection of the First Seven AI Factories to Drive Europe's Leadership in AI", 10 December 2024, https://eurohpc-ju.europa.eu/selection-first-seven-ai-factories-drive-europes-leadership-ai-2024-12-10_en.

163 Mariana Mazzucato and Fausto Gernone, "Governments Must Shape AI's Future", Project Syndicate, 12 April 2024, https://www.project-syndicate.org/onpoint/governments-must-shape-ai-future-by-mariana-mazzucato-and-fausto-gernone-2024-04.

164 Van Djjck et al. 2024, Conditional computing: a new paradigm for public-interest AI in the EU in Francesca Bria et al., "Time To Build A European Digital Ecosystem", 9 December 2024, https://feps-europe.eu/wp-content/uploads/2024/12/Time-to-build-a-European-digital-ecosystem.pdf.

165 "Aleph Alpha Raises a Total Investment of More than Half a Billion US Dollars from a Consortium of Industry Leaders and New Investors", Aleph Alpha, 6 November 2023, https://aleph-alpha.com/aleph-alpha-raises-a-total-investment-of-more-than-half-a-billion-us-dollars-from-a-consortium-of-industry-leaders-and-new-investors/.

Box 3 – Biotechnology and medtech: Precision and dependency

Biotechnology and medtech are among the most innovative and transformative industries, influencing sectors such as healthcare, agriculture, and life sciences. Europe has emerged as a global leader in areas uch as genomics and biomanufacturing, exemplified by the German company BioNTech, which developed the first COVID-19 vaccine authorized for regular use. However, despite these achievements, the sector remains heavily reliant on foreign technologies at critical stages of the value chain.

Specialized inputs, including chemicals, reagents, and biological samples, are predominantly sourced from major U.S. firms such as Merck and ATCC. These dependencies also extend to digital infrastructure, where network systems facilitate real-time data sharing, and AI workloads demand substantial computational power. AI is playing an increasingly central role in drug discovery and biological research, as demonstrated by AlphaFold's groundbreaking protein-structure predictions – a product of the London-based DeepMind, now owned by Alphabet. While Bayer's collaboration with Microsoft in agricultural AI demonstrates Europe's innovation potential, it also underscores the persistent reliance on third-country technology.

Cloud services, dominated by U.S. companies such as AWS, Microsoft Azure, and Google Cloud, are vital for genomics and drug discovery. In the field of human genomics, the Chinese company BGI is becoming increasingly dominant. Reliance on non-European platforms for high-throughput data analysis and storage poses a significant challenge to European sovereignty. At the same time, imaging and monitoring equipment critical to healthcare – where European firms like Siemens Healthineers and Philips Healthcare are leaders – relies on digital systems that are increasingly cloud-integrated. Cybersecurity remains paramount for protecting sensitive research and patient data; however, Europe continues to depend on non-European solutions in this domain.

The EuroStack offers an opportunity to address these vulnerabilities by fostering an ecosystem that integrates European digital infrastructure with the biotechnology and medtech value chain. Strengthening AI and cloud services within Europe and ensuring secure data flows can enable the sector to flourish while safeguarding European sovereignty and innovation leadership.

Cybersecurity: The cornerstone of digital resilience and autonomy

Cybersecurity is a critical component across the stack and serves as both a conditio sine qua non and an opportunity for EU strategic autonomy. Technically, it encompasses a wide range of software and hardware, including secure access, device-level data encryption, end-to-end secure communications, system and device sensors, firewalls, antivirus solutions, and cyber-incident monitoring and analysis (e.g., Security Information and Event Management, or SIEM). Many of these components are increasingly reinforced by, and in some cases dependent on, artificial intelligence. Cybersecurity also includes governance, encompassing standardized procedures, processes, and EU legislation. However, oversight is generally imposed by national rather than EU authorities, reflecting a decentralized approach. Governance and technology are closely linked.

Europe is home to numerous cybersecurity companies, including large firms such as Thales, but the majority are small and face significant challenges in scaling within the European market. These challenges include a lack of risk capital, fragmented regulations, and the need to build trust with buyers. European firms also compete with well-established global suppliers, particularly from the United States and Israel, who benefit from global brand recognition, substantial resources, access to scale-up capital, and extensive legal expertise.

Despite extensive EU cybersecurity legislation[166] and financial support through EU programs, the absence of a coherent EU cybersecurity industrial policy remains a critical gap.[167] Such a policy is urgently needed to address the risk of long-term erosion of European autonomy while acknowledging the immediate necessity of robust cyber-resilience amid rising geopolitical tensions, widespread cybercrime, and outright war. A comprehensive industrial policy would not only enhance adoption at scale through public procurement and defense spending but also ease legislative compliance within the internal market. Furthermore, it could foster synergies between cybersecurity in the internal market and digital diplomacy,[168] and make the sector more attractive to European investors by demonstrating that EU-made cybersecurity solutions are viable and competitive.

166 Paul Timmers, "EU Cybersecurity Policy", in The Making of a Global Digital Rulebook: Digital Sovereignty and International Action in the EU, Thibaut Kleiner and Andrea Garcia Rodriguez (Eds) (Springer, 2025); Christina Rupp, "Navigating the EU Cybersecurity Policy Ecosystem", 27 June 2024, https://www.interface-eu.org/publications/navigating-the-eu-cybersecurity-policy-ecosystem.

167 Paul Timmers, "EU Cybersecurity Policy".

168 See also the program of the Polish Presidency of the Council, Polish Presidency, "Polish Presidency of the Council of the European Union", Polish presidency of the Council of the European Union, 2025, https://polish-presidency.consilium.europa.eu/en/.

Defense: Strengthening strategic capabilities

Geopolitical tensions and the war in Ukraine have underscored Europe's military vulnerabilities. In response, defense investment has been increasing, with annual growth exceeding 15% in recent years.[169]

In addition, civil-defense synergies are expanding.[170] At the European level, related funding includes the European Defense Fund (€8 billion through 2027), the EU Space Programme (€13 billion through 2027), and EU Secure Connectivity, which incorporates quantum communications (€2 billion through 2027). EU-NATO collaboration is also advancing, with joint European Investment Fund (EIF)-NATO investments in the private sector and the development of shared strategies, such as those for undersea cables. Total defense expenditures by EU member states are projected to rise significantly, from €326 billion in 2024.[171] Entrepreneurial and risk capital investments in defense-related technologies are also increasing. A notable example is the Germany-based AI company Helsing, whose valuation tripled to $4.5 billion in 2024.

There is an increasingly urgent call for action to strengthen Europe's civil and military preparedness and readiness, as emphasized by the 2024 Niinistö report. Defense funding, both at the national level and through mechanisms like the European Defense Fund and NATO, is beginning to flow across the spectrum, from advanced research to scaling up promising technologies. Defense requirements are increasingly overlapping with civil R&D efforts.

169 EDA, "2024 Defence Review Paves Way for Joint Military Projects (CARD 2024)", 19 November 2024, https://eda.europa.eu/news-and-events/news/2024/11/19/2024-defence-review-paves-way-for-joint-military-projects.

170 Reference documents at EU level are Examples are the 2021 Action Plan on Synergies between Civil, Defence and Space Industries, the Observatory for Critical Technologies across civil, defence and space industries programmes, CARD – the Coordinated Annual Review of Defence in the EU, and the European Defence Industrial Strategy 2024.

171 European Defence Agency EDA, "Coordinated Annual Review on Defence (CARD)", Default, 19 November 2024, https://eda.europa.eu/what-we-do/EU-defence-initiatives/coordinated-annual-review-on-defence-(card).

Examples from other countries demonstrate that adopting an early adopter role in defense – by defining requirements, piloting technologies, and validating innovations – can help unlock markets, enhance security, and bolster sovereignty.

However, Europe remains highly dependent on imports: 78% of its military equipment and services (many of them digital) are imported, with two-thirds sourced from the United States. Only 18% of these goods and services are procured from other EU countries. The European Defense Industrial Strategy has outlined ambitious objectives to address this dependency by 2030:

- at least 50% of member states' procurement should come from the European Defense and Technology Industrial Base (EDTIB);
- the value of intra-EU defense trade should account for at least 35% of the EU defense market;
- member states should procure at least 40% of defense equipment through collaborative mechanisms.

Challenges in stepping up civil-military cooperation in the EU include aligning military innovation with the speed of market developments and ensuring adherence to ethical standards – particularly as technology evolves in areas such as AI, drones, sensors, and satellites. A significant challenge is the reluctance of conventional banks to invest in the defense sector. The European Commission (EC) has outlined options for R&D focused on technologies with dual-use potential. At the same time, the League of European Research Universities has emphasized the need for a careful approach, advocating safeguards to clearly demarcate civil and military research.[172]

Quantum technologies: Unlocking tomorrow's potential

Quantum technologies (QT) represent a transformative force within the technology stack. By leveraging quantum mechanics, they enable radically new approaches to computing, communications, and sensing, addressing problems that are beyond the capabilities of conventional systems. For instance, quantum computing could significantly accelerate drug discovery and materials development, while quantum sensing has the potential to revolutionize navigation, medical diagnostics, subsea cable surveillance, and industrial quality control.

Quantum communications, particularly through QKD, already enable unbreakable secure communications and are beginning to be commercialized. China leads in this area, operating a 2,032 km QKD ground link between Beijing and Shanghai. The EU is advancing its capabilities through initiatives like the **European Quantum Communication Infrastructure** (EuroQCI),[173] which will integrate with the **EU's IRIS2 satellite program**.[174]

However, QKD alone is insufficient to address all security challenges posed by quantum technology, and its merits remain the subject of ongoing debate.[175] It is urgent to also adopt PQC to secure existing systems and encrypted data, as quantum computing has the potential to break widely used traditional encryption methods. This urgency exists even though quantum computing at scale may still be five to ten years away. PQC also serves as a necessary

172 LERU, "Enhancing Dual Use Technologies: Leveraging Synergies in EU Funding Streams", LERU, April 2024, https://www.leru.org/publications/options-for-enhancing-support-for-research-and-development-involving-technologies-with-dual-use-potential.

173 European Commission, "The European Quantum Communication Infrastructure (EuroQCI) Initiative | Shaping Europe's Digital Future", 23 April 2024, https://digital-strategy.ec.europa.eu/en/policies/european-quantum-communication-infrastructure-euroqci.

174 EU Agency for the Space Programme, "IRIS2 | EU Agency for the Space Programme", 2024, https://www.euspa.europa.eu/eu-space-programme/secure-satcom/iris2.

175 Renato Renner and Ramona Wolf, "The Debate over QKD: A Rebuttal to the NSA's Objections" (arXiv, 27 July 2023), https://doi.org/10.48550/arXiv.2307.15116.

complement to QKD.[176] The U.S. National Institute of Standards and Technology has already issued three PQC standards, highlighting the strategic importance of early preparedness.

The economic dynamics of quantum technologies

Global public investment in QT reached over $42 billion in 2023, with China as the leading investor[177] and Europe in second place. Private funding is also growing, fueled by the recognition that QT has the potential to redefine industries. However, no single EU member state can match the resources of China or the United States. Initiatives such as the EU Quantum Flagship, supported by €1 billion in funding, and the 167-member Quantum Industry Consortium reflect Europe's commitment to QT. Nonetheless, a lack of coordination persists in translating research into market-ready applications.

With more than 500 scientists from over 100 institutions collaborating across Europe, EBRAINS 2.0 is accelerating breakthroughs in neuroscience, brain medicine, and brain-inspired technologies. Supported by advanced infrastructure, such as Jülich's quantum computing ecosystem in Germany – home to Europe's first quantum computer integrated with a supercomputing environment – EBRAINS 2.0 exemplifies Europe's strategy to leverage cutting-edge computing and quantum innovation for transformative solutions in healthcare and neuroscience.[178]

However, demand-side fragmentation within the EU remains a significant barrier. Public and defense procurement is inconsistent, and there is no unified goal for quantum computing by 2030 – an ambitious „moonshot" initiative that could serve to galvanize efforts. Additionally, QT development depends on critical materials and high-precision components, where Europe faces supply constraints.

Building resilience and strategic interdependencies

To strengthen its position, Europe must adopt a coordinated approach that balances self-reliance with strategic partnerships. Exclusive control over quantum technologies critical to national security, such as QKD and quantum hardware secure modules, is essential. For other areas, Europe should foster mutual interdependencies with like-minded countries, such as the UK and Switzerland, leveraging their expertise to build a competitive quantum ecosystem. The UN Year of Quantum in 2025 offers a platform for global collaboration to harness quantum technologies in addressing humanity's most pressing challenges.[179] Europe's leadership in this effort could align its strategic interests with broader international goals, positioning it as a key player in shaping the future stack.

Quantum's integration into the EuroStack should account for its current nascent stage while recognizing its long-term transformative potential. In the medium term, embedding quantum technologies within existing layers (e.g., networks and chips) will ensure seamless integration into today's stack. In the long term, as quantum capabilities mature, elevating it to a distinct layer would underscore its role as a foundational pillar of Europe's digital sovereignty.

Given the EuroStack's emphasis on strategic autonomy, sustainability, and resilience, quantum technologies represent a critical enabler of these goals. Whether incorporated into existing layers or designated as a dedicated layer, quantum's inclusion

176 Georg Serentschy, "Unraveling the confusion around Quantum-Safe Encryption – Serentschy Advisory Services", 2024, https://www.serentschy.com/unraveling-the-confusion-around-quantum-safe-encryption/; Bart Preneel, "The Quantum Threat and Post-Quantum Cryptography (PQC)", 2024.

177 World Economic Forum, "Explainer: What Is Quantum Technology and What Are Its Benefits?", World Economic Forum, 3 July 2024, https://www.weforum.org/agenda/2024/07/explainer-what-is-quantum-technology/.

178 See: "EBRAINS Research Infrastructure Secures €38 Million in Funding for New Phase of Digital Neuroscience", Forschungszentrum Jülich, 9 January 2024, https://www.fz-juelich.de/en/news/archive/press-release/2024/ebrains-research-infrastructure-secures-20ac38-million-in-funding-for-new-phase-of-digital-neuroscience.

179 United Nations, "International Year of Quantum Science and Technology", 7 June 2024, https://quantum2025.org/en/.

should be explicitly articulated in the EuroStack framework to reflect its transformative potential.

The evolution of the digital stack is a defining challenge for Europe's digital sovereignty. By prioritizing edge cloud computing and quantum technologies, the EU can carve out a competitive position in a landscape currently dominated by centralization and integration. Achieving this vision requires significant investments, harmonized regulation, and clear strategic goals.

Financial power: The driver of digital dominance

Financial power is a cornerstone of technological dominance, determining which companies and regions lead in innovation, shape ecosystems, and set global standards. U.S. and Chinese firms have not only achieved technological breakthroughs but have also leveraged substantial financial resources to secure supremacy across the digital stack. Their access to venture capital (VC), sovereign wealth funds (SWFs), and robust equity markets has enabled aggressive investments in research, acquisitions, and talent – often at scales Europe struggles to match.[180]

Venture capital and sovereign wealth funds as strategic levers

Venture capital serves as the engine of innovation, fueling the rapid growth and global dominance of U.S. and Chinese tech companies. In 2023 alone, U.S. AI startups attracted approximately €62.5 billion in private investment, compared to Europe's €9 billion in cumulative VC investment in AI startups (including the UK).[181] While Europe has experienced growth in VC funding, its fragmented financial markets and risk-averse culture, rooted in its bank-based financing system, continue to hinder large-scale investments. This disparity undermines Europe's ability to nurture startups capable of achieving successful exits on European stock exchanges and scaling globally. Instead, promising companies often become acquisition targets for foreign players, further eroding Europe's innovation ecosystem. While achieving exits on European stock exchanges is feasible, it remains challenging due to fragmented equity markets, lower valuations, and a preference for short-term returns, which can disincentivize long-term growth and innovation.

The dominance of U.S. VC ecosystems allows firms to pursue bold, long-term projects, fostering foundational research that redefines industries. OpenAI exemplifies this dynamic, leveraging substantial VC funding to develop large language models such as GPT-4, which have been integrated into Microsoft's Azure platform. Microsoft's multibillion-dollar investment in OpenAI has facilitated the development of advanced AI models and their training and deployment at scale, reshaping computational power and AI.[182] The partnership between OpenAI and Microsoft has led to concerns about potential monopolistic practices and the centralization of AI resources.[183] These developments underscore the importance of scrutinizing such alliances to ensure they foster a competitive and diverse technological ecosystem.[184]

In contrast, Europe's fragmented and less dynamic capital markets often hinder similar trajectories, leaving startups undervalued, underfunded, and

180 Douglas J. Cumming and Pedro Monteiro, "Sovereign Wealth Fund Investment in Venture Capital, Private Equity, and Real Asset Funds", SSRN Scholarly Paper (Rochester, NY: Social Science Research Network, 24 October 2022), https://doi.org/10.2139/ssrn.4258254., https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4258254&utm_source=chatgpt.com.

181 Maslej, et al., "AI Index Report 2024 – Artificial Intelligence Index".

182 Jai Vipra, "Computational Power and AI", AI Now Institute (blog), 27 September 2023, https://ainowinstitute.org/publication/policy/compute-and-ai.

183 Charles Duhigg, "The Inside Story of Microsoft's Partnership with OpenAI", The New Yorker, 1 December 2023, https://www.newyorker.com/magazine/2023/12/11/the-inside-story-of-microsofts-partnership-with-openai.

184 Tejas N. Narechania and Ganesh Sitaraman, "An Antimonopoly Approach to Governing Artificial Intelligence", SSRN Scholarly Paper (Rochester, NY: Social Science Research Network, 17 January 2024), https://doi.org/10.2139/ssrn.4597080, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4597080.

vulnerable to acquisition by foreign players.[185] High-profile acquisitions of European tech firms underscore the challenges of scaling independently in a fragmented market. Google's acquisition of DeepMind significantly enhanced its AI capabilities, while NVIDIA's purchase of Dutch-based Bright Computing strengthened its leadership in semiconductors and data center networking. Although Mellanox Technologies is based in Israel, its strong European presence further reinforced NVIDIA's regional influence. These acquisitions, combined with NVIDIA's involvement in European supercomputing projects like LUMI in Finland and Leonardo in Italy, have cemented its position in global AI and high-performance computing innovation. Similarly, Apple's acquisition of Xnor.ai enabled the integration of energy-efficient AI into its devices, deepening user dependency on its ecosystem. These examples highlight how Big Tech leverages strategic acquisitions to dominate the digital stack. In Europe, the loss of critical companies such as ARM and DeepMind underscores the urgent need for stricter merger oversight and strategic protections to safeguard technological sovereignty and critical assets.

Without robust policies, Europe risks losing its most promising innovations to foreign control, further eroding its competitive position. Limited access to growth capital is a significant barrier for European startups, leaving them exposed to external acquisition. The European Investment Bank has highlighted that Europe's fragmented financial system restricts startups from securing the funding necessary to scale, underscoring the urgent need for more integrated and dynamic capital markets to retain and grow innovation within the region.[186]

Equity markets play a pivotal role in sustaining technological dominance by enabling high valuations and sustained R&D investments. NVIDIA, with a market capitalization of approximately $3 trillion as of February 2025, exemplifies this dynamic.[187] Its substantial valuation has supported aggressive acquisitions and ambitious ventures in AI and cloud technologies. In contrast, Europe's fragmented equity markets often impede similar growth trajectories. European firms frequently face lower valuations and pressure for short-term returns, limiting their capacity for long-term innovation. This disparity leaves promising startups vulnerable to foreign acquisitions, further eroding the region's innovation ecosystem and weakening its digital sovereignty.

The European Investment Bank notes that Europe's fragmented financial system restricts startups' ability to access the necessary funding to scale, leaving them exposed to external acquisition. However, it is important to consider whether replicating the U.S. model of high-growth markets is desirable – or even feasible – for Europe.[188] While high valuations can drive innovation, they also pose risks, including the potential for financial bubbles. Therefore, while addressing the challenges in Europe's equity markets is crucial to enhancing competitiveness, it is equally important to consider the advantages of a balanced approach. Building a stable, innovation-driven ecosystem may better align with Europe's economic values and long-term strategic interests than pursuing rapid and potentially unsustainable growth.

Sovereign wealth funds are increasingly influential in shaping global digital ecosystems through strategic investments in transformative technologies.[189] They

185 European Investment Bank, Financing the Digitalisation of Small and Medium-Sized Enterprises: The Enabling Role of Digital Innovation Hubs (European Investment Bank, 2020), https://doi.org/10.2867/210258, https://www.eib.org/attachments/thematic/financing_the_digitalisation_of_smes_summary_en.pdf.

186 European Commission: Directorate-General for Research and Innovation, Science, Research and Innovation Performance of the EU, 2024 – A Competitive Europe for a Sustainable Future (Publications Office of the European Union, 2024), https://doi.org/10.2777/965670, https://op.europa.eu/en/publication-detail/-/publication/c683268c-3cdc-11ef-ab8f-01aa75ed71a1/language-en.

187 CompaniesMarketCap, "NVIDIA (NVDA) – Market Capitalization", accessed 12 January 2025, https://companiesmarketcap.com/nvidia/marketcap/.

188 BCG, "Europe's Growth Equity Landscape", BCG Global, 4 March 2024, https://www.bcg.com/publications/2024/opportunity-in-europes-growth-equity-landscape.

189 H. Kent Baker, "Sovereign Wealth Funds: An Overview", in The Palgrave Handbook of Sovereign Wealth Funds, ed. H. Kent Baker, Jeffrey H. Harris, and Ghiyath F. Nakshbendi (Cham: Springer International Publishing, 2024), 3–18, https://doi.org/10.1007/978-3-031-50821-9_1.

are emerging as powerful geopolitical tools in the global race for technological dominance, particularly against the backdrop of intensifying U.S.-China competition. Traditionally focused on financial returns, these state-owned funds have become integral to national strategies aimed at securing supply chains and establishing leadership in transformative technologies such as semiconductors, artificial intelligence, cloud infrastructure, and defense technologies. The strategic deployment of SWFs highlights a broader global trend: the fusion of economic and technological competition with geopolitical strategy. These developments underscore the growing interdependence of financial resources, technological leadership, and geopolitical power in the 21st century.[190]

China's National Integrated Circuit Industry Investment Fund, known as the "Big Fund," exemplifies this strategic use of SWFs. With its latest $47.5 billion phase launched in 2024, the fund seeks to strengthen domestic semiconductor production and reduce reliance on foreign technology, aligning with China's ambition for technological self-sufficiency.[191] This comes as the United States tightens export controls on advanced technologies, seeking to curtail China's tech ambitions. The United Arab Emirates' Mubadala Investment Company and Saudi Arabia's PIF are leveraging sovereign wealth funds to reshape global competitive dynamics in technology.

Mubadala has acquired key assets, such as GlobalFoundries, to strengthen its technological footprint and influence supply chains,[192] while the PIF pursued investments in fast-growing AI startups. Recent data highlights a fivefold increase in Middle Eastern SWF funding for AI companies in the past year. These investments align with broader national strategies like Saudi Vision 2030, which aims to diversify the Gulf economies and reduce their dependency on oil revenues.

In contrast, Europe's sovereign wealth funds lack the scale and strategic focus to drive a similar impact. Norway's Government Pension Fund, the world's largest SWF, prioritizes diversified financial returns over transformative technology investments.[193] [194] The deployment of SWFs in this geopolitical context underscores their dual role as financial instruments and strategic levers capable of shaping technological standards, securing supply chains, and gaining a decisive edge in the global competition for digital dominance. To remain competitive, Europe must adopt a more strategic SWF model, pooling resources and prioritizing investments in critical technologies such as AI, semiconductors, and quantum computing to strengthen its digital sovereignty.

The EIF, while instrumental in supporting innovation, remains limited in scope compared to global counterparts. To enhance its competitiveness, Europe could explore collaborative pooling of SWF resources across EU member states, combined with a stronger mandate for strategic investments in transformative technologies. Such initiatives could significantly bolster Europe's capacity to compete in the global digital economy, despite the previous failure of similar efforts under EU President von der Leyen.[195]

190 Brad Setser, "A Taxonomy of Sovereign Wealth Funds", Financial Times, 25 September 2024, sec. FT Alphaville, https://www.ft.com/content/a65135e9-1fde-4aee-a422-b0d783c62e14.

191 Reuters, "China Sets up Third Fund with $47.5 Bln to Boost Semiconductor Sector", 27 May 2024, sec. Technology, https://www.reuters.com/technology/china-sets-up-475-bln-state-fund-boost-semiconductor-industry-2024-05-27/.

192 Arab Gulf States Institute in Washington, "The Emergent Gulf Sovereign Wealth Fund-Global Tech Nexus", Arab Gulf States Institute in Washington (blog), 2 May 2024, https://agsiw.org/the-emergent-gulf-sovereign-wealth-fund-global-tech-nexus/.

193 Norway's Ministry of Finance, "Investment Strategy", Redaksjonellartikkel, Government.no (regjeringen.no, 17 April 2023), https://www.regjeringen.no/en/topics/the-economy/the-government-pension-fund/government-pension-fund-global-gpfg/investment-strategy/id696849/.

194 David Chambers, Elroy Dimson, and Antti Ilmanen, "The Norway Model", The Journal of Portfolio Management 38, no. 2 (31 January 2012): 67–81, https://doi.org/10.3905/jpm.2012.38.2.067.

195 Luigi Serenelli, "European Commission President's Plan for Common SWF Stalls", IPE, 27 March 2024, https://www.ipe.com/news/european-commission-presidents-plan-for-common-swf-stalls/10072442.article.

Addressing Europe's financial gaps

To reclaim digital sovereignty, Europe must adopt a bold, coordinated financial strategy that addresses structural weaknesses in its venture capital ecosystem. Scaling up late-stage funding and fostering risk-taking are critical for enabling European tech firms to grow and compete globally. While initiatives like the European Scale-Up Initiative and InvestEU provide a foundation, their mandates and resources remain insufficient compared to the financial power of global competitors.

The European Tech Champions Initiative (ETCI), a €10 billion fund-of-funds launched in 2023, represents a significant step forward. By supporting high-growth technology companies, the ETCI aims to retain innovation within Europe, offering late-stage funding to prevent promising startups from seeking capital or exits outside the continent. Similarly, the European Innovation Council (EIC) Venture Fund, with a €10 billion budget for 2021-2027, supports transformative innovations from early research to scaling. Complemented by Horizon Europe with its €95.5 billion budget, these initiatives address Europe's funding deficit but require greater ambition and alignment into a cohesive strategy to achieve meaningful impact.

Expanding the role of the European Investment Fund and fostering cross-border collaboration among sovereign wealth funds can provide the scale needed for Europe to compete globally. The Pan-European VC Funds-of-Funds Programme (VentureEU), launched by the Commission and EIF, aims to boost investment in startups and scaleups across Europe. The European Investment Bank (EIB) also supports early-stage innovation through equity investments, while InvestEU (€26.2 billion) guarantees investments to commercialize research, digitize industries, and scale innovative companies. Additionally, the European Defense Fund (€8 billion) promotes cutting-edge defense technologies and encourages startups and SMEs to participate in collaborative projects.

A unified strategy is essential to pool resources and focus investments on critical technologies. Establishing a European Tech Sovereignty Fund under the European Competitiveness Fund could bridge gaps in sectors such as AI, cloud infrastructure, and semiconductors. This fund would offer patient capital to drive long-term innovation while safeguarding Europe's technological independence. This funding could potentially be linked to the recently announced European Competitiveness Fund as well as the TechEU investment program deployed by the EIB, which aims to expand Europe's industrial capacity by supporting key technology sectors, such as AI, robotics, clean energy, space, and quantum technologies.[196]

National Promotional Institutions and the EIB should play a proactive role by acquiring equity stakes in strategic companies. For example, Bpifrance has invested in AI startups like Mistral, while Germany's KfW has supported semiconductors, satellites, and renewable energy. A similar coordinated approach across Europe could foster homegrown innovation and protect critical industries.

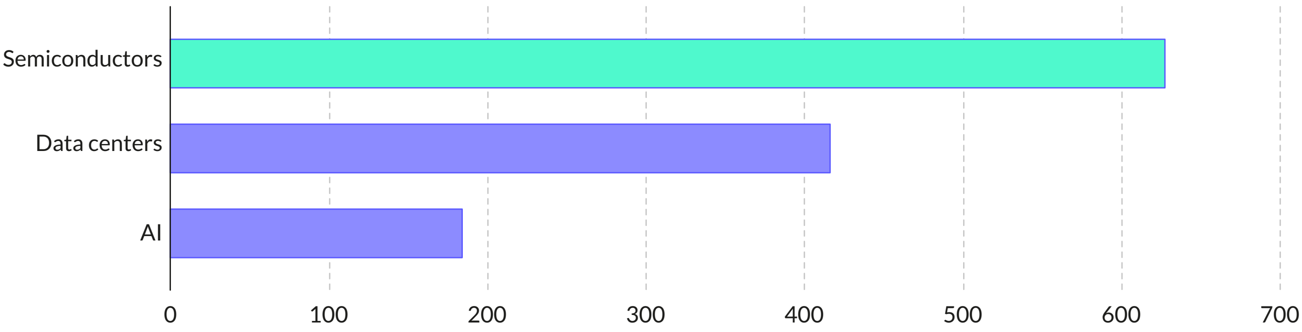
Europe must also ensure rigorous merger controls to prevent foreign acquisitions of strategic assets. Regulations should prioritize long-term innovation and ensure key technologies remain under European control. Public procurement policies must emphasize European solutions, creating demand for domestic innovations in cloud services, AI applications, and network infrastructure, as outlined in subsequent policy chapters.

Lessons can be drawn from countries like South Korea and Japan, which have successfully aligned financial and industrial strategies to maintain technological independence. South Korea's support for conglomerates like Samsung and LG, combined with targeted investments in semiconductors and AI, demonstrates how strategic alignment can achieve global leadership. Similarly, Japan's focus on

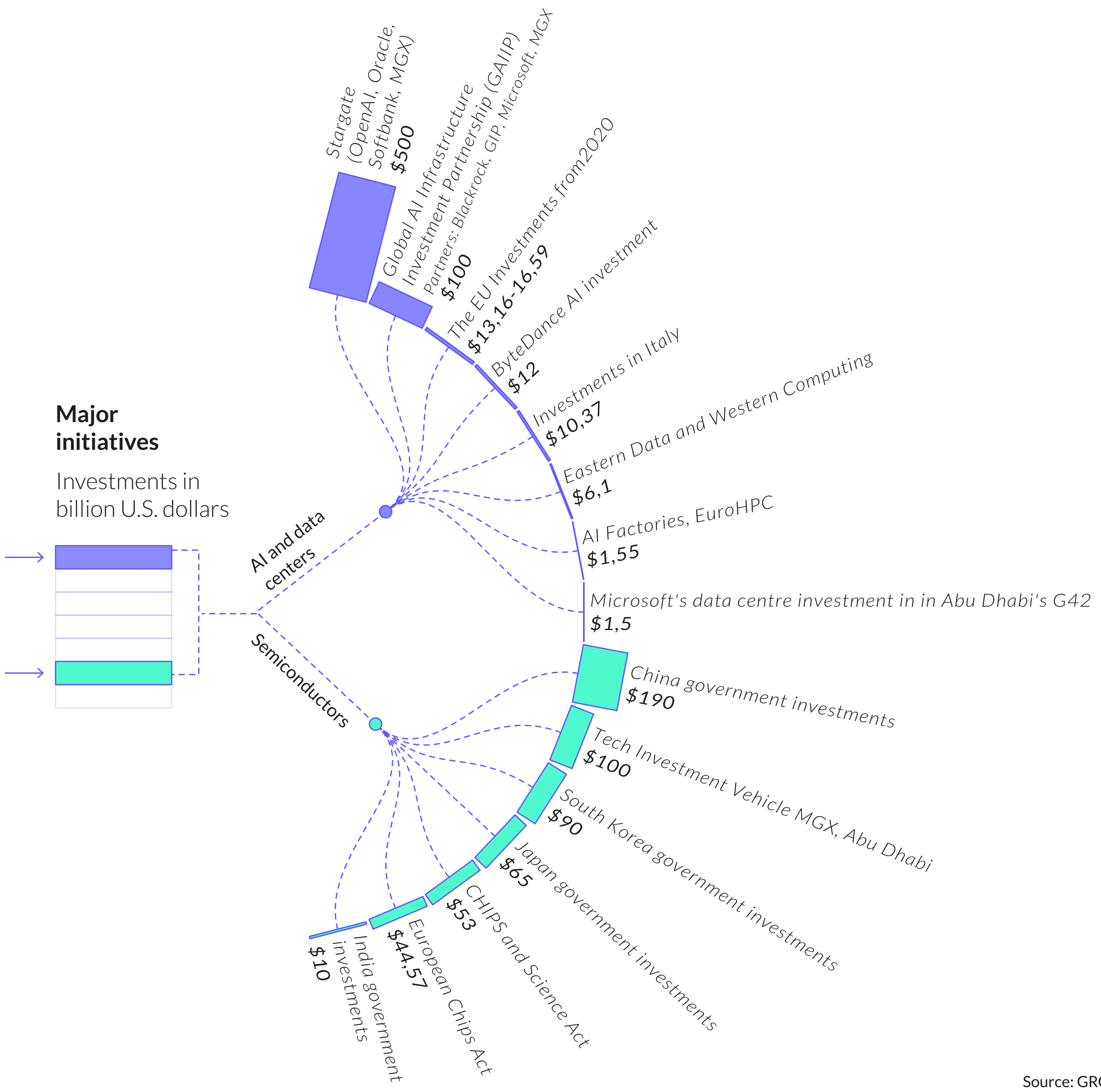
196 https://commission.europa.eu/document/download/10017eb1-4722-4333-add2-e0ed18105a34_en

The financial dimension

Market size of certain digital sectors, 2024
in billion U.S. dollars

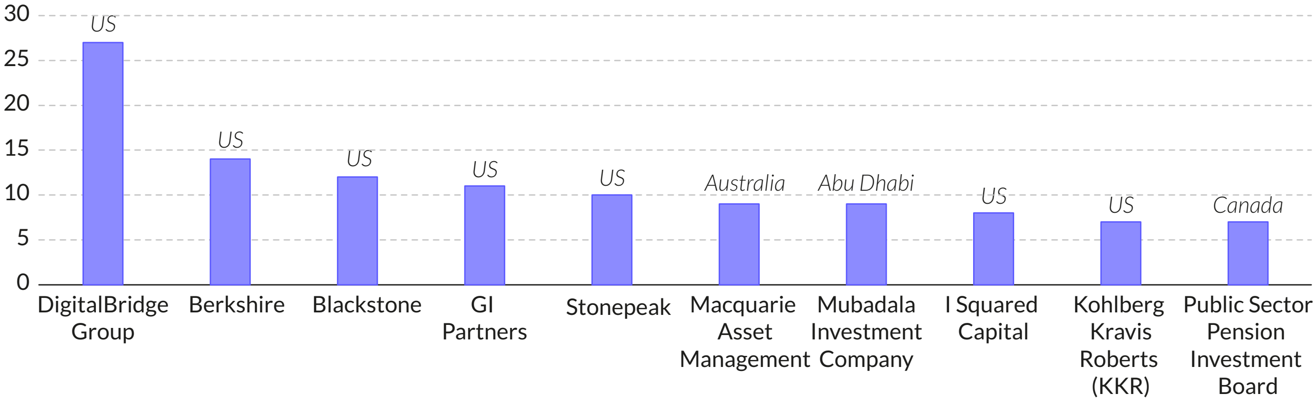


Source: Statista



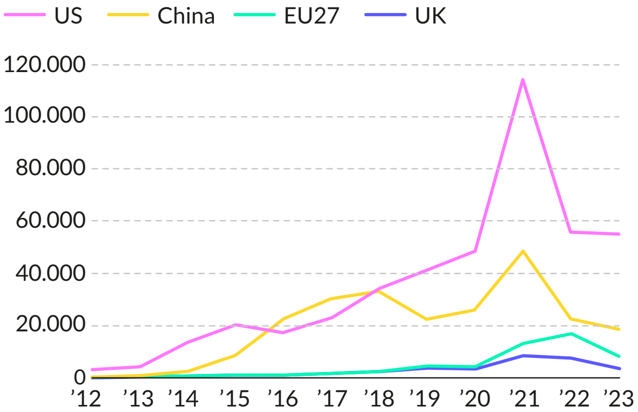
Source: GRC

Most active investors in data centers and their country of origin
Number of PE deals since 2018



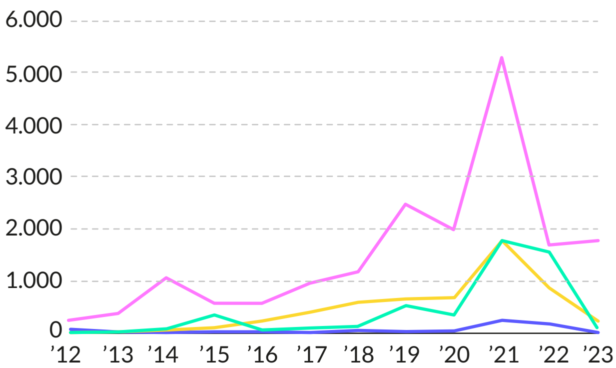
Source: Pitchbook

VC investments in AI by region
in million U.S. dollars



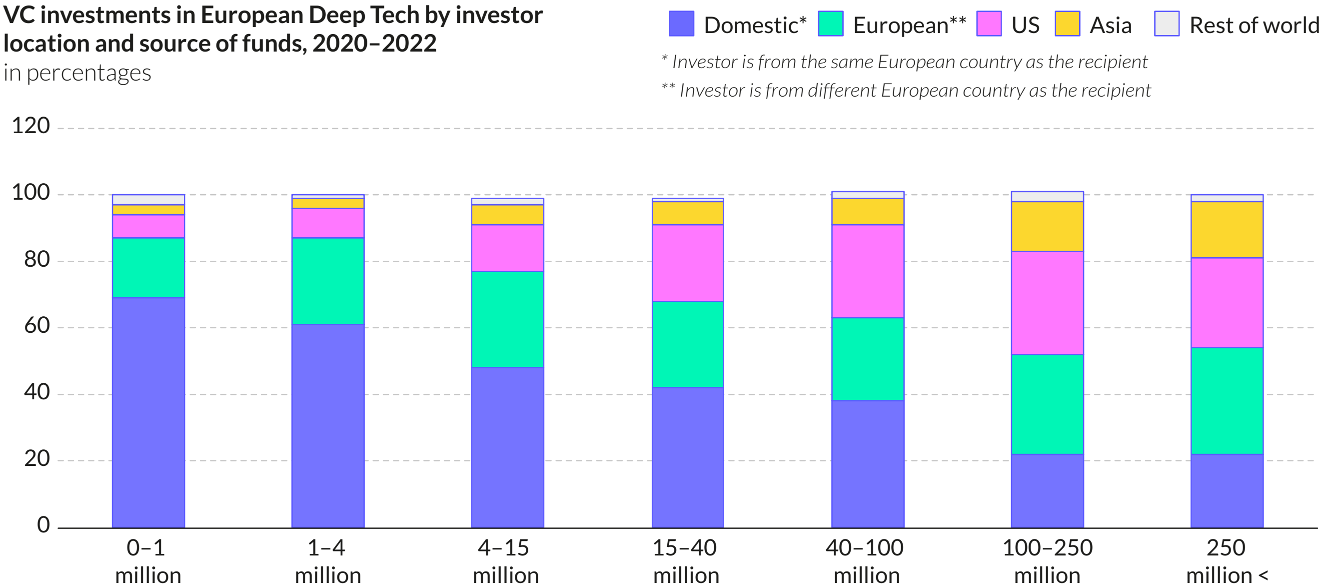
VC investments in data startups by region
in million U.S. dollars

R&D INVESTMENT GAP
The share of global venture capital funds raised in the EU is only 5%, compared to 52% in the US and 40% in China.



Source: OECD

VC investments in European Deep Tech by investor location and source of funds, 2020–2022
in percentages



** Investor is from the same European country as the recipient*
*** Investor is from different European country as the recipient*

Source: Dealroom.co

robotics and precision engineering has preserved its competitive edge in key industries.

Europe's financial strategy must recognize the interconnectedness of investment, innovation, and sovereignty. Mobilizing financial resources, fostering a culture of long-term risk-taking, and implementing coordinated industrial policies are essential to reclaiming technological leadership. By expanding its VC ecosystem, empowering SWFs, and protecting its innovation assets, Europe can position itself as a competitive global player while safeguarding its strategic interests. Achieving this requires not only funding but also vision, collaboration, and the ability to translate financial power into sustained technological leadership.

The geopolitical dimension: Shaping Europe's multipolar vision

In the global race for technological dominance, two powers – China and the United States – are vying for control across all layers of the digital stack.

China, under state-led initiatives like Made in China 2025,[197] has rapidly expanded its capabilities in semiconductors, telecommunications, advanced manufacturing, and emerging technologies such as quantum computing. These efforts, often dual-use in nature, are supported by significant public funding and aggressive talent acquisition strategies targeting Europe and the United States. At the same time, China has tightened market access and strengthened its control over critical raw materials through initiatives like the Belt and Road Initiative and export restrictions, using these dependencies as tools of economic and political leverage. Under the banner of the Digital Silk Road, Chinese firms have entered numerous overseas markets, exporting cloud, telecommunications, and AI technologies.

The United States, through measures like the CHIPS Act,[198] is shoring up its semiconductor production and bolstering the global dominance of its tech giants in AI, cloud infrastructure, and advanced chip manufacturing. Increasingly stringent export controls targeting high-tech industries also impact European companies, as do industrial policy measures such as the massive Inflation Reduction Act[199] and tariffs affecting strategic user industries such as energy and automotive. Additionally, President Trump's pledge to return to tariff wars underscores the ongoing competitive and protectionist nature of U.S. policies, posing further challenges to global trade stability and supply chain resilience.

Europe, while unable to compete head-to-head with these nations across the entire digital stack, must focus on reducing dependencies, safeguarding its strategic assets, and strengthening domestic capabilities. Internationally, Europe should prioritize partnership alliances that share its values, respect international rules, and aspire to balanced, inclusive and resilient digital ecosystems. Europe must reduce dependencies on digital superpowers while fostering values-driven cooperation. Partnerships with democratic nations are vital for securing supply chains, co-developing technologies, and shaping global standards, with a strong emphasis on mutual respect in market access, data governance, and technology transfer.

Engaging rising powers such as Brazil, Chile, India, South Africa, and Singapore offer opportunities to diversify dependencies and expand influence. These partnerships should support industrial capacity-building and sustainable, non-extractive supply chains, aligning with shared priorities in clean energy, climate adaptation, and digital public services.

197 China State Council, "Made in China 2025", 2015, http://english.www.gov.cn/2016special/madeinchina2025/.

198 In full: Chips and Science Act, US Congress, "CHIPS and Science Act", 9 August 2022, https://www.govinfo.gov/content/pkg/PLAW-117publ167/html/PLAW-117publ167.htm.

199 USG, "Inflation Reduction Act of 2022", 16 August 2022, https://www.regulations.gov/document/EPA-HQ-OAR-2023-0434-0066.

Amid the dominance by U.S. Big Tech and China's state-driven model, Europe has the opportunity to lead an alliance for digital strategic autonomy. This vision emphasizes fair technology transfer, robust digital public infrastructures, democratic data governance, and global regulatory frameworks to curb tech monopolies. By advancing shared governance in AI, cybersecurity, and sustainability, Europe can set a global standard for ethical, inclusive, and sustainable digital leadership while navigating the complexities of diverse partnerships.

Value-added for partner nations in Europe's digital foreign policy

India: India's transformative **India Stack**,[200] the Aadhaar digital identity system and Unified Payments Interface (UPI) payments platform, demonstrates how scalable public digital goods can drive financial inclusion and innovation. In 2022 alone, UPI processed over $1.5 trillion in transactions. However, Europe's collaboration with India must consider differences in governance frameworks. Europe's GDPR prioritizes privacy, decentralized systems, and user consent, in contrast to Aadhaar's centralized, biometric-based model, which, while impactful, has raised concerns about surveillance and inclusion. Europe's Digital Identity Wallet offers a privacy-first alternative that India could adopt elements of to enhance Aadhaar's transparency and trustworthiness. Collaboration between Europe and India provides opportunities for mutual learning: Europe can benefit from India's experience with large-scale digital ecosystems built on decentralized protocols, while India can leverage Europe's expertise in privacy-enhancing technologies and data governance. Joint innovation in areas such as fintech, health tech, and interoperable digital services could combine India's scalability with Europe's regulatory strengths, fostering interoperable, privacy-centric solutions that set global standards.

Brazil: Brazil's PIX payment system,[201] with over 142 million users and daily transactions exceeding $9.5 billion, exemplifies its leadership in digital financial inclusion. Developed by the central bank of Brazil, PIX has transformed financial access and could benefit from interoperability with Europe's Digital Euro, facilitating cross-border payments and reducing remittance costs. Conversely, Europe can draw valuable insights from Brazil's success in scaling user-driven financial solutions across diverse economic contexts.

Beyond payments, Brazil's National Artificial Intelligence Strategy underscores its growing role in digital innovation, with applications in agriculture, healthcare, and financial services. This aligns with Europe's priorities for ethical, human-centric technologies. Joint efforts could focus on integrating AI into broader industrial policies, addressing supply chain dependencies, and adhering to privacy standards under Europe's GDPR and AI Act. The ongoing EU-Brazil Digital Dialogue expands this partnership, targeting connectivity in underserved regions, 5G/6G advancements, and HPC collaboration. However, disparities in governance, scalability, and regulatory approaches challenge harmonization. To move beyond symbolic gestures, the partnership must prioritize measurable objectives, particularly in diversifying semiconductor supply chains, fostering interoperable and independent digital systems, and advancing AI governance. Collaborative efforts should also address shared challenges such as financial inclusion and climate adaptation.

Latin America, Africa, Indonesia and Australia: Resource-rich nations such as Chile and Argentina (lithium), Indonesia (nickel), and the Democratic Republic of Congo (cobalt) are advancing domestic industrial capacities to create value locally. Europe can support these efforts through investments in processing and refining technologies, clean manufacturing expertise, and co-developing green

200 See: "India Stack", accessed 12 January 2025, https://indiastack.org/.

201 See: "Pix", Banco Central do Brasil (BCB), accessed 12 January 2025, https://www.bcb.gov.br/en/financialstability/pix_en.

technologies, aligning with climate goals while ensuring secure access to critical materials. Chile and Europe are already collaborating under the EU-Chile Advanced Framework Agreement for sustainable lithium extraction, while Argentina is exploring ways to expand its battery value chain through the EU-CELAC partnership. Similarly, Indonesia has partnered with BASF and Eramet to develop nickel refining powered by renewable energy, and the EU's Global Gateway Initiative supports ethical cobalt sourcing in the DRC. Meanwhile, Europe is working with Australia through the EU-Australia Partnership on Sustainable Critical and Strategic Minerals to diversify and green supply chains.

Japan and South Korea: Japan and South Korea are key partners in addressing Europe's semiconductor vulnerabilities. South Korea's Samsung and Taiwan's TSMC dominate over 70% of global advanced chip production, while Japan leads in critical materials such as silicon wafers and photoresists. These capabilities complement Europe's Chips Act, which aims to increase Europe's global market share in semiconductor production to 20% by 2030. Collaborative initiatives, such as the EU-Japan Green Alliance and R&D agreements with Samsung, enhance supply chain resilience and foster innovation. Europe's expertise in ethical AI and secure data-sharing frameworks aligns with Japan's and South Korea's advancements in AI-driven manufacturing and edge computing. Beyond semiconductors, joint efforts in quantum technologies, high-performance computing, and advanced AI could strengthen Europe's position as a global leader in critical digital capabilities.

Middle East: Emerging digital hubs Saudi Arabia and the United Arab Emirates (UAE) are rapidly advancing as digital innovation hubs through state-led initiatives like Saudi Vision 2030 and UAE's smart city projects. Programs like Saudi Arabia's NEOM and Project Transcendence aim to integrate AI and modernize infrastructure, while partnerships with firms like Huawei drive progress in 5G and cloud infrastructure. However, these centralized, state-driven and often surveillance-oriented approaches contrast sharply with Europe's decentralized, rights-based frameworks, including GDPR and ethical AI standards. Concerns about data sovereignty, privacy, and the governance of AI and digital platforms highlight key areas of divergence. Constructive collaboration should leverage Europe's strengths in data governance, sustainable urban planning, and renewable energy technologies, aligning innovation with shared values of transparency and sustainability. Diplomatic engagement must ensure that projects address these concerns while fostering balanced and forward-looking partnerships.

Africa: Africa offers numerous opportunities for mutually beneficial partnerships across its diverse countries. The Africa-EU Partnership and EU-Africa Business Forum provide overarching governmental and private sector frameworks, complemented by a range of bilateral agreements and financial support through initiatives like the Global Gateway and other EU programs. Key areas of collaboration include high-tech R&D, with South Africa serving as the EU's largest research and innovation partner on the continent; digital and legislative capacity-building, as exemplified by cooperation with Ghana; digital infrastructure development, including undersea cables and related operational capabilities, such as projects with Senegal; and rare mineral exploration, including partnerships with the Democratic Republic of Congo.

Cross-layer opportunities

Europe's leadership in data privacy and governance aligns with global efforts to establish ethical digital ecosystems. Initiatives such as International Data Spaces position Europe as a frontrunner in developing interoperable and secure data-sharing frameworks. Collaborating with key partners like India, Brazil, and other emerging powers strengthens this position by fostering systems that emphasize inclusivity, privacy, and resilience.

Governance and steering efforts

Europe's digital foreign policy must balance reducing dependencies on digital superpowers with fostering cooperative, values-based relationships with a diverse range of global actors. A coordinated governance structure is crucial to achieving these objectives.

- **Existing units for coordination:** Europe already has an institutional framework in place within the European External Action Service, including units dedicated to digital foreign policy and cybersecurity cooperation. Furthermore, European Commission directorates and units play pivotal roles in coordinating international activities across the European Commission.

- **Enhanced coordination:** Strengthening these existing structures can improve high-level steering and decision-making in digital foreign policy. This includes aligning internal policies, such as foreign direct investment (FDI) screening and state aid, with external initiatives like the joint procurement of raw materials under the proposed Critical Raw Materials Platform, as proposed in the Draghi Report.

- **Strategic dialogue:** To advance synergies, systematic dialogue among industry, research, civil society, and governance bodies across Europe must be prioritized. These discussions should focus on accelerating the implementation of international cooperation frameworks, advancing the EuroStack initiative, and ensuring alignment between Europe's digital foreign policy and its internal regulatory priorities.

- **Review of existing external strategies:** Current strategies, such as those addressing the Indo-Pacific region and Latin America, should be reassessed in light of evolving geopolitical realities and the objectives of Europe's digital foreign policy.

Annex A – Strategies of dominance among selected Big Tech

This section outlines the primary elements of the business strategies employed by the key dominant companies within the digital stack. These strategies represent a blurring of traditional boundaries – between hardware and software, platforms and infrastructure, consumer and enterprise markets, and national borders. Their integrated ecosystems foster significant innovation while effectively rewriting market rules, accumulating and leveraging data at scale, and entrenching high switching costs. his concentration of power has led to growing calls from regulators, policymakers, and civil society to better understand and govern the multifaceted power these firms wield.

Amazon holds a dominant position in cloud infrastructure, e-commerce, logistics, and AI. As an early mover in cloud computing, AWS commands over 30% of the global market. AWS bundles raw computing power with specialized chips, storage solutions, machine learning frameworks (e.g., Amazon SageMaker), and integrated dev-ops tools. This integration makes migrating workloads away from AWS both costly and complex, creating significant switching barriers. AWS's privileged position also allows Amazon to gain strategic insights into broader market trends, shaping its decisions on where and how to invest in capacity. In e-commerce, Amazon's control over fulfillment, warehousing, and last-mile delivery not only reduces internal costs but also imposes stringent terms on third-party sellers who rely on its logistics infrastructure. By managing both the marketplace and the rules that govern it, Amazon can subtly prioritize its private-label products and services, extracting rents and gathering data that informs its advertising and retail strategies.

Microsoft wields a comparable level of infrastructural dominance, anchored by Windows, which has maintained approximately 70% of the global desktop operating system market share for decades.[211] This dominance is reinforced by its integration with productivity tools, cloud services, and AI capabilities. Azure, which holds 24% of the global cloud market,[212] integrates seamlessly with Office, Teams, and other Microsoft products , embedding its services into business operations. Microsoft's partnership with OpenAI further enhances its AI capabilities across its ecosystem, with advanced models such as GPT-4 integrated into Azure and productivity tools like Word and Teams. Microsoft's significant investments in data centers and custom AI chips enable it to meet increasing demand while cementing its control over critical layers of the digital stack.

At the core of **Google's** model is its flagship search engine, which commands roughly 90% of the global market.[213] By channeling the immense volume of search queries into Google Ads, supplemented by data from its video platform YouTube, the company refines its targeting algorithms to deliver highly

211 StatCounter, "Desktop Operating System Market Share Worldwide", accessed 12 January 2025, https://gs.statcounter.com/os-market-share/desktop/worldwide/.

212 Synergy Research Group, "Cloud Market Gets Its Mojo Back; AI Helps Push Q4 Increase in Cloud Spending to New Highs".

213 StatCounter, "Search Engine Market Share Worldwide", accessed 12 January 2025, https://gs.statcounter.com/search-engine-market-share.

relevant advertisements, driving both click-through rates and advertiser demand. Google also capitalizes on its Android operating system, which powers over 70% of smartphones worldwide.[214] This enables the seamless integration of services such as Search, Chrome, and the Play Store, embedding its ecosystem into billions of devices while consolidating control over app distribution and user data. Beyond mobile, Google dominates in cloud and AI with platforms like Google Cloud and TensorFlow, embedding its technologies into business operations. Advanced AI models like Bard address disruptions to its core search business, which commands 90% of the market. Google's dominance in digital advertising, driven by Google Ads and YouTube, is fueled by data collected across its ecosystem. This data powers precise targeted advertising, reinforcing its market position across the stack.

Apple's tightly controlled ecosystem integrates hardware such as the iPhone, iPad, and Mac with its operating systems (iOS, macOS) and services like the App Store and iCloud. This vertical integration ensures a superior user experience, cultivates strong customer loyalty, and creates significant barriers for competitors. Apple's exclusive control over the App Store enables it to impose terms on third-party developers, including commission rates of up to 30%, extracting substantial financial rents and further consolidating its market power.

Meta extends its dominance in social media by monetizing user data and integrating open-source AI models like Llama to attract developers and enhance its services. The company's investments in virtual reality aim to complement its existing platforms, fostering deeper integration between social media and immersive technologies. Additionally, Meta's control over undersea cable infrastructure bolsters its global reach, further reinforcing its influence across digital ecosystems.

214 StatCounter Global Stats, "Mobile Operating System Market Share Worldwide", accessed 12 January 2025, https://gs.statcounter.com/os-market-share/mobile/worldwide.

NVIDIA, the leader in GPU chip design, extends its dominance through an integrated software ecosystem, including CUDA, which fosters customer lock-in and enhances AI capabilities. By tightly aligning its hardware and software offerings, NVIDIA secures its position at the forefront of the AI-driven computing market.

Tesla leads innovation in electric vehicles through its advanced software ecosystem and AI-powered features like Autopilot. SpaceX leverages Tesla technologies and expands global connectivity through Starlink, which operates over 60% of the world's active satellites, dominating satellite communications.[215] Musk's AI venture, xAI, increasingly supports this broader ecosystem by advancing Tesla's autonomous driving capabilities and exploring wider AI applications. This ecosystem is further fueled by data from X (formerly Twitter), a social media platform Musk aims to transform into a hub for communication, payments, and AI services. However, X's role in amplifying unregulated or harmful content has attracted significant scrutiny. Together, these strategies consolidate control across transportation, connectivity, AI, and communication, raising pressing concerns about regulatory oversight and the ethical implications of concentrated power in critical technologies.

China also boasts a number of influential Big Tech firms that rely on infrastructural dominance. Supported by ambitious industrial policies and large-scale investment, these companies exemplify China's pursuit of technological self-reliance and vertical integration. By leveraging dominance in core areas, they consolidate power across the digital stack.

Originally gaining prominence through telecommunications equipment, **Huawei** has leveraged its infrastructure expertise to expand into consumer electronics, cloud computing, AI, and domestic chip manufacturing – often bolstered by state-led industrial policies. In telecommunications, Huawei's d dominance grew through its cutting-edge

215 Werner, "Want to Challenge Starlink in the Satcom Market?"

5G technology and turnkey solutions for telecom carriers worldwide, embedding its equipment deeply into global communication networks. Beyond telecom, Huawei diversified its portfolio to include smartphones, tablets, and laptops, powered by its proprietary HarmonyOS operating system and Kirin chips developed by its subsidiary HiSilicon. U.S.-led restrictions on semiconductor supply chains spurred Huawei to intensify its domestic R&D efforts and chip fabrication capabilities, a strategy aligned with Beijing's emphasis on technological self-reliance. Today, Huawei's cloud platform integrates AI accelerators, data analytics tools, enterprise services, and IoT frameworks, effectively replicating the global cloud ecosystem within China's "walled garden" of technology. Through these initiatives, Huawei positions itself as a vertically integrated, end-to-end solutions provider, spanning critical infrastructures from network layers to consumer-facing services.

Initially celebrated as an e-commerce pioneer, **Alibaba** spans digital commerce, cloud computing, fintech, logistics, and media. At the core of its ecosystem are the Taobao and Tmall marketplaces, which process an immense volume of transactions and generate data streams that drive the development of Alibaba's other businesses. Alibaba Cloud, the leading cloud provider in China, delivers compute, storage, AI services, and database solutions. It serves as the backbone of an ecosystem where merchants depend on Alibaba's infrastructure for payment processing (via Alipay), supply chain management, and customer analytics. Over the years, Alibaba has expanded its operations to include Cainiao, a logistics network integrating delivery partners and warehouses, as well as ventures into entertainment (Youku, Alibaba Pictures), education technology, and enterprise software. Each segment feeds into the other: the cloud business profits from the enormous traffic and data generated by e-commerce and financial services, and the marketplace benefits from the cloud's capacity, scalability, and analytical insights. Together, these integrations create a near-seamless environment for consumers, businesses, and developers, allowing Alibaba to extract rents, shape standards, and reinforce switching costs within China's digital economy.

Tencent initially emerged as a social and gaming powerhouse before branching into infrastructure and enterprise solutions. It dominates social media and messaging through WeChat, a "super-app" integral to daily life in China. WeChat integrates chat, mobile payments (WeChat Pay), mini-programs, e-commerce and, increasingly, business services. This ecosystem, by design, captures comprehensive user data, enabling granular personalization and targeted advertising. In parallel, Tencent's gaming portfolio – encompassing both domestic titles and global investments – serves as a major revenue driver while also acting as a testing ground for advanced technologies, such as cutting-edge graphics, network scaling, and AI-driven matchmaking. Tencent's expansion into cloud computing and AI leverages this platform advantage, offering solutions to enterprises that want to tap into its vast user base and computational power. Beyond IT infrastructure, Tencent maintains a diverse portfolio with stakes in fintech, music streaming, video platforms, healthcare, and numerous startups aligned with its ecosystem strategy. This integration results in a multifaceted digital empire that not only sets rules for content distribution, social interactions, and commerce but also acts as a critical layer of digital infrastructure for other businesses.

Often referred to as "China's Google," **Baidu** initially built its reputation on search, advertising, and mapping services before expanding into AI, autonomous driving, and cloud solutions. As the dominant player in China's search market, Baidu's algorithms continuously refine user intent and data mining capabilities, providing an advertising backbone that funds R&D in emerging technologies. Building on its robust data analytics and natural language processing expertise, Baidu launched Baidu Brain and a suite of AI platforms that contribute to industries like healthcare, finance, and urban planning. The company's Apollo platform leads the domestic autonomous driving initiative, utilizing extensive real-world data gleaned from its mapping and location-based services. In addition, Baidu Cloud offers enterprise-level solutions – ranging from machine learning frameworks to IoT services – that capitalize on Baidu's research labs and AI know-how. Through this integrated stack of products and services, Baidu extends its algorithms and data applications beyond search, influencing everyday life and infrastructure. This creates a virtuous cycle of user engagement and technological advancement, strengthening its market position and deepening customer lock-in.

Best known internationally for TikTok, **ByteDance** leveraged its success in short-form video and sophisticated recommendation algorithms to build a diverse digital ecosystem. Its offerings include Douyin (the Chinese counterpart to TikTok), Toutiao (a leading content aggregator), and other niche apps that cater to various verticals. ByteDance's AI recommendation engines, powered by granular data collection and massive user engagement, deliver highly personalized content feeds with remarkable precision. This sophisticated personalization has proved easily transferable to new domains: ByteDance invests in ed-tech, enterprise software, and e-commerce, integrating shopping features into its short-video platforms and branching out into livestreaming sales. Meanwhile, the firm's entry into cloud services and enterprise AI tools builds on its algorithmic expertise, effectively turning its consumer-facing successes into a foundation for B2B solutions. ByteDance is thus emerging as both a media and tech infrastructure player, powering new digital business models and reinforcing its role as a standard-setter for content discovery, user engagement, and targeted advertising.

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