



ABSTRACT

This article examines Europe's competitive position in critical and frontier technologies, assessing where the European Union holds measurable or plausible strategic strength relative to the United States and China. Drawing on official European Commission documents—including the Competitiveness Compass, the Strategic Technologies for Europe Platform (STEP), and the Critical Raw Materials Act—the analysis identifies a concentrated set of technology ecosystems in which European actors exhibit genuine industrial capability, research depth, or regulatory shaping power. These include **clean technologies (wind energy, electrolysers, hydrogen systems), advanced materials, quantum technologies, biotechnology, robotics, space systems, and advanced connectivity.**

The article establishes that European advantage is structurally concentrated rather than broadly distributed, and that scale-up failure, fragmented capital markets, and regulatory complexity remain the principal bottlenecks converting research excellence into global commercial leadership. The article introduces a multi-dimensional assessment framework—comprising scientific capacity, industrial capacity, and strategic autonomy—to analyze these dynamics systematically. The article concludes that Europe's most defensible competitive positions lie at the intersection of engineering quality, standards authority, and system integration, and that durable advantage requires coherent industrial policy coordinated across member states, the Commission, and private-sector actors.

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1. Introduction

The question of Europe's technological competitiveness has moved from academic discussion to urgent political priority. The publication of the Draghi Report in 2024 crystallised a widely-held but insufficiently examined concern: that Europe risks falling permanently behind the United States and China not only in the commercial applications of digital technology, but more broadly in its capacity to generate, scale, and retain the economic value of innovation. This concern is no longer confined to semiconductors or artificial intelligence; it spans the full frontier of technologies—from quantum systems and biotechnology to advanced materials, clean energy infrastructure, and autonomous systems.

Yet the framing of European technological 'decline' is both partially accurate and analytically imprecise. Europe remains a world-class scientific producer, hosting several of the world's leading research universities and public research institutions, contributing disproportionately to global peer-reviewed output in physics, chemistry, materials science, and life sciences. European firms hold commanding positions in specific industrial segments—wind turbines, industrial robotics, precision instruments, specialty chemicals, and pharmaceutical active ingredients. The European Union has emerged as a global standard-setter and regulatory authority whose choices shape product design and market access worldwide. These are not trivial advantages. But they are also insufficient, by themselves, to constitute sustained global technological leadership in the contemporary sense of that term.

This article is organized around a central diagnostic problem: why does Europe's scientific and engineering excellence not translate more consistently into global commercial leadership, and which structural conditions would have to change for it to do so? The analysis addresses four interrelated questions. First, in which specific technology domains does Europe hold measurable or plausible strategic strength? Second, how does that strength compare—in depth, breadth, and commercial reach—with the positions of the United States and China? Third, what structural and institutional factors explain the gap between European research capacity and commercial scale? Fourth, which policy instruments and governance arrangements offer the most credible pathways for protecting and amplifying European technological strengths?

The article is grounded in official European Commission policy architecture—particularly the Competitiveness Compass, the STEP Regulation, the European Chips Act, the Critical Raw Materials Act, and the Net-Zero Industry Act—and draws on a body of comparative innovation literature, sectoral industry data, and patent analytics. It proceeds by establishing a conceptual framework for defining technological advantage (Section 2), presenting the methodological design (Section 3), analysing Europe's strategic strengths across selected technology ecosystems (Section 4), benchmarking those strengths against the United States and China (Section 5), examining structural constraints on scale-up and commercialization (Section 6), and deriving policy conclusions (Section 7).

2. Conceptual Framework: Defining Technological Advantage

2.1 Beyond Research Excellence

A persistent conceptual error in European technology policy discourse is the conflation of research excellence with technological advantage. Research excellence—measured by publication volume, citation impact, Fields Medal and Nobel Prize counts, and university rankings—is a necessary but insufficient condition for competitive technological leadership. The history of innovation economics from Schumpeter onwards establishes that the conversion of

scientific knowledge into economic value requires a complex sociotechnical infrastructure that extends well beyond the laboratory: venture capital, procurement markets, regulatory frameworks, skilled workforce pools, platform ecosystems, intellectual property regimes, and the tacit organizational knowledge embedded in high-technology firms.

This article defines technological advantage along three analytically distinct but practically interrelated dimensions. The first is scientific capacity: the ability to generate frontier knowledge, produce trained researchers, and sustain internationally competitive research institutions. The second is industrial capacity: the ability to translate knowledge into manufactured goods, scalable services, or deployable systems at commercially competitive cost and quality. The third is strategic autonomy: the ability to maintain control over critical inputs, production processes, and platform architectures, thereby reducing exposure to supply disruption, coercion, or unilateral standard-setting by external actors.

These three dimensions do not necessarily co-occur. A region may exhibit high scientific capacity but low industrial capacity—a common European pattern in computing and biotechnology. It may exhibit high industrial capacity but low strategic autonomy—a common pattern in sectors dependent on Chinese rare earth supply or American cloud infrastructure. Genuine technological advantage requires reasonable strength across all three dimensions, a condition that Europe meets systematically only in a limited number of sectors.

Dimension	Definition	Indicative Metrics
Scientific Capacity	Ability to generate frontier knowledge, produce trained researchers, and sustain internationally competitive research institutions.	Publication volume; citation impact; Nobel counts; ERC grant success rates; top-100 university presence
Industrial Capacity	Ability to translate knowledge into manufactured goods, scalable services, or deployable systems at commercially competitive cost and quality.	Manufacturing value-added; export share; patent commercialisation rates; TRL progression speed; global market share
Strategic Autonomy	Ability to maintain control over critical inputs, production processes, and platform architectures, reducing exposure to supply disruption or external coercion.	Import dependency ratios; domestic production share; platform infrastructure ownership; standards participation index

Table 1. Three-Dimension Framework for Assessing Technological Advantage

2.2 Competitiveness and Strategic Autonomy

The European Commission's own conceptual apparatus has evolved significantly since 2019 towards an explicit embrace of strategic autonomy as a dimension of competitiveness. The 2023 Competitiveness Compass operationalises this shift by treating dependency reduction as a core competitiveness objective, not a subsidiary policy concern. This represents an important conceptual development, because it acknowledges that competitive strength in a world of geopolitical fragmentation requires not only cost efficiency and innovation dynamism, but also supply-chain resilience and the avoidance of structural vulnerabilities exploitable by external actors.

The Competitiveness Compass identifies three pillars: closing the innovation gap, jointly implementing decarbonization and competitiveness, and reducing dependencies. Each pillar generates distinct but complementary policy instruments. The innovation gap pillar focuses on R&D spending, venture capital access, and the regulatory conditions for technology commercialization. The decarbonisation pillar emphasizes industrial transformation in energy, transport, and manufacturing. The dependency reduction pillar targets critical raw materials, digital infrastructure, and strategic technology inputs.

Compass Pillar	Core Objective	Principal Policy Instruments
Closing the Innovation Gap	Increase R&D investment; improve commercialisation; deepen VC access	Horizon Europe; EIC equity fund; Capital Markets Union; patent reform
Decarbonisation & Competitiveness	Transform energy, transport, and manufacturing while maintaining market position	Net-Zero Industry Act; European Hydrogen Bank; ETS reform; NZIA targets
Reducing Dependencies	Secure supply of critical materials, digital infrastructure, and strategic technology inputs	Critical Raw Materials Act; European Chips Act; STEP; data governance; foreign subsidy screening

Table 2. European Commission Competitiveness Compass: Three Pillars and Associated Instruments

2.3 The Technology Ecosystem Concept

Rather than treating technologies as isolated assets, this article adopts an ecosystem perspective that captures the systemic character of innovation advantage. A technology ecosystem comprises the full set of actors, institutions, knowledge flows, and infrastructure elements that together enable a specific technology to be developed, manufactured, deployed, and commercialized at scale. This includes research universities and public laboratories; specialized suppliers and component manufacturers; technology-intensive firms at multiple points in the value chain; public procurement agencies; venture and growth capital providers; standards bodies; and regulatory authorities.

The ecosystem perspective has several analytical implications. It suggests that competitive advantage is often more durable when it is embedded in a complex web of relationships and capabilities rather than in any single firm or laboratory. It suggests that the loss of one element—a key supplier, a talent pool, a regulatory anchor—can cascade through the ecosystem in ways that purely asset-based assessments do not capture. And it suggests that policy interventions are more effective when they target ecosystem-level constraints rather than attempting to replicate individual firm-level capabilities.

3. Methodology

3.1 Research Design

The article employs a comparative mixed-methods design. The primary comparative axis is between the European Union, the United States, and China, chosen because these three actors collectively define the global frontier in most of the technology domains under analysis. The design combines: (a) sectoral benchmarking using quantitative innovation indicators; (b) value-chain analysis to identify points of strength and vulnerability within specific technology ecosystems; (c) dependency mapping to assess exposure to external supply disruption; and (d) policy benchmarking to compare the scale, design, and effectiveness of technology policy instruments across the three actors.

3.2 Technology Selection Criteria

Technologies were selected using five criteria developed from and consistent with the Commission's identification of strategic technologies in the STEP Regulation and the Competitiveness Compass. These criteria are applied to each technology domain using a structured three-level assessment (strong / partial / weak position) based on the available quantitative and qualitative evidence. Technologies meeting three or more of the five criteria were included in the analysis.

Criterion	Definition	Operationalisation
Strategic Relevance	Significant implications for economic productivity, military capability, environmental sustainability, or geopolitical leverage	Commission STEP priority list; NATO dual-use designations; IEA critical clean tech mapping
European Capability	European actors exhibit measurable research output, industrial capacity, or market position above global median	EPO patent share; Scopus publication rank; industry market share data; TRL distribution
Global Market Potential	Technology addressed by large and growing global markets with material economic consequences	IEA, IDC, IMARC market sizing projections 2025–2035; CAGR benchmarks
Dependency Exposure	European actors face significant dependence on external supply of critical inputs, components, or platforms	EU Observatory critical technology gap index; HHI import concentration scores
Policy Leverage	Public policy instruments can plausibly affect competitive outcomes in the sector	Historical policy effectiveness studies; presence of market failure indicators; state aid case law

Table 3. Technology Selection Criteria: Definitions and Operationalisation

The resulting selection—clean technologies (wind, electrolyzers, hydrogen), advanced materials, quantum technologies, biotechnology, industrial robotics, space systems, and advanced connectivity—reflects the Commission's own priority list while maintaining analytical tractability. Semiconductors, AI, and digital platforms are included as reference cases to contextualize areas of vulnerability alongside areas of strength.

3.3 Indicators and Data Sources

The quantitative dimension of the analysis draws on a combination of patent analytics, R&D expenditure statistics, venture capital and growth finance data, manufacturing and trade statistics, and academic publication metrics. These are complemented by firm-level data from industry associations and sectoral reports, and by qualitative evidence from Commission impact assessments, European Court of Auditors evaluations, and academic case study literature.

Indicator Category	Primary Sources	Coverage & Limitations
R&D Expenditure	Eurostat; OECD MSTI; UNESCO UIS	Classification differences introduce ~0.2–0.4% GDP measurement error
Patent Analytics	EPO PATSTAT; WIPO IP Statistics; USPTO PatentsView	Filing strategy differences limit comparability; triadic families used for quality-weighting
Venture & Growth Capital	PitchBook; Invest Europe; Crunchbase Pro; EIF Annual Report	Private-round data incomplete for China; currency conversion introduces noise
Manufacturing & Trade	Eurostat PRODCOM; UN Comtrade; ITC Trade Map; OECD TiVA	Re-export and processing trade complicate origin attribution in global value chains
Scientific Publications	Scopus; Web of Science; Nature Index; SCImago	English-language bias; field normalisation required for cross-domain comparison
Policy Assessment	European Court of Auditors; Commission Impact Assessments;	Evaluation quality varies; time-lag between policy and measurable

Indicator Category	Primary Sources	Coverage & Limitations
	OECD STI Outlook	outcome

Table 4. Analytical Indicators and Data Sources by Category

3.4 Limitations

Several methodological limitations warrant acknowledgment. First, data comparability across jurisdictions is imperfect: R&D classifications, patent regimes, and industrial output definitions differ between the EU, US, and China, introducing systematic measurement error. Second, the rapidly evolving character of frontier technologies means that any snapshot assessment carries temporal limitations; positions that appear strong in 2024 may erode or strengthen significantly by 2027. Third, the ecosystem perspective, while analytically productive, resists full quantification; many of the most important mechanisms—tacit knowledge transfer, institutional trust, ecosystem co-ordination—are not adequately captured by available indicators.

4. Europe's Strategic Strengths: Sectoral Analysis

4.1 Clean Technologies: Wind Energy and Electrolysers

Clean technology is the domain in which Europe's aggregate claim to global technological leadership is strongest and most empirically grounded. The European Commission's own assessment, reflected in multiple communications and impact assessments, describes Europe as a world leader in wind turbines and electrolysers—a characterization that withstands close scrutiny when applied to these specific industrial segments.

KEY FINDING: Europe accounts for more than one-fifth of the world's clean technology innovations and hosts the headquarters or principal R&D centres of the world's leading wind turbine manufacturers, including Vestas (Denmark), Siemens Gamesa (Spain/Germany), and Nordex (Germany). European electrolyser manufacturers hold significant shares of global capacity, particularly in PEM (proton exchange membrane) and alkaline electrolyser segments.

4.1.1 Wind Energy

The European wind energy ecosystem is characterized by deep vertical integration across the value chain. European firms design and manufacture turbine components—nacelles, blades, gearboxes, power electronics—and control the intellectual property underpinning the most advanced offshore and onshore turbine architectures. Offshore wind in particular represents a domain in which European industrial and regulatory experience substantially exceeds that of any other region. The North Sea, Baltic, and Atlantic coasts host the world's most advanced operational offshore wind capacity, and European project developers, engineering consultancies, and port infrastructure providers have accumulated decades of deployment experience that constitutes a significant barrier to entry for foreign competitors.

The principal threat to European wind leadership is not technological displacement from the US or Japan, but the emergence of Chinese wind turbine manufacturers—particularly Goldwind, Ming Yang, and CSSC Haizhuang—whose rapid domestic capacity growth and cost-competitive manufacturing have enabled entry into selected third-country markets. The Chinese advantage lies primarily in manufacturing cost and domestic market scale, not in turbine technology per se. European manufacturers retain a quality and reliability premium in offshore systems, high-

wind-class turbines, and grid-integration services. However, the cost differential is substantial enough that it poses a credible medium-term threat to European market share in price-sensitive developing economy markets.

Value Chain Segment	EU Position	Key European Actors	Competitive Risk
Turbine Design & IP	STRONG	Vestas, Siemens Gamesa, Nordex, Enercon	Chinese firms narrowing IP gap in lower-spec onshore turbines
Nacelles & Gearboxes	STRONG	Winergy, Renk, ZF Wind Power	Moderate — premium drivetrain systems retain quality premium
Blades	PARTIAL	LM Wind Power (GE-owned)	Chinese blade manufacturers scaling rapidly
Offshore Installation	STRONG	Jan De Nul, DEME, Heerema, Saipem	Low — installation vessels and expertise remain Europe-dominant
Grid Integration	STRONG	Siemens Energy, ABB, Prysmian, Nexans	Cable supply bottleneck; congestion in order books
Project Development	STRONG	Orsted, Vattenfall, RWE, Equinor, EDP	Permitting delays and cost inflation threaten pipeline

Table 5. European Position Across the Offshore Wind Energy Value Chain

4.1.2 Electrolysers and Hydrogen Systems

Electrolysers—devices that produce hydrogen by splitting water using electricity—represent a second clean technology domain in which European manufacturers hold a significant global position. The European electrolyser industry is anchored by firms including Nel (Norway), ITM Power (UK), Cummins (with European operations), and Thyssenkrupp nucera (Germany). European research institutions, including Fraunhofer ISE, CEA, and DLR, maintain world-leading R&D programs in electrolyser stack design, membrane technology, and system integration.

The hydrogen strategy embedded in the REPowerEU plan and the European Hydrogen Bank represents a substantial policy commitment to scaling this industrial segment. The European Clean Hydrogen Alliance has mapped a pipeline of projects with aggregate capacity exceeding 60 GW of electrolyser capacity by 2030—a figure that would represent a twentyfold increase from current European installed capacity. Whether this pipeline materialises depends on the resolution of three critical bottlenecks: the cost of renewable electricity inputs, the availability of patient capital for capital-intensive first-of-a-kind projects, and the development of demand-side offtake agreements that provide the revenue certainty required for project financing.

4.2 Quantum Technologies

Quantum technologies constitute one of the most strategically consequential domains in the current innovation landscape, with potential applications spanning computation, sensing, communication, and navigation. Europe's position in quantum is characterized by genuine research excellence—particularly in quantum computing hardware, quantum sensing, and quantum communication—combined with a commercialization gap that has allowed US and, to a lesser degree, Chinese actors to establish early industrial leads in certain quantum computing modalities.

KEY FINDING: The EU Quantum Flagship, with a committed budget of approximately EUR 1 billion over ten years (2018–2028), represents one of the world's largest coordinated public quantum research programs. European research institutions have produced internationally recognized contributions to superconducting qubits, trapped-ion systems, photonic quantum computing, and quantum key distribution.

The European quantum ecosystem is distributed across several national centres of excellence: the Netherlands (Delft, QuTech), Germany (Jülich, Fraunhofer IAF, University of Cologne), France (CEA, Institut d'Optique), Austria (University of Innsbruck, Vienna), and the UK. This distributed structure reflects the historically national organization of European science funding, and has produced a fragmented landscape of specialized capabilities that is scientifically productive but industrially suboptimal.

The principal European quantum advantage lies in quantum sensing and quantum communication, where European firms and institutions have achieved technology readiness levels approaching commercial deployment. Quantum key distribution (QKD) networks are operational or under active development in Germany, the Netherlands, and Austria. In quantum computing, the European position is more contested. US technology companies—IBM, Google, Microsoft, Intel—and a growing ecosystem of US quantum computing startups have established market-facing positions in gate-model quantum computing that are ahead of European equivalents.

Quantum Modality	EU TRL	EU Research Leaders	US Leaders	EU Commercialisation Gap
Superconducting Qubits	TRL 3–5	IQM (FI), FZ Jülich, Chalmers	IBM, Google	HIGH
Trapped-Ion Qubits	TRL 4–6	Univ. Innsbruck, eleQtron (DE)	IonQ, Quantinuum	MODERATE
Photonic Quantum	TRL 3–5	QuiX Quantum (NL), ICFO	PsiQuantum	MODERATE
Quantum Key Distribution	TRL 6–8	ID Quantique (CH), Toshiba EU	Quantum Xchange	LOW
Quantum Sensing	TRL 6–8	PTB (DE), Muquans (FR), Q.ANT	SandboxAQ	LOW
Quantum Computing Software	TRL 4–6	ParityQC (AT), Pasqal (FR)	Microsoft, QC Ware	HIGH

Table 6. European Quantum Technology Landscape by Modality: TRL, Key Actors, and Commercialisation Gap

4.3 Advanced Materials

Advanced materials—encompassing high-performance alloys, composites, ceramics, semiconducting materials, functional coatings, and nano-structured materials—represent a domain of deep and broadly distributed European industrial competence. European leadership in advanced materials is in many respects the least visible of the strategic strengths examined in this article, because advanced materials are typically intermediate goods embedded in finished products rather than consumer-facing technologies. This invisibility has contributed to policy under-attention, despite the centrality of materials innovation to competitive position across multiple strategic sectors.

Germany is the unambiguous centre of European advanced materials competence. The German materials science and engineering ecosystem—anchored by the Fraunhofer-Gesellschaft, the Max Planck Institute for Iron Research, the Helmholtz Association, and a dense industrial ecosystem of specialty chemicals and materials firms (BASF, Evonik, Merck KGaA, Henkel, Schott)—constitutes one of the world's two or three leading national systems in this domain. French grandes écoles and grandes établissements scientifiques contribute significantly in functional materials, nuclear materials, and photovoltaic materials. The Critical

Raw Materials Act (2023) explicitly addresses upstream dependency in lithium, cobalt, manganese, nickel, and rare earth elements.

4.4 Biotechnology

European biotechnology presents a complex picture of genuine scientific excellence, selective industrial strength, and persistent commercialization deficit. Europe is home to several of the world's leading research institutions in molecular biology, genomics, structural biology, and synthetic biology—including EMBL (European Molecular Biology Laboratory), the Wellcome Sanger Institute, and university hospitals across Germany, France, Sweden, and the Netherlands. European pharmaceutical firms—Roche, Novartis, AstraZeneca, Sanofi, GSK, Bayer—remain globally competitive in drug development and have increasing biotech capability through acquisition and internal R&D.

Policy Context: *The COVID-19 pandemic demonstrated both the potential and the limits of European biotech capacity. BioNTech's mRNA vaccine development—the most significant European biotech success of the decade—emerged from a German SME with deep university research ties but required US manufacturing partnerships (Pfizer) and US regulatory market access to achieve global scale. This encapsulates the broader European biotech dynamic: research and early innovation capacity is strong, but the institutional and capital infrastructure for rapid scale-up remains underdeveloped relative to the US biotech cluster model.*

European biotech faces three structural challenges relative to the United States. First, the European venture capital ecosystem for life sciences remains smaller and more risk-averse, resulting in later-stage funding gaps that often force European biotech companies to list on NASDAQ or seek US acquisition. Second, European drug approval pathways are less harmonised across member states for clinical trial authorisation than the single-pathway FDA process in the US. Third, European public procurement of biopharmaceuticals is highly price-sensitive, which reduces revenue certainty for innovative products.

4.5 Industrial Robotics

Industrial robotics is the technology domain in which European manufacturers hold the strongest and most durable global commercial position. Europe—specifically Germany, Switzerland, and Sweden—is home to four of the world's leading industrial robot manufacturers: KUKA (Germany, now Chinese-owned), ABB (Switzerland/Sweden), FANUC (Japan, but with major European operations), and Stäubli (Switzerland). European robot manufacturers lead in precision, safety, and integration in demanding manufacturing environments—automotive assembly, pharmaceutical production, food processing, and advanced electronics.

KEY FINDING: According to the International Federation of Robotics (IFR), Europe (EU + UK + Switzerland) accounts for approximately 27% of global industrial robot installations annually and holds a dominant position in the high-value articulated robot segment. Germany alone installs more industrial robots annually than the entire North American market.

The competitive threat to European robotics leadership comes from two directions. Chinese robot manufacturers—Siasun, ESTUN, Inovance—have achieved rapid capability growth in lower-specification industrial robots and are beginning to export into third-country markets.

More significantly, US-based companies focused on software-defined robotics and AI-powered flexible automation—including Boston Dynamics (Hyundai-owned), Figure AI, and Apptronik—are developing next-generation robotic systems that may disrupt the traditional European hardware-intensive model.

Dimension	Europe (EU+CH)	Japan	United States	China
Global robot installation share	~27%	~22%	~13%	~31%
Articulated robot market	STRONG (ABB, KUKA*)	Strong (Fanuc, Yaskawa)	Niche	Growing
Collaborative robots (cobots)	STRONG (Universal Robots)	Moderate	Moderate	Weak
AI-native / software-defined	WEAK	Moderate	STRONG (Boston Dynamics, Figure)	Developing
Robot density (per 10k workers)	DE: 415; SE: 274	399	255	392
Annual revenue (est.)	~EUR 14bn	~USD 16bn	~USD 7bn	~USD 9bn

Table 7. Industrial Robotics Competitive Snapshot (2023). *KUKA majority-owned by Chinese Midea since 2016. Source: IFR World Robotics 2024.

4.6 Space Technologies and Dual-Use Capacities

European space technology represents one of the clearest examples of public-sector-anchored technological advantage that has generated genuine industrial depth. The European Space Agency (ESA), with an annual budget exceeding EUR 9 billion in 2024, has sustained Europe's independent access to space through the Ariane and Vega launcher families and supported a broad ecosystem of satellite manufacturers, ground segment operators, and downstream service providers.

Europe's Galileo navigation system, now fully operational with 30 satellites, represents a major strategic achievement—providing European actors with independent positioning capability not reliant on the US GPS system. Copernicus, Europe's Earth observation programme, generates the world's largest open-access repository of satellite imagery data, enabling a downstream economy of observation-based services. The principal challenge facing European space is the disruption of the established launch market by SpaceX's Falcon 9 and Starship platforms, which have dramatically reduced launch costs and shifted competitive dynamics in ways that the Ariane 6 launcher is ill-equipped to match.

4.7 Advanced Connectivity

Advanced connectivity—encompassing 5G and 6G infrastructure, open radio access networks (Open RAN), satellite broadband, and sub-terahertz communication systems—is a domain of significant strategic importance and mixed European competitive position. European telecommunications equipment manufacturers once dominated global markets: Ericsson (Sweden) and Nokia (Finland) together represent the primary non-Chinese suppliers of cellular infrastructure globally, following the exclusion or restriction of Huawei and ZTE from most Western network deployments.

However, European connectivity faces a structural paradox: while European equipment manufacturers supply the world's networks, European connectivity infrastructure itself lags the US and several Asian markets in deployment density, network performance, and adoption of next-generation capabilities. For 6G—with commercial deployment expected in the early 2030s—Europe has established early research leadership through Hexa-X and Hexa-X-II projects, and

the Smart Networks and Services Joint Undertaking (SNS JU) is investing EUR 900 million in 6G R&D.

5. Comparative Benchmarking: Europe, United States, and China

5.1 Innovation Input Comparison

The most cited indicator of innovation capacity—gross domestic expenditure on R&D as a percentage of GDP—reveals a persistent European deficit relative to both the United States and, increasingly, China. The EU average R&D intensity in 2022 was 2.22 percent of GDP, compared to 3.45 percent in the United States and approximately 2.54 percent in China. The EU's 3-percent Lisbon target for R&D intensity—established in 2000—has never been achieved and has receded in plausibility relative to both US and Chinese trajectories.

The composition of R&D investment differs importantly across the three actors. In the United States, business R&D accounts for approximately 75 percent of total R&D expenditure. In China, state-directed R&D is increasingly oriented towards AI, semiconductors, advanced manufacturing, and quantum technologies. In Europe, public-sector R&D accounts for a higher share of the total than in the US or China, which reflects both the strength of European public research institutions and the relative underdevelopment of corporate R&D investment.

Economy / Region	R&D / GDP (2022)	Business R&D Share	Trend 2015–22	2030 Target
United States	3.45%	~75%	↑ +0.6pp	~3.8%
South Korea	4.93%	~79%	↑ +0.4pp	>5.0%
China	2.54%	~77%	↑ +0.8pp	3.0%+
EU-27 Average	2.22%	~64%	↑ +0.2pp	3.0%*
— Sweden	3.40%	~71%	→ stable	—
— Germany	3.13%	~68%	→ stable	—
— Austria	3.20%	~67%	↑ +0.3pp	—
— Italy	1.33%	~58%	↑ +0.2pp	—
— Romania	0.47%	~40%	→ stable	—
Japan	3.26%	~78%	→ stable	~3.5%

Table 8. R&D Intensity Benchmarking: EU versus Major Competitors (2022). *EU Lisbon/Barcelona target, never achieved. Source: OECD MSTI 2023; Eurostat.

5.2 Venture Capital and Scale-Up Financing

The financing gap between Europe and the United States is the single most consistently cited structural constraint on European technology commercialization. In 2023, US venture capital investment in technology firms totaled approximately USD 130–170 billion. European venture capital investment, while growing strongly (from EUR 12 billion in 2016 to approximately EUR 55 billion in 2022 before retracting in 2023), remains substantially smaller in absolute terms and more heavily weighted towards early-stage investment.

The European Valley of Death: *The consequence of the growth-stage financing gap is what analysts have termed the 'European Valley of Death': a segment of the innovation lifecycle between proof-of-concept validation (which European public funding systems support reasonably well) and large-scale commercial deployment (which requires capital commitments that European private markets struggle to*

provide). Many of Europe's most promising deep technology companies have been compelled to seek US listings, US strategic investors, or US acquirers to access the capital required for global scale.

Metric	United States	EU-27	China	EU Gap
Total VC invested (2022 peak)	~USD 170bn	~EUR 55bn	~USD 70bn	3:1 (US:EU)
Total VC invested (2023)	~USD 130bn	~EUR 35bn	~USD 42bn	Widening
Growth-stage (Series C+) share	~55% of total	~30% of total	~45% of total	Severe
Unicorns created (2020–2023)	~850	~230	~180	3.7:1
Pension fund allocation to PE/VC	~8–12%	~2–4%	N/A (state-led)	Structural
Average growth-stage round size	~USD 45m	~EUR 18m	~USD 28m	2.5:1
Deep tech VC share	~22%	~35%	~28%	EU leads

Table 9. Venture Capital and Growth Finance: EU–US–China Comparison (2022–2023). Sources: PitchBook; Invest Europe; EIB Investment Report 2023.

5.3 Innovation System: Full Comparison

Beyond the R&D and VC dimensions, a more comprehensive comparison across the full innovation system—encompassing platform dominance, regulatory standard-setting, industrial policy scale, and knowledge transfer infrastructure—reveals a nuanced picture in which European strengths (regulatory authority, deep tech research, precision engineering) co-exist with significant weaknesses in the digital and platform economy.

Dimension	European Union	United States	China
R&D Intensity (% GDP, 2022)	2.22% (target: 3.0%)	3.45%	2.54% (↑ rapidly)
Dominant R&D Funder	Mixed public/private; national fragmentation	Large corporate + Federal (DARPA, NIH, DOE)	State-directed + national champions
Venture Capital Ecosystem	Growing; growth-stage deficit; EUR ~35–55bn/yr	Dominant globally; USD ~130–170bn/yr	State-influenced; retreating from tech post-2021
Platform / Hyperscale Leaders	None in top-20 global tech firms by mkt cap	Google, Microsoft, Amazon, Apple, Meta, Nvidia	Alibaba, Tencent, Baidu, ByteDance (domestic)
Industrial Policy Scale	EUR 43bn (Chips); EUR 95bn (HE); NZIA (reg.)	USD 52bn (CHIPS); USD 369bn (IRA)	Multi-hundred billion USD; Made in China 2025
Regulatory Standard-Setting Power	DOMINANT globally (GDPR, AI Act, DMA)	Strong sector-specific (FDA, FCC, SEC)	Domestic; growing in Global South via BRI
Deep Tech Patent Share (EPO, 2022)	~22% of global triadic families	~28%	~19% (fast growing)
University–Industry Knowledge Transfer	Improving; still below US levels	Strong; Stanford/MIT model established	State-directed; improving rapidly

Table 10. Innovation System Comparison: European Union, United States, and China across Key Dimensions

5.4 Strategic Dependencies: Mapping European Vulnerabilities

Strategic dependencies represent the inverse of competitive strength: they are the points in Europe's technology ecosystem where external actors hold leverage over European actors' capacity to produce, deploy, or operate critical technologies. The EU Observatory of Critical Technologies has catalogued these dependencies systematically, and the results are sobering across several domains—particularly in upstream materials, advanced semiconductors, and digital infrastructure.

Dependency Area	Primary Source	EU Import Dependency	Risk Level	Mitigation Instrument
Rare Earth Elements	China (>85% refined)	>90%	CRITICAL	Critical Raw Materials Act; EIT RawMaterials
Battery-grade Lithium	Chile/Australia raw; China refined	>85% refined	CRITICAL	CRMA strategic projects; Vulcan Energy (DE)
Advanced Semiconductors (<10nm)	TSMC (Taiwan); Samsung (Korea)	~100%	CRITICAL	European Chips Act; TSMC Dresden (2027)
Cloud Computing Infrastructure	AWS, Microsoft Azure, Google Cloud	~65–70% by revenue	HIGH	GAIA-X; EU Cloud Rulebook; Sovereign Cloud
AI Foundation Models	US (OpenAI/MS, Google, Anthropic)	>95% frontier models	HIGH	EU AI Act; Mistral (FR); Aleph Alpha (DE)
Solar PV Modules	China (~90% global mfg)	>80%	HIGH	NZIA; Net-Zero Industry Act domestic targets
EV Batteries (cells)	China, South Korea, Japan	~70% cells imported	HIGH	IPCEI on Batteries; Northvolt; ACC; CATL DE
Space Launch Capacity	SpaceX (US) — Ariane 6 delay gap	Transitional 2023–25	MODERATE	ESA budget increase; NewSpace support

Table 11. European Strategic Technology Dependency Map: Principal Vulnerabilities and Mitigation Instruments

5.5 China's Industrial Policy Challenge

China's industrial policy model—characterized by state-directed capital allocation at scale, domestic market protection that allows national champions to achieve cost-competitive manufacturing volumes, and aggressive technology acquisition through inward investment and partnership—represents a fundamentally different competitive challenge than the US technology ecosystem. The appropriate European response to Chinese industrial competition differs by sector.

In clean technology—particularly solar photovoltaics and, increasingly, wind turbines, batteries, and electric vehicles—Chinese state support has enabled manufacturing cost positions that European producers cannot match without equivalent public support. The EU's anti-dumping and anti-subsidy investigations in solar panels and electric vehicles reflect a policy judgement that market-access reciprocity norms have been violated, justifying protective measures.

6. Structural Constraints on European Technology Scale-Up

6.1 Market Fragmentation

The single most persistent structural constraint on European technology commercialisation is the fragmentation of European markets along national lines. Despite decades of single market integration, European technology companies face meaningfully higher costs and complexity in scaling across member states than US companies face in scaling across US states. These frictions operate at multiple levels: regulatory divergence (different national transpositions of EU directives), language and cultural heterogeneity, fragmented digital payment systems and identity verification, diverse national procurement norms, and different national standards or certification requirements in specific sectors.

The consequence of market fragmentation is that European technology firms must achieve profitability in a subset of European national markets before attempting pan-European scale—a process that is slower, more expensive, and more management-intensive than the equivalent process for US firms serving a genuinely integrated domestic market of 330 million relatively homogeneous consumers.

6.2 Regulatory Complexity and the Innovation Paradox

European regulatory authority—the 'Brussels Effect' whereby EU standards shape global product design—is simultaneously one of Europe's strongest strategic assets and a source of domestic innovation friction. The EU's early mover advantage in data protection (GDPR), AI governance (EU AI Act), digital market regulation (DMA, DSA), and product safety has positioned European regulators as global standard-setters. When European standards are adopted internationally, they confer competitive advantages on firms that have already adapted to meet them—effectively exporting compliance costs to foreign competitors.

However, the regulatory process also imposes real costs and delays on European innovators, particularly in sectors where the pace of regulatory review does not match the pace of technological development. Clinical trial approval timelines in pharmaceuticals, permitting delays in renewable energy and industrial infrastructure, and product certification timelines in advanced manufacturing create systematic disadvantages relative to the faster market-access environment available to US competitors.

6.3 Skills and Talent

Europe faces a structural talent challenge in specific high-demand technology domains. The demand for engineers, data scientists, quantum physicists, advanced materials scientists, and bioprocess engineers substantially exceeds domestic supply in most European countries, and the global competition for this talent—particularly from US technology firms offering compensation packages that European employers rarely match—results in persistent net outflows from European research and technology ecosystems.

The talent challenge is compounded by the mismatch between European educational systems—which produce strong foundational science and engineering graduates—and the practical skills most demanded by high-growth technology firms, particularly in software engineering, AI application development, and entrepreneurial management.

Constraint	Mechanism of Impact	Severity	EU Policy Response
Market Fragmentation	27 regulatory environments; language heterogeneity; divergent procurement norms raise cross-border scaling costs	HIGH	Savings & Investments Union; DSA/DMA; harmonised permitting

Constraint	Mechanism of Impact	Severity	EU Policy Response
Growth-Stage Capital Deficit	European Valley of Death forces US listing or acquisition; depletes domestic ecosystem	HIGH	Capital Markets Union; ELTIF 2.0; EIC equity; pension fund reform
Regulatory Complexity	Cumulative compliance burden from overlapping EU and national regulation increases costs and slows market entry	HIGH	Simplification Omnibus; one-in-one-out principle; sandbox regimes
Technology Talent Gap	Brain drain to US tech sector; insufficient STEM graduates in AI, quantum, and advanced engineering	MODERATE	European Research Area talent mobility; STEM investment; Blue Card reform
Platform Dependency	Reliance on US cloud, AI, and digital infrastructure creates systemic vulnerability and reduces data sovereignty	HIGH	GAIA-X; EU Cloud Rulebook; AI Act; European Data Act
Permitting & Administrative Delay	Renewable energy, semiconductor fab, and infrastructure projects face 5–10 year timelines, deterring investment	MODERATE	NZIA permitting reform; REPowerEU emergency permits; STEP fast-track
Industrial Policy Incoherence	27 national strategies compete for same investments; EU-level coordination incomplete; state aid distortions	MODERATE	STEP; updated state aid frameworks; IPCEI coordination mechanism

Table 12. Structural Constraints on European Technology Scale-Up: Mechanism, Severity, and Policy Response

7. Policy Conditions for Sustaining European Technological Advantage

7.1 Industrial Policy Architecture

The return of industrial policy as an acceptable instrument of technology strategy—after decades of suppression in mainstream economic policy orthodoxy—is perhaps the most significant policy-environment shift of the current decade. The US CHIPS and Science Act (USD 52 billion in direct semiconductor subsidies), the Inflation Reduction Act (USD 369 billion in clean energy incentives), and China's consistent deployment of state-directed capital in strategic technology sectors have created a new competitive landscape in which European adherence to subsidy restraint norms imposed market disadvantages in key sectors.

Europe's response—through STEP, IPCEI (Important Projects of Common European Interest), the European Chips Act, the NZIA, and the Critical Raw Materials Act—represents a substantive, if belated, embrace of strategic industrial policy. The architecture is complex but coherent in intent: STEP provides a financial framework for directing EU funds towards strategic technologies; IPCEI enables member states to provide state aid at scale in specific value chains; the sector-specific acts establish domestic production targets and create demand-side incentives.

Instrument	Budget / Scale	Technology Focus	Mechanism	Key Limitation
Horizon Europe (2021–	EUR 95.5bn	All domains; KDT JU, SNS JU, Quantum	Competitive grants;	Low TRL focus; slow disbursement

Instrument	Budget / Scale	Technology Focus	Mechanism	Key Limitation
Instrument 27)		Flagship, ERC	consortium-based	
European Innovation Council (EIC)	EUR 10bn	Deep tech; climate; health; digital	Grants + equity co-investment; Accelerator	Equity mandate slow to deploy
STEP (Strategic Technologies)	EUR 1.5bn direct + leverage	Digital, clean, biotech; EU sovereignty criteria	Grants; loans; guarantees via existing EU funds	Small vs. US CHIPS Act scale
European Chips Act	EUR 43bn public+private	Semiconductors; design; advanced fab	State aid facilitation; IPCEI; research hubs	20% market share target ambitious
Net-Zero Industry Act (NZIA)	Regulatory; no direct budget	Wind, solar, batteries, heat pumps, CCS, H ₂	40% domestic content targets; permitting reform	Enforcement across 27 member states
European Hydrogen Bank	EUR 3bn (initial auctions)	Green hydrogen production and infrastructure	Competitive auctions; fixed premium contracts	Demand-side offtake underdeveloped
Critical Raw Materials Act	Regulatory + EIB finance	34 critical raw materials; mining, processing, recycling	Strategic project status; domestic benchmarks	Long lead times for new mines
IPCEIs	EUR 10bn+ (batteries, H₂, cloud, micro)	Batteries; H ₂ ; cloud; microelectronics	Member state state aid; transnational consortia	Co-ordination complexity; variable commitment

Table 13. Principal EU Policy Instruments for Strategic Technologies: Scale, Focus, and Limitations (2024–2027 framework)

7.2 Capital Market Reform

The Capital Markets Union and its successor Savings and Investments Union represent the most structurally important long-term policy initiative for European technology competitiveness, because they address the fundamental mechanism by which European technology firms access the growth capital needed for global scale. The evidence strongly suggests that European institutional investors—pension funds, insurance companies, endowments—have historically underallocated to technology equity and venture capital relative to US and Canadian institutional investors, resulting in a structural underprovision of patient capital.

Addressing this requires reform across several dimensions: harmonised fund regulation that reduces cross-border friction for pan-European VC funds; revised Solvency II and pension fund regulations that do not inappropriately penalize long-duration illiquid investments in technology equity; development of pan-European fund-of-funds vehicles that can aggregate institutional capital at sufficient scale; and the creation of a genuinely integrated European public equity market for technology companies.

7.3 Research and Innovation Infrastructure

Horizon Europe, the EU's flagship R&D programme with a budget of EUR 95.5 billion for 2021–2027, is the world's largest multinational public research funding programme. This research infrastructure has underpinned European scientific excellence and has created significant cross-border research collaboration networks. The challenge is to better connect this infrastructure to the commercialization pathway—to bridge the gap between ERC-funded frontier research and the IP-protected prototype development funded by industry.

Increasing the proportion of Horizon Europe funding allocated to Technology Readiness Levels 4–7 (bridging from proof-of-concept to prototype) would address the 'valley of death' in technology development. Reforming EU intellectual property frameworks to make it easier for publicly-funded research outputs to be licensed to European SMEs and startups would improve domestic commercialization rates.

7.4 Standards and Regulatory Strategy

Europe's power to shape global technology standards through its regulatory authority is a unique strategic asset that has been underexploited as an active instrument of industrial policy. The Brussels Effect operates most powerfully when European regulatory standards are adopted by foreign jurisdictions either because of market access requirements or because of regulatory contagion. An active standards strategy for European technology would involve early engagement in international standards-setting bodies (ISO, IEC, ITU, IEEE) to ensure European technical positions are embedded in emerging standards before they are finalised.

8. Strategic Conclusions

8.1 Strategic Postures Across Technology Domains

The analysis presented in this article supports a qualified optimism about European technological competitiveness—qualified because the advantages are real but concentrated, and because the structural conditions for translating them into durable global leadership are only partially in place. Rather than treating all technology domains uniformly, the evidence supports differentiated strategic postures—Lead, Defend, Catch Up, or Resilience—each implying a different mix of policy instruments and investment priorities.

Technology Domain	Strategic Posture	Competitive Basis	Principal Risk	Priority Action
Wind Energy	LEAD	Deep offshore ecosystem; engineering quality; standards authority; EU demand scale	Chinese cost competition in emerging markets	NZIA; permitting reform
Electrolysers / H ₂	LEAD	First-mover IP; Hydrogen Bank demand pull; industrial chemistry integration	Green H ₂ cost vs. fossil fuels	Hydrogen Bank auctions; RFNBO rules
Advanced Materials	LEAD	German/Nordic cluster depth; specialty chemistry; cross-sector demand	CRM upstream dependency; talent	CRMA; processing investment
Industrial Robotics	LEAD	Precision manufacturing; systems integration; cobot innovation	AI-native robotics challengers (US)	AI integration R&D; EUROBENCH
Quantum Sensing / QKD	LEAD	High TRL; near-term commercialization; EU sovereign comms need	Scale-up capital; US sensor incumbents	Quantum Flagship Transition Fund
Space Systems	DEFEND	Galileo/Copernicus strategic infrastructure; downstream service economy	SpaceX launch cost disruption	ESA reusability; NewSpace support

Technology Domain	Strategic Posture	Competitive Basis	Principal Risk	Priority Action
Biotechnology	DEFEND	EMBL; pharma heritage; industrial biotech clusters (NL, DK, DE)	US VC advantage; slow clinical trials	BioTech Act; EIC biotech equity
Advanced Connectivity	DEFEND	Ericsson/Nokia equipment duopoly; 6G research lead	Open RAN disruption; US hyperscaler integration	SNS JU; spectrum harmonisation
Quantum Computing (gate)	CATCH UP	Strong research (Innsbruck, Delft, Jülich); 3 credible European startups	IBM/Google compute advantages; capital gap	EuroHPC quantum nodes; EIC equity
Semiconductors (advanced fab)	CATCH UP	ASML monopoly in EUV; Infineon, STMicro in mature nodes	TSMC Dresden execution risk; talent	Chips Act; EUV supply leverage
AI Foundation Models	RESILIENCE	Strong academic AI; Mistral, Aleph Alpha emerging; regulatory shaping power	Compute deficit; US capital and talent dominance	AI Act; domain-specific models; EuroHPC
Digital Platforms / Cloud	RESILIENCE	Regulatory leverage (GDPR, DMA, DSA); public sector demand	US hyperscaler dominance structural; lock-in deep	GAIA-X; portability; sovereign cloud

Table 14. Strategic Conclusions Grid. Posture: LEAD = defensible global leadership; DEFEND = protect existing position; CATCH UP = close targeted gap; RESILIENCE = reduce dependency, accept non-leadership.

8.2 Areas of Defensible Leadership

The technology domains in which Europe can most plausibly sustain global leadership or strategic differentiation over the coming decade include wind energy and offshore systems; industrial robotics and precision automation; electrolyser and hydrogen infrastructure; space observation and navigation services; quantum sensing and communication; and advanced materials and specialty chemicals. Across these domains, the common denominator is the intersection of engineering quality, standards authority, and system integration—characteristics that reflect accumulated industrial and institutional capital not easily replicated by new entrants.

8.3 Areas of Strategic Vulnerability

Equally important is honest identification of domains where European actors should prioritise resilience and dependency reduction rather than aspiring to global technology leadership. Digital platforms and hyperscale cloud are dominated by US firms in a manner that is structural and durable. AI foundation models and large-scale compute face US capital and infrastructure advantages that are significant. Battery cell manufacturing faces cost-structure challenges relative to Chinese producers that require sustained demand-side support.

8.4 The Coherence Imperative

The overarching conclusion of this analysis is that European technological competitiveness is not primarily constrained by a lack of ideas, researchers, or industrial tradition. It is constrained by incoherence—the failure to align, at the system level, the research infrastructure, the capital environment, the regulatory framework, the talent pipeline, and the industrial policy

instruments that together determine whether scientific excellence is converted into industrial leadership.

Coherence in this context means alignment between research priorities and industrial needs; coordination between national industrial policies and EU-level instruments to avoid duplication; sequencing of demand-creation and supply-side support to de-risk investment at scale; and strategic patience—the willingness to sustain commitments across political cycles in domains where competitive advantage is built over decades.

Europe's most successful technology ecosystems—the German engineering cluster, the Scandinavian clean energy ecosystem, the Dutch semiconductor equipment supply chain (ASML), the Nordic quantum research cluster—share a common characteristic: they reflect sustained, coherent, multi-decade investment in human capital, research infrastructure, and industrial capability by public and private actors acting in systematic alignment. The policy challenge is to replicate this coherence at the European scale.

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Annex A: Technology Matrix

The following matrix assesses the thirteen principal technology domains examined in this article across the five analytical criteria defined in Section 3.2. Ratings: ★ = weak; ★★ = partial; ★★★ = strong. Colour coding: green = STRONG, yellow = DEVELOPING, orange = PARTIAL, red = WEAK.

Technology	Strategic Relevance	EU Capability	Market Potential	Dependency Exposure	Policy Leverage	Overall Assessment
Wind Energy	★★★	★★★	★★★	★★	★★★	STRONG
Electrolysers / H ₂	★★★	★★★	★★★	★★	★★★	STRONG
Advanced Materials	★★★	★★★	★★	★★★	★★	STRONG
Industrial Robotics	★★★	★★★	★★★	★★	★★	STRONG
Quantum Sensing / QKD	★★★	★★★	★★	★★	★★★	STRONG
Quantum Computing	★★★	★★	★★★	★★	★★★	DEVELOPING

Technology	Strategic Relevance	EU Capability	Market Potential	Dependency Exposure	Policy Leverage	Overall Assessment
Semiconductors	★★★	★	★★★★	★★★★	★★★★	DEVELOPING
Battery Cells	★★★	★★	★★★★	★★★★	★★★★	DEVELOPING
Biotechnology	★★★	★★	★★★★	★★	★★	PARTIAL
Space Systems	★★★	★★	★★	★★	★★★★	PARTIAL
Advanced Connectivity	★★★	★★	★★★★	★★★★	★★★★	PARTIAL
AI / Foundation Models	★★★	★	★★★★	★★★★	★★★★	WEAK
Digital Platforms	★★★	★	★★★★	★★★★	★★★★	WEAK

Table A1. Technology Matrix — all ratings reflect the state of European competitive position as assessed in the primary literature available to 2024–2025.