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Shaping resilience: Defend. Secure. Innovate.

February 2025

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Foreword

In the face of evolving security threats, European NATO countries are striving to increase the impact of their defense spending to deter conflict. The need to manage defense investments wisely will ensure they maximize the benefits for Europe's security and resilience. The trade-offs that governments of European NATO countries could be faced with revolve around three categories: replenishing stocks and supplies quickly, improving equipment availability and mission readiness, and developing new capabilities to maintain technological excellence.

In this compendium, we focus mainly on the third of these categories. The articles in the compendium highlight the role that innovation and technology can play in delivering impact from defense investment. They also analyze how commercial markets adjacent to defense can help ramp up innovation and efficiency.

The compendium covers:

— **The role of defense tech start-ups.** Europe can foster a robust environment in which its innovation potential can scale. It is crucial to address funding gaps, attract talent, and streamline processes to boost the European defense tech start-up ecosystem.

— **How to create a modernized defense frontier.** Scaling technologies such as AI and quantum computing takes more than funding; it needs to be driven by public and private investments. It requires collaboration across venture capital firms, start-ups, government labs, allied innovation units, and the traditional defense industrial base, capturing value from what is estimated to be a more than $250 billion opportunity.

— **The role of AI and quantum in defense innovation.** An interview with Patrice Caine, CEO of Thales, in which he discusses the importance of innovation in the defense sector, highlighting two critical technologies and the capabilities required to harness their potential.

— **The significance of maintenance, repair, and overhaul (MRO).** MRO can play a role in improving the availability of mission-ready systems in a cost-effective way. As inventories of defense equipment expand, age, and increase in complexity, incumbent and new providers of MRO services can, through collaboration and utilizing new technologies, improve their operations and support military customers in enhancing resilience and readiness.

— **How defense spending in Europe is evolving.** European NATO countries are increasing their defense spending amid ongoing debate about the budget targets. We analyze how targeted defense spending could impact defense outputs and readiness.

In February 2024, *The future of European defense and security* outlined the challenges associated with the lack of scale and the fragmentation of the European defense industry, as well as the need to seize innovation and talent imperatives. Europe is currently faced with active conflicts on its doorstep and novel hybrid threats against its critical infrastructure and economy. In this context, innovation will be a key enabler for the European defense industrial base as it seeks ways to better collaborate, drive more productivity, build scale, and ensure its industrial competitiveness.

David Chinn
Senior Partner
Tel Aviv

Hugues Lavandier
Senior Partner
Paris

Nadine Grießmann
Client Activation Director
Berlin

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European defense tech start-ups: In it for the long run?

A defense tech start-up ecosystem is developing in Europe as countries look to boost innovation in defense capabilities.

This article is a collaborative effort by David Chinn and Jakob Stöber, with Hannes Fischer, Jessica Köhler, Katharina Wagner, and Nadine Grießmann, representing views from McKinsey's Aerospace & Defense Practice.

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European NATO countries are shifting their defense priorities and rearming to meet new threats on European borders and increase defense spending.[1] To achieve these objectives, they are discussing three key areas: replenishing and expanding stocks of weapons systems and munitions, improving mission readiness by increasing the availability of existing weapons systems, and developing new capabilities to stay at the forefront of technology as battlefield lessons emerge and opportunities arise—sparked by innovation.

While European governments will likely seek to focus their existing defense industrial base around the first two priorities, new industrial options—including start-ups and private capital funding—could play a major role in the third area of maintaining an edge in technology. An expert on the topic who we recently interviewed suggested that a balanced approach that incorporates both the agility of start-ups and the established capabilities of traditional defense players could be essential as countries increase spending to meet defense needs.[2]

In this article, we explore the current state of the European defense technology landscape and how start-ups can help boost innovative solutions for countries' defense readiness and resilience (see sidebar, "Our methodology").

Learning from the US ecosystem

The future battlefield could look very different: Technological advancements from the civilian commercial world—including satellite constellations, first-person view (FPV) drones, and AI—are rapidly being adopted by military forces. Geopolitical instability, particularly the war in Ukraine, has accelerated this trend.[3] However, military leaders of European NATO countries are facing challenges in adopting these new technologies, including those already successfully deployed in Ukraine, and building new capabilities.

As we have written before, start-ups and investors are actively seeking to meet these needs—both in Europe and the United States.[4] But as the data in Exhibit 1 show, the emerging European defense tech start-up ecosystem is about five years behind the United States' in terms of maturity. European nations can learn from the United States' experience and accelerate their own start-up ecosystem to improve the development of innovative defense capabilities.

[1] NATO Secretary General Mark Rutte, "To prevent war, NATO must spend more," Speech at the Concert Noble, Brussels, NATO, December 12, 2024.
[2] "Innovation at Thales: An interview with Patrice Caine," McKinsey, February 2025; "EU defense spending hits new records in 2023, 2024," European Defense Agency, December 4, 2024.
[3] "Emerging and disruptive technologies," NATO, August 8, 2024.
[4] Jess Klempner, Christian Rodriguez, and Dale Swartz, "A rising wave of tech disruptors: The future of defense innovation?," McKinsey, February 22, 2024.

Our methodology

We examined the European defense technology landscape, drawing from multiple sources, including a proprietary McKinsey database with more than 130 European start-ups, supplemented by PitchBook data and McKinsey's internal knowledge. Additionally, we conducted a survey among investors and start-ups, complemented by in-depth interviews with start-up leaders and venture capitalists.

This comprehensive data collection formed a robust foundation for analyzing the current state of the European defense tech ecosystem, including technological focus areas, the number of start-ups, sources of funding, and identifying key areas for improvement.

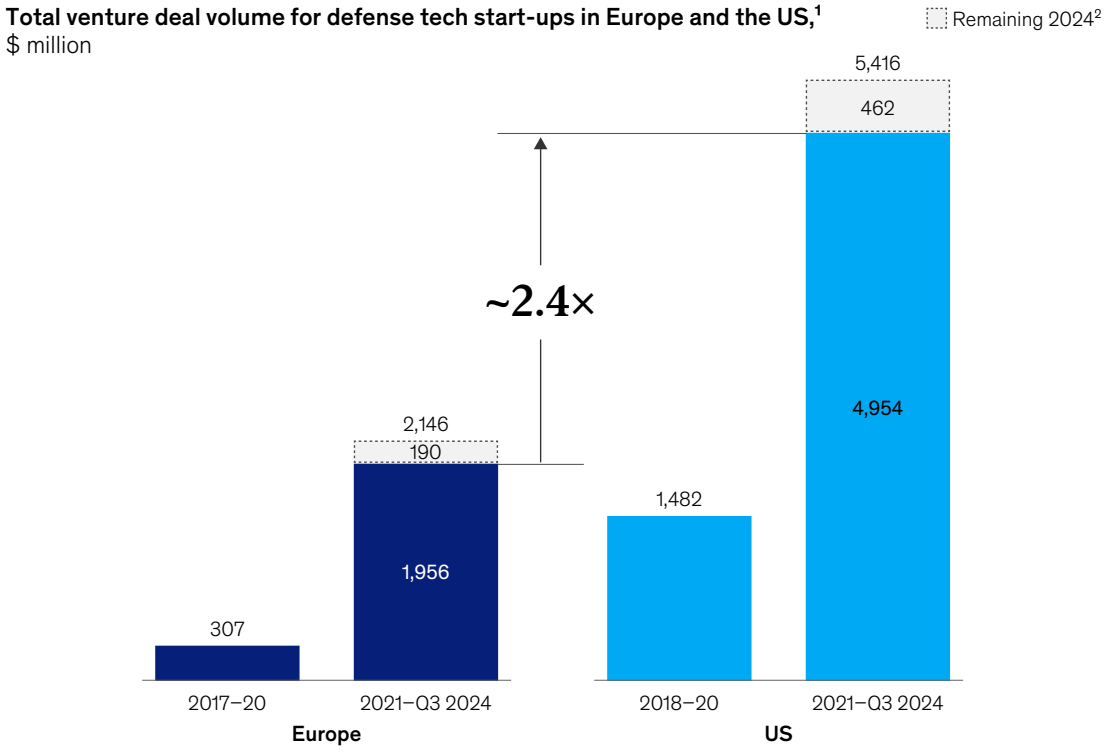
We analyzed the European tech start-up funding environment to determine how it differs from the United States and what could accelerate its development. Four themes emerged:

Differing levels of maturity. The United States has a more mature defense start-up environment, which is reflected in the volume of capital deployed, the age of the more mature and scaled companies, as well as the number of completed funding rounds (two to four times more rounds in the United States than in Europe) (Exhibit 1). This is largely due to the deeper venture markets in the United States, which are benefiting from the Defense Innovation Unit (DIU), which—ten years after inception—is awarding larger, nine-digit contracts today, stimulating further investment and scale. Unlike in Europe, an increasing number of US companies, such as Anduril and Palantir, have emerged as significant global players and are even beginning to act as primes or form consortiums independent of established players. Additionally, talent with expertise from more established defense tech players in the United States have left those companies and founded new US start-ups, further boosting the ecosystem.

In addition, the environment in which European and US start-ups are developing differs greatly. European start-ups' geographical proximity to the war in Ukraine has accelerated their development—from idea to deployment with accelerated learning due to battlefield lessons—which could enable European defense start-ups to close the gap to

Exhibit 1

The US deal volume for defense tech start-ups is approximately 2.4 times greater than in Europe, showing significant growth opportunities.



[1]Includes venture capitalists, incubators, business angels, and other venture funding; excludes private equity and corporate funding.
[2]Based on data only available until November 2024.
Source: McKinsey analysis, leveraging data by PitchBook, Inc.

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their US peers or even emerge as the innovation leader in some technology areas.

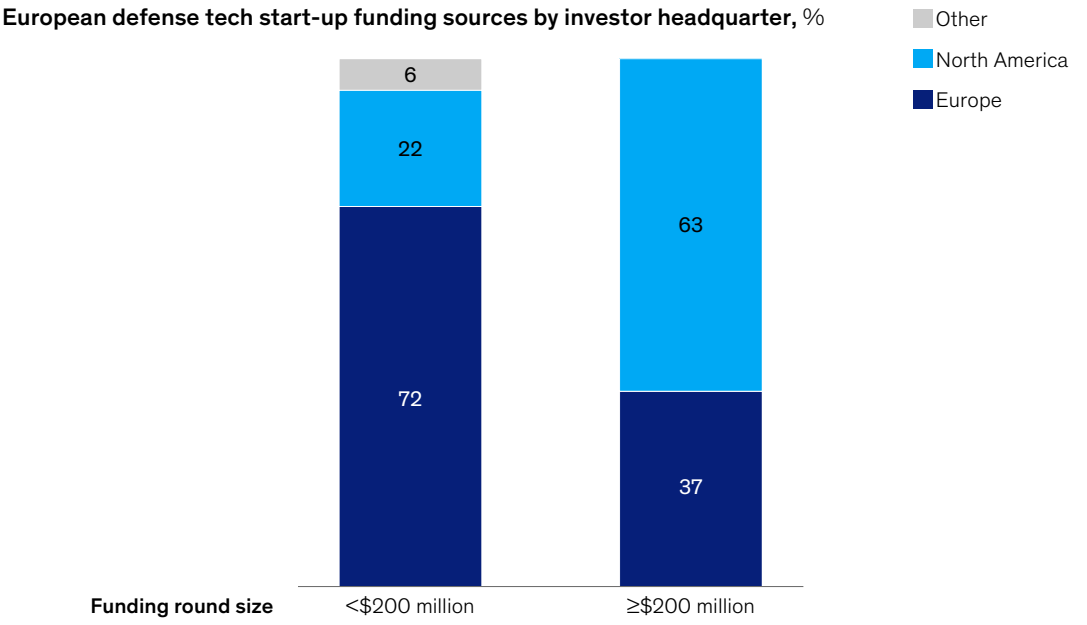
A significant increase in funding. Our analysis shows that investment into European defense tech start-ups has increased by over 500 percent in the 2021 to 2024 period compared to the preceding three years. The number of venture capital (VC) investors is growing, too, highlighting the expansion of the ecosystem. These include defense-focused investors, for instance, D3, Decisive Point, and Tholus Capital; more generalist investors such as Lakestar; and corporate VC funds; as well as public funds (for example, the NATO Innovation Fund) and national initiatives such as Ukraine's Brave1.

A gap in European capital for later-stage rounds. On the whole, European deep-tech start-ups struggle to secure late-stage funding from domestic investors, with the share of capital from Asian and United States' investors rising to nearly 50 percent at these stages.[5] This trend is mirrored in the defense tech sector, where the growth in early-stage funding described above is not mirrored in later stages. Here, US investors dominate larger, later-stage rounds, providing more than 60 percent of the capital in funding rounds exceeding $200 million (Exhibit 2).[6] This is supported by our survey data, which confirms that a significant percentage of start-ups find it easier to secure large-scale funding from US investors than European ones. And despite

[5] *The 2023 European deep tech report,* a joint report by Dealroom, Lakestar, and Walden Catalyst, 2023.
[6] "Investment: Taking the pulse of European competitiveness," McKinsey Global Institute, June 20, 2024.

Exhibit 2

Larger funding rounds for European defense tech start-ups are dominated by US investors.



Note: Considering all recorded funding rounds between 2016 and Q3 2024.
Source: McKinsey analysis, leveraging data by PitchBook, Inc.

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the existence of European defense innovation structures, limited budgets often prevent start-ups from securing large-scale contracts that are essential for their growth.

Crowning the winners with capital. When examining the funding dynamics in Europe, our analysis reveals that each application category is dominated by a single, large start-up, which often receives more than 50 percent of all funding in a category (Exhibit 3). This phenomenon is not unique to Europe (where, for example, Helsing, an AI-focused defense tech unicorn, has achieved remarkable prominence)[7]; it is also observed in the United States, where companies such as Anduril, Epirus, and Saronic lead their respective sectors in terms of funding that they have attracted.

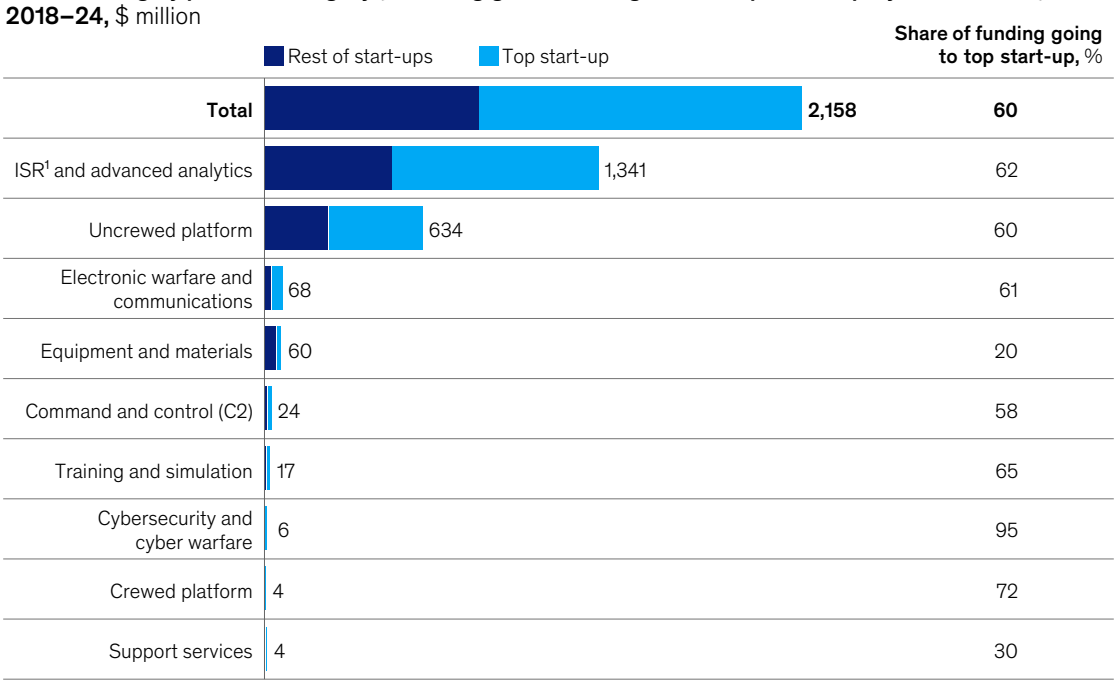
In interviews, investors expressed a clear preference for identifying and supporting these leading companies early on, effectively seeking to "crown the winners with capital." Moreover, the specific dynamics of the defense market, especially customers' understandable focus on reliability and trustworthiness, may contribute to this pattern: Once a start-up has earned the trust of end users and the procurement agency, these established relationships can serve as a competitive advantage, effectively creating a barrier to entry for potential competitors.[8]

[7] Sylvia Pfeifer, "European AI specialist Helsing unveils attack drone," *The Financial Times*, December 2, 2024.
[8] Brian Steckman, "My view from the CRO perspective: The network effect to me is actually trust in Anduril," Not Boring, October 2023.

Exhibit 3

European defense tech start-ups have received over $2 billion in funding since 2018, with a large percentage going to the top start-up.

Total funding by product category (including government grants and private equity investments), 2018–24, $ million



Note: Companies with disclosed funding. Figures may not sum, because of rounding.
[1]Intelligence, surveillance, and reconnaissance.
Source: McKinsey analysis, leveraging data by PitchBook, Inc.

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Nevertheless, the defense tech start-up ecosystem is still young, even in the United States. With a typical life cycle of ten to 15 years for the maturation of VC-funded companies and very few start-ups more than five years old, the evolution of the sector is far from clear.

Boosting the European defense tech start-up ecosystem

To further unlock the potential of European defense tech start-ups and accelerate the growth of the ecosystem, stakeholders could consider decisive action in various areas. The order of these actions does not reflect their prioritization or importance.

1. Shift public perception to attract potential founders to defense-related challenges

Despite their growth, European defense tech start-ups still only accounted for 1.8 percent of Europe's VC funding in 2024.[9] Many potential deep-tech founders and start-up employees view dual-use or military cases as "off limits," hindering company formation and shrinking the available talent pool. Shifting public perception to view defense as central to Europe's security and resilience could help attract more founders. Public institutions could consider how to address the explicit and implicit constraints which are inhibiting research with military relevance and funding for such research. This could help to increase the body of research available for industrialization and signal public support to researchers for these efforts.

Investors may consider inspiring potential founders by publicizing start-up success cases that highlight the link between purpose, prosperity, and strengthening the defense capabilities of European NATO countries. They could also seek to encourage military veterans to become founders, who could bring their experience to launch defense tech companies.

Military reserve programs could be a way to make the roles of the armed forces more accessible to civilians (and for them to understand the challenges). This could also be done through what is being referred to as "total defense" approaches, modeled after practices in Scandinavian countries such as Sweden.[10] Governments and industry leaders could strengthen support systems for founders by establishing and funding accelerators and incubators with dedicated defense tech programs.

2. Adapt the incentive system to attract funders to defense-related businesses

Many start-ups struggle to secure VC and growth investment due to regulatory requirements and limited pools of potential capital. For example, limited partner investors—both public and private—often prohibit investments in lethal or purely military technologies. By addressing the challenges that cause these investment constraints, available capital could be expanded, and the ecosystem growth could be accelerated. The issue of insufficient capital is twofold, involving both private and public capital. Potential measures include:

For private capital:

- While investors are changing their policy statements, some governments and the European Union are already discussing the scope of the official definitions of environmental, societal, and governance (ESG) criteria and adapting them to explicitly include defense and dual-use technologies.[11] These changes could also support start-ups in building and maintaining relationships with banks.

- Governments could explore capital attraction tools, such as tax incentives, as a way to motivate private investors to allocate more resources to later-stage start-ups.

- Private investors could revisit limited partnership (LP) agreements to remove restrictions or

[9] "The state of defence investment 2024—resilience builders in NATO & Europe," Dealroom, September 26, 2024.
[10] Sweden's total defense involves the whole of society, integrating both military and civil defense to prepare for various threats, thereby increasing civilian involvement and understanding of defense efforts.
[11] For example, the European Commission is considering amendments to the EU Taxonomy to clarify the inclusion of defense under sustainable investments, and France has been vocal about redefining ESG to include national security considerations. *Strengthening the EDTIB's access to finance and its ability to contribute to peace, stability, and sustainability in Europe,* European Defence Agency, November 14, 2023; *National strategic review 2022*, Republic of France, 2022.

consider establishing subfund structures that cater to the needs of different LPs rather than adopting the most restrictive common denominator. This would allow investors who are navigating regulatory constraints, such as pension funds and insurance companies, to participate in various dual-use investments and more flexibly adjust their stance as guardrails change.

For public capital:

— National and multilateral institutions could adapt the requirements for public funding vehicles—such as the European Investment Fund (EIF) and European sovereign wealth funds—to allow a broader range of defense investments.

— Governments could make investment in defense VC funds more attractive by providing nondilutive capital to defense start-ups and offering low-cost leverage to VCs, similar to the approach taken by the Office of Strategic Capital (OSC) in the United States.

3. Adapt procurement mechanisms to access innovative solutions from a wider supply base

The government procurement processes associated with defense programs can be complicated, country-specific, and administration-heavy, placing high costs, lengthy procedures, and hard-to-meet requirements on young companies that lack the resources and experience to navigate such processes. Current European procurement systems often operate on very long cycles, which can be incompatible with the fast-paced, iterative nature of venture-backed innovation. To work effectively with start-ups, a significant cultural shift toward more agile procurement processes is needed.

Multiple start-ups have raised concerns about "innovation theater" that captures public attention without allocating resources at the scale required to achieve significant revenue growth.[12] In addition, the fragmented procurement environment in Europe is a significant disadvantage for defense start-ups compared to the unified US market, as the start-ups have to deal with individual nations sourcing from domestic, regional, and global suppliers, with additional requirements to meet different regulations in each country.[13]

Measures can be taken by procurement agencies, governments, and end users to address these challenges and build a robust European defense ecosystem. These could include procurement agencies establishing dedicated innovation units with their own contracting staff, similar to, for example, the DIU, to speed up access to innovative solutions and support start-ups to meet growing demand.[14]

In addition, governments could ensure that their budgets allow for evolution from prototype to larger-scale purchases with visible pathways. Investors are clear that this is essential for start-ups to raise capital beyond progress in achieving procurement stage gates.

4. Strengthen collaboration between start-ups and primes

Both start-ups and primes have pointed out potential concerns about working with each other. Start-ups have described issues with funding delays, restrictive exclusivity agreements, and the way that primes can treat start-ups as subcontractors rather than innovation partners. Conversely, primes mention different ways of working, their need to adhere to more stringent obligations (for example, on risk management), and adequate resourcing for long-term programs as sources of tension. However, there are ways that the value of partnerships could be emphasized to boost support for defense innovation.

Tailored operating models for innovation partnerships could be developed by primes (instead of standard program consortiums), as well as alternative commercial models that grow the strengths of and provide mutual benefits to all parties involved. An example

[12] Based on interviews with defense tech start-ups.
[13] "Innovation and efficiency: Increasing Europe's defense capabilities," McKinsey, February 28, 2024.
[14] For further information, see the Defense Innovation Unit's website: diu.mil.

could be to streamline investment processes, enabling quicker decision-making on funding or contract opportunities for start-ups. The choice of operating model becomes particularly relevant when primes collaborate with more mature start-ups. A conscious decision must be made about which engagement model to use, which requires a thorough understanding of their own technology competencies and their ability to outperform their tech peers in innovation.

Governments could act, too, by considering putting requirements in place for the use of commercial and dual-use technologies in program tenders. They could also encourage primes to include innovators in their supply chains, for instance, by adapting criteria in their supplier selection processes.

Start-ups are able to take action by thinking about incorporating "prime collaboration" as an explicit part of their capability profile, for example. This could be done by hiring talent that understands the dynamics of working with larger industry players and that can navigate the complexities of these relationships.

5. Enable iterative development of solutions with end users

Start-ups' core value proposition lies in their ability to move quickly, fund their own R&D, and develop solutions in close collaboration with end users. Currently, this rapid, iterative development can be constrained by the challenges young start-ups encounter when trying to access military end-user feedback and data. While the military's stringent standards on quality, reliability, and access to classified information are in place for good reasons and need to be adhered to, finding ways to ease collaboration between start-ups and end users is likely to enable better solutions aligned with practical needs and operational realities.

To address these issues, private capital providers could utilize innovation hubs and defense technology foundries to enable real-time codevelopment and refine solutions with end users—demonstrated by the Cyber Innovation Hub of the German armed forces.[15] These could also allow for closer connections between industry players, start-ups, and Ministry of Defense (MoD) end users. Meanwhile, public capital providers (government agencies or state-owned VC funds) could consider adopting elements of successful US vehicles, such as the DIU or In-Q-Tel. For instance, In-Q-Tel provides start-ups with capital while supporting them in building strong customer and user relationships and adhering to customers' standards for protecting classified data. And, last, investors, MoDs, and armed forces could offer low-threshold formats to connect military customers, end users, and innovators (such as workshops, hackathons, and networking events).

The European defense tech start-up ecosystem is expanding as countries pursue innovative solutions to enhance their defense capabilities in response to geopolitical challenges. While progress has been made, it is crucial to address funding gaps, attract talent, and streamline procurement processes to boost the ecosystem. Collaboration between government customers, capital providers, and entrepreneurs will be vital in driving this transformation. Going forward, synergy between start-ups and established defense players could unlock unprecedented opportunities, ensuring that Europe stays at the forefront of defense innovation and resilience.

David Chinn is a senior partner in McKinsey's Tel Aviv office; **Jakob Stöber** is a partner in the Munich office, where **Jessica Köhler** is a consultant; **Hannes Fischer** is a consultant in the Stuttgart office; and **Katharina Wagner** is an associate partner in the Berlin office, where **Nadine Grießmann** is a client activation director.

The authors wish to thank Bartek Bak, Isabel Tretow, Lea Baltussen, Matthias Karl, and Saoirse Collins for their contributions to this article.

[15] For further information, see Bundeswehr Cyber Innovation Hub's website: cyberinnovationhub.de.

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Creating a modernized defense technology frontier

Public and private investment dollars are fueling defense innovation. The prize? A $250 billion opportunity to build a modernized defense frontier by scaling technology, from AI to quantum computing.

by Dale Swartz and Ryan Brukardt
with Karl Hujsak

February 2025

The defense ecosystem today is at a critical junction, ripe with opportunity for private capital, the traditional defense industrial base (DIB), and other commercial players such as hyperscalers to take critical roles in leading disruption within the innovation pipeline. Yet the window to reorient how public and private organizations invest to meet the challenges facing Western security is limited, with the coming decade being the most critical.

That's because increasing geoeconomic tensions and evolving security threats are transforming the global defense landscape. Rising competition in technology is driving up defense budgets and mobilizing defense innovators across sectors. Major powers, such as Australia, Germany, Japan, and the United States, are seeking to rapidly modernize their defense capabilities across multidomain operations, a feat not possible without significant, concerted public and private investment to accelerate adoption.

Governments are investing. The North Atlantic Treaty Organization's (NATO's) €1 billion Innovation Fund, the first multination venture capital (VC) initiative in defense technology, announced its first round of deep-tech investments in June 2024.[1] The United States committed more than $150 billion to research, development, testing, and evaluation (RDT&E) in fiscal year 2024 to support agencies such as the US Defense Innovation Unit (DIU) and the Office of Strategic Capital (OSC), marking a 55 percent expansion of defense funding during the past five years.[2] And new institutional frameworks are emerging globally, from Japan establishing its Defense Innovation Technology Institute[3] to the United Kingdom launching the Defense Innovation Initiative[4] as part of a confirmed plan to raise overall defense spending.[5]

Private capital is similarly mobilizing defense technologies,[6] with global VC investments in defense-related companies jumping by 33 percent year-over-year to $31 billion in 2024. Investments span defense-dedicated and dual-use technologies with both defense and commercial applications. Notable investment areas include AI ($12 billion), next-generation communication networks and autonomous systems ($4 billion each), next-generation renewables ($3 billion), and biotechnology ($2 billion).[7]

But money alone is inadequate to unlock the next evolution of these emerging technologies. With increasingly open customers keen on modernizing, real opportunity remains within the fragmented defense ecosystem across players—including VC firms, start-ups, government labs, allied innovation units, and the traditional DIB—to lead collaboration toward achieving at-scale adoption. These actors stand to gain immensely by reshaping our defense capabilities, developing during the next decade what we call a "modernized defense frontier"—a foundation for Western security.

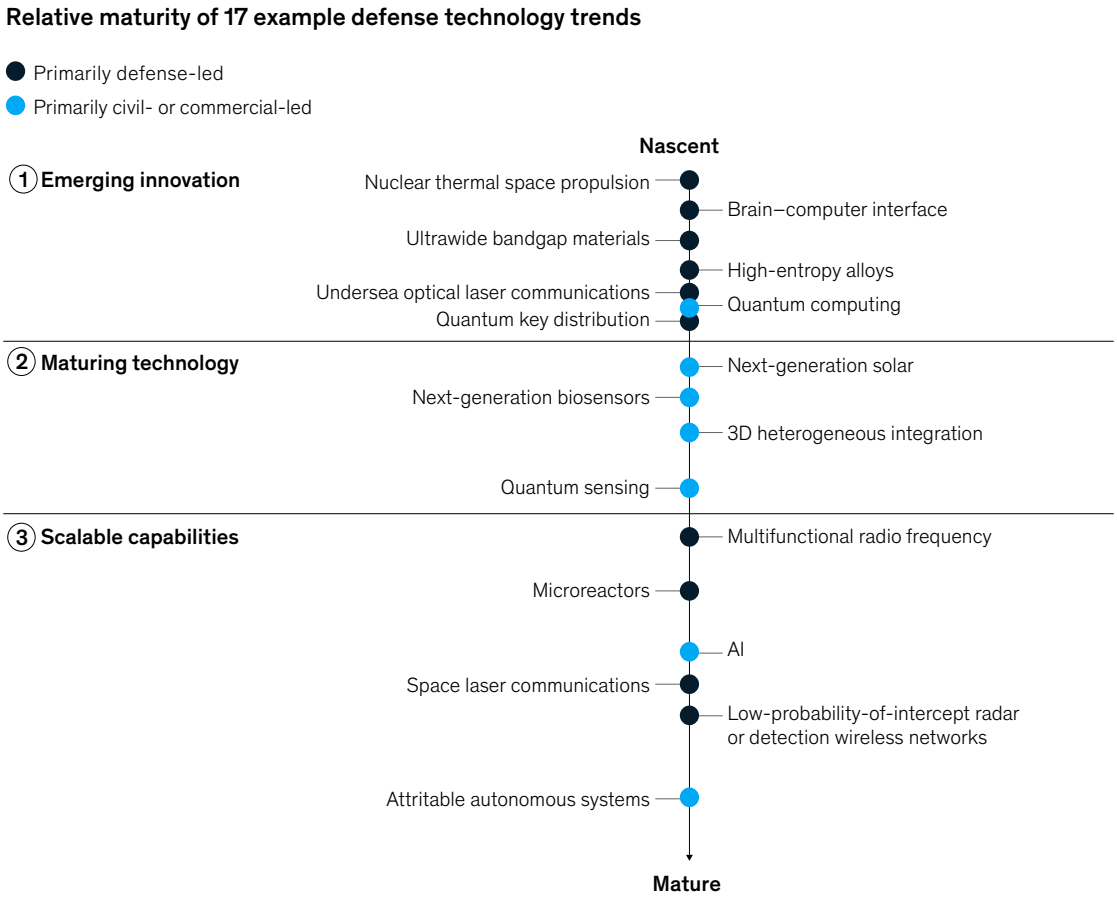
The defense ecosystem: Three critical technology stages

Technological innovation is central to modernization efforts. Institutions have been rapidly assessing gaps and publishing calls to action, such as the NATO Emerging and Disruptive Technology Strategy and the United States Critical and Emerging Technologies List. We identified 17 disruptive technologies, spanning different phases of maturity, that have great potential to disrupt the national security landscape during the next decade (Exhibit 1). They also underscore broader themes in defense technology, such as an expanding definition of "critical technology" and dual-use technologies becoming more pervasive.[8] In addition, they showcase private sector innovation leading a greater share of later-stage development[9] and the urgency with which the innovation ecosystem seeks

[1] "NATO Innovation Fund makes first investments in future deep technologies," NATO, June 24, 2024.
[2] "FY2024 Department of Defense," American Institute of Physics, updated April 2, 2024.
[3] "Japan to open US-inspired defense tech research center in October," Kyodo News, August 12, 2024.
[4] *Advantage through innovation*, Ministry of Defence, September 16, 2016.
[5] James Tobin, "UK defence spending: 2.5% of GDP target," House of Lords Library, October 28, 2024.
[6] Jesse Klempner, Christian Rodreguez, and Dale Swartz, "A rising wave of tech disruptors: The future of defense innovation?," McKinsey, February 22, 2024.
[7] McKinsey analysis of Pitchbook data, accessed on December 10, 2024.
[8] Harriett Baldwin, "2024—Critical dual-use technologies: Commercial, regulatory, societal, and national security challenges," NATO Parliamentary Assembly, November 22, 2024.
[9] James Ivers, Willer Roper, Matt Watters, and John Willison, "Evolving federal R&D to meet the challenges of tomorrow," McKinsey, April 26, 2024.

Exhibit 1

Key defense technology trends span three critical stages, depending on maturity and readiness.



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to modernize across all levels of maturity and readiness.[10]

Despite the criticality of these 17 technologies, they risk being underfunded or failing to reach operational deployment if stakeholders are not appropriately aligned on funding and acquisition pathways.[11] We see three distinct stages that each reflect the unique roles for stakeholders in the defense ecosystem:

Emerging innovation. These capital-intensive technologies are cutting-edge innovations representing significant opportunities accompanied by higher risk. These efforts often lack commercial incentives given the long horizon of development. This often leaves public funding as the principal catalyst to turn bold ideas and research into investable areas, bringing down the cost of capital to innovate.

[10] "Emerging and disruptive technologies," NATO, August 8, 2024.
[11] *National security innovation base report card,* Ronald Reagan Presidential Foundation & Institute, March 2024.

Maturing technology. These are innovations with growing technical proof points that are not yet scaled or prepared to scale in defense. Private partners have an opportunity to lean in with public players to develop tailored support to accelerate technology from prototype to fielded capability.

Scalable capabilities. These mature defense-ready technologies are established but need to be adopted at scale to achieve full impact. For many of these technologies, there are critical infrastructure gaps that are barriers to broader adoption, but for private players—whether commercial to accelerate scaling or the traditional DIB adopting—leaning into these innovations earlier presents significant opportunities for growth and differentiation.

1. Emerging innovation

Technologies in this early-stage category are characterized by high capital intensity and extended development timelines. For example, producing high-quality ultrawide bandgap diamond substrates—which are regarded as a critical input for next-generation applications such as high-power radio frequency switches and limiters and extreme-environment electronics and sensors—requires costly investment in materials, equipment, and processes (for example, seed crystals, vacuum chambers, and polishing). Without clear demand or near-term procurement from defense or civil sectors, private capital often hesitates to invest in such technologies due to inherent risks and long timelines to achieve returns (Exhibit 2). Other hurdles, such as navigating the niche regulatory environments for each technology, further reduce incentives for private involvement.[12]

Across these technologies, defense-led publicly funded programs play a critical role in driving innovation and catalyzing technological advances through what can be ten or more years of development. But there are steps defense and civil research entities can consider to maximize the impact of their R&D investments.

For instance, multiple agencies often research the same technology by design to provide fresh perspectives on the same problems. High-entropy alloy funding in the United States, for example, remains split between several entities. While having multiple independent efforts is a core aspect of research and can unlock new answers, the scale of duplication across many of these disruptive technologies may warrant review. In addition, when technologies begin to gain traction with private capital, public funding can sometimes be uncoordinated between sources and risk duplicating or contradicting private capital investments.[13] Better coordination between publicly funded programs could stretch R&D budgets further and clarify demand signals around innovation priorities, making it more likely for private capital to enter the picture.

The defense sector benefits significantly from the influx of private capital that typically follows successful demonstration of dual-use technologies initially supported by government funding. For instance, a company developing innovative medical technology that received initial government support later obtained regulatory approval and subsequently raised more than $100 million in private investment to further its development.

2. Maturing technology

Maturing technologies are technologies that are developed past the early-stage archetype but are not yet ready to scale for defense; they do not meet security and reliability standards for defense contexts. Maturing technologies have seen growing private investment following early proof points, such as the $12 million in VC funding raised by a perovskite solar cell start-up to build production scale.[14] As these technologies mature,

[12] For example, existing reactor regulations do not cleanly apply to nuclear thermal space propulsion engines and require testing new regulatory pathways as detailed in "Regulatory approach for nuclear thermal population," NTRS—NASA Technical Reports Server, April 13, 2023.

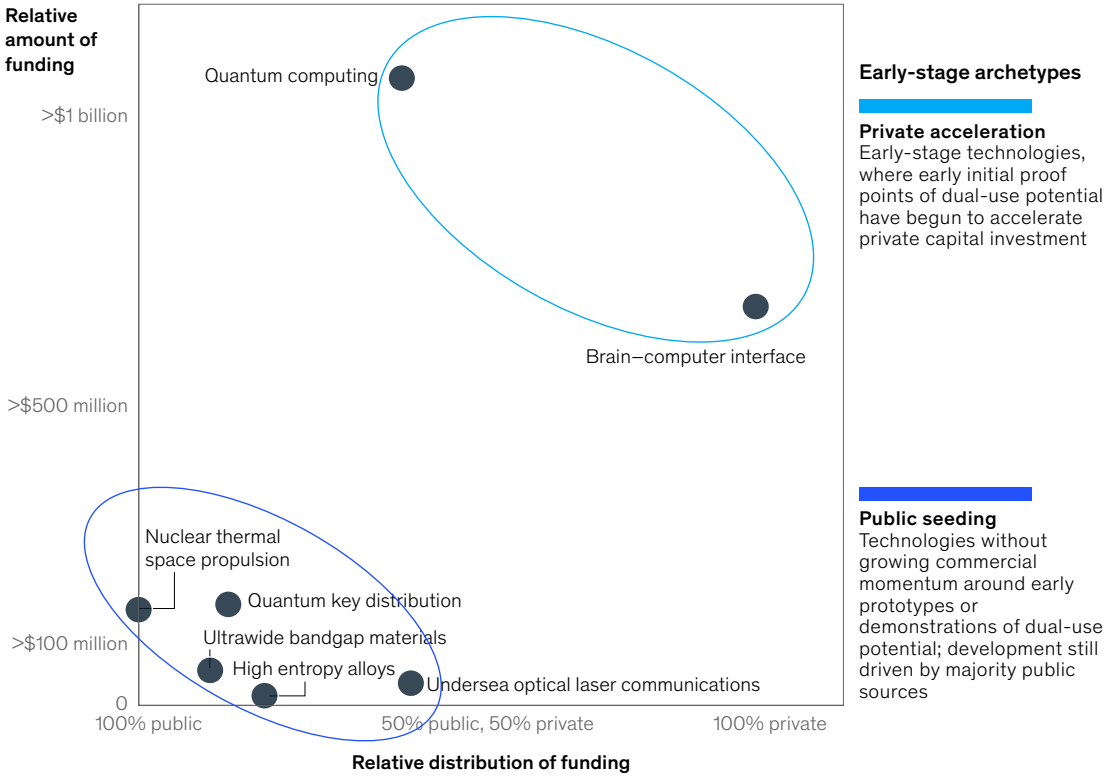
[13] From 2023 to 2025, the Department of Defense invested about $2 billion in 50 separate R&D projects across all three military departments and the Office of the Secretary of Defense to develop manned-unmanned teaming technologies. The Army, Navy, Air Force, Defense Advanced Research Projects Agency, NASA, and others were all investing in this space with little to no coordination. Based on McKinsey analysis of 2025 RDT&E Justification Books for each of the departments and public budget data from NASA.

[14] "Caelux announces $12M to fund next-generation solar innovation with perovskite technology," PR Newswire, August 14, 2023.

Exhibit 2

Private capital often hesitates to invest in early-stage technologies.

Private funding vs public funding for early-stage technologies, 2022–24



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however, so do their core technical challenges and nontechnical hurdles, such as the quantum talent shortage that could threaten US leadership in space.[15]

Technologies at this maturity stand to benefit from private players that can help develop tailored enabling strategies to push these technologies into an investable threshold. Public funding is a critical enabler because these technologies are not commercially viable on their own due to longer development lead times. Public sector incentives, such as direct research funding, US Department of Defense Small Business Innovation Research contracts, and large-scale government programs, can significantly accelerate technology development. Active engagement and feedback on these incentives from private players can help overcome barriers preventing defense readiness and production scaling while also providing unique market opportunities for these early-moving private players that lean in.

3. Scalable capabilities

Scaling technologies have mature applications but have not been adopted at scale, often due to infrastructure gaps and significant investment required. Examples include low-probability-of-intercept and low-probability-of-detection (LPI/LPD) networks and space-based optical lasers.

[15] Less than 50 percent of quantum computing jobs may be filled by 2025. Niko Mohr, Kiera Peltz, Rodney Zemmel, and Matija Zesko, "Five lessons from AI on closing quantum's talent gap—before it's too late," McKinsey, December 1, 2022.

One common gap in scaling technologies is computing power constraints, especially for devices at the tactical edge, such as deploying AI at the point of action for real-time insights in dynamic, resource-constrained environments. Autonomous systems require substantial computing for mission execution and navigation. Space-based optical lasers, which are tasked with handling vast volumes of data, need improved computing power for efficient data transfer. LPI/LPD networks resolve waveform design but require more computing for waveform selection and data packaging. Defense AI also has a large deficit in computing power. Unlike commercial AI with its data centers and fast, reliable communications networks, defense systems must operate efficiently in contested environments, requiring greater computing efficiency and reliability at the edge.

Beyond the computing gap, there are several other major challenges to adoption at scale. Scaling technologies need to function alongside a mix of legacy and modern platforms, each with distinct standards, protocols, and architectures; standardization efforts and significant investments may be needed to reduce the cost to adopt new technologies at scale. Further, defense organizations often struggle with integrating new technologies into entrenched processes given their size and complexity. Private players that can coordinate adoption of innovation and manage change effectively within their organization stand to gain immensely in terms of reliability, cost, and potential differentiation on ongoing missions.

Catalyzing the modernized defense frontier

Emerging defense technologies are advancing, offering groundbreaking potential for military superiority and operational effectiveness. From AI to advanced manufacturing, the innovation pipeline is accelerating—and that's worth celebrating. However, technology adoption remains a sizable hurdle, with significant barriers threatening to delay or derail progress.

The current defense innovation ecosystem is fragmented, with distinct roles spread across government labs conducting foundational research, public institutions providing demand signals and funding, start-ups pioneering breakthrough technologies, large traditional commercial players scaling solutions, and the DIB mobilizing, deploying, and sustaining military operations. This fragmentation causes inefficiencies, significantly slowing the transition of technologies from the lab to the edge of the battlefield.

To streamline the tech transition, we need a modernized defense frontier—a new way of operating that transforms how we scale emerging technologies and accelerate adoption by removing barriers. Specifically, public and private sectors will need to collaborate to address funding inefficiencies, infrastructure barriers, and critical talent gaps, working together in an ecosystem in which departments and ministries of defense, leading contractors, and disruptive innovators can easily convene and drive results. Achieving and adopting this frontier means capturing value from what is estimated to be a more than $250 billion opportunity, realized by overcoming three challenges to defense innovation adoption.

1. Revolutionizing capital and funding, deployment, and efficiency

Efficiently allocating the more than $180 billion in public and private R&D capital[16] is essential to overcoming the defense sector's longstanding challenges in developing and scaling disruptive technologies. However, R&D investment in many critical technology areas (excluding AI) appears to be flat-to-declining, creating a significant risk to the maturation cycle for these technologies. Without sufficient funding growth, promising innovations may stagnate in areas such as in-space propulsion, ultrawide bandgap materials, and high-entropy alloys, limiting their operational impact.

This challenge is further compounded by the fragmented nature of defense tech funding. Multiple defense tech funding sources—including

[16] About $30 billion in defense tech VC capital based on Pitchbook data, and about $150 billion based on FY2024 allocations for RDT&E (McKinsey analysis; "FY2024 Department of Defense," American Institute of Physics, updated April 2, 2024), with a potentially greater pool of resources if rest of private capital R&D is included.

international treatise organizations, government agencies, VC firms, and corporate VC—operate independently, often resulting in redundant efforts. Unified frameworks and coordinated technology road maps across global and domestic stakeholders are critical for efficient allocation of funding.

To maximize return on funding, the modernized defense edge needs updated fit-for-purpose acquisition pathways tailored to the specific needs of each technology category. The US Space Force's new commercial space strategy is just one instance that exemplifies how a commercial-led innovation approach can rapidly scale certain technologies, such as low-Earth-orbit satellite communications.[17] However, while this example approach is effective for specific technologies, broader reforms are necessary to address unique challenges across different development stages. Without clear role definitions and collaboration pathways, defense entities risk coordination failures in investment and deployment, which can further delay the transition of technologies from development to operational use.

2. Investing in a culture of innovation and leveraging tech to grow and retain aerospace and defense talent

Workforce challenges and organizational health have been longstanding issues across the DIB, with 70 percent of aerospace and defense (A&D) companies reporting organizational health scores below the global median.[18] Further, there are three core employee issues driving significant annual productivity losses, estimated at $300 million for a median-sized A&D company: a lack of skills, a lack of engagement, and an inability to prioritize high-value-add work.[19]

These emerging technologies are only expected to exacerbate existing talent concerns as pressure to adapt and scale new technologies increases. Across defense innovators, there is significant opportunity to reevaluate internal processes, skills, and talent base needs to improve the health of their organizations. At the same time, leveraging innovations that are more cutting-edge can increase differentiation, improving the employee value proposition to attract and maintain a workforce that is energized by its work and equipped for execution.

3. Unlocking next-generation infrastructure for production, computing, and connectivity

The most significant opportunity for disruption across ecosystem players may be through unlocking infrastructure, scaling production of these technologies, removing barriers to adoption by building up assets (such as property, plants, and equipment), and increasing computing and connectivity capacity.

The industrial base today is heavily reliant on raw materials that often experience shortages, and established manufacturers are also experiencing a growing tech debt. Both challenges result in a scarcity of production capacity needed to deliver at-scale solutions at the rates required by existing conflicts, let alone to deter potential future adversaries. While some of these challenges require allied nations to come together (for example, by increasing the transparency of global supply chains and implementing shared private sector advanced manufacturing solutions), there is real opportunity for private players to meet this challenge head-on, particularly disruptors and traditional DIBs.

If the industry is to realize the full potential of these technologies, it needs the talent and infrastructure to build and deploy these systems at scale. This may require an expansion of the current DIB to provide additional services and

[17] *U.S. Space Force commercial space strategy: Accelerating the purposeful pursuit of hybrid space structures,* United States Space Force, April 8, 2024.

[18] Brooke Weddle, Giulietta Poltronieri, Hugues Lavandier, and Andy Voelker, "The talent gap: The value at stake for global aerospace and defense," McKinsey, July 17, 2024.

[19] A median-sized company is defined as having 20,000 to 30,000 full-time employees, having annual revenues of $5 billion to $8 billion, taking an average of 70 to 90 days to fill a vacant position, and having a roughly 15 percent attrition rate. Brooke Weddle, Giulietta Poltronieri, Hugues Lavandier, and Andy Voelker, "The talent gap: The value at stake for global aerospace and defense," McKinsey, July 17, 2024.

infrastructure necessary to deliver on ongoing and arising missions. With an average today of about $6 billion to $7 billion in property, plant, and equipment from major platform-focused defense prime contractors deploying existing technologies, future industrial base players may need similar investments—amounting to an estimated $18 billion to $30 billion opportunity over multiple years to build the necessary capital. Rewards will flow to those that effectively scale production capacity while establishing themselves as leaders in this evolving ecosystem.

But that's not all. Little attention has been paid to the most significant adoption challenge: the lack of computing power and connectivity necessary to support the influx of updates required to take advantage of emerging technologies. For computing and connectivity, there is not a widely established reference architecture for edge computing in the defense ecosystem. Major AI infrastructure programs that have recently been announced (for example, Stargate) are also unlikely to address this gap given the need for computing at or near the defense edge. This reference architecture gap—coupled with a complex array of standards—results in challenges when integrating new technologies with legacy platforms such as aircraft and maritime vessels, as well as a significant opportunity for players actively working to close the gap. Closing just this computing gap is estimated to require an investment of $160 billion to $230 billion over multiple years across more than 75 platforms and a total network of more than 700,000 nodes (Exhibit 3).[20]

The standards and protocols of current computing and connectivity infrastructure are fractured across the services and US allies, lacking the throughput and capacity to handle an expanding ecosystem of connected devices. There is tremendous need within the system to add more clarity, but above that, there is a real business opportunity to drive the transformation and an upgrade of the install base at the foundation of all this technological change.

[20] This McKinsey analysis cost estimate excludes integration, communications, or other hardware enhancements needed for adoption but factors in current and future platforms, required computing power to host new technologies, and existing upgrade cycles.

Exhibit 3

Closing the defense computing gap could take years and cost up to $230 billion.

Cost to close the computing gap, $ billion

[1]High-mobility multipurpose wheeled vehicles.
[2]Next-Generation Air Dominance; unmanned ground vehicles.

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The race to modernize Western and allied-partner defense capabilities has catalyzed billions of dollars in technological investment from public and private entities, but it is only by scaling adoption of these critical technologies that the future of Western defense can be secured in an increasingly contested landscape. This requires aligning stakeholders on funding priorities, creating a strong foundation for successful technology transfer, and attracting the next generations of innovators to transition emerging technologies from potential to mission-critical operational impact.

Dale Swartz is a partner in McKinsey's Silicon Valley office, where **Karl Hujsak** is an associate partner; **Ryan Brukardt** is a senior partner in the Miami office.

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Aerospace & Defense Practice

Innovation at Thales: An interview with Patrice Caine

Patrice Caine, chair and CEO of Thales, shares insights on the role innovation plays in the defense sector, especially the current status of AI and the future of quantum technologies.

February 2025

The conflict in Ukraine has highlighted the critical role technological innovation can play in the defense sector. The use of technologies such as drones, cybersecurity, high-speed dissemination of information, and electronic warfare, along with their countermeasures, have proven to play a particularly important role.

In this interview, Patrice Caine talks to Hugues Lavandier, senior partner coleading McKinsey's Aerospace & Defense Practice worldwide, and Alexandre Ménard, senior partner coleading the McKinsey Industry & Technology Practice in France, about the critical importance of innovation in the defense sector. He discusses the role of two major technologies, in particular, AI and quantum, and how the development of a combination of scientific and digital skills is crucial for technologies tailored to the needs of defense players. Patrice Caine has been the chair and CEO of Thales since December 2014 and chair of the National Association of Research and Technology (ANRT) in France since December 2019.

McKinsey: Thales is a leading technology company. That's why we would like to start this discussion by talking about a subject that's right at the heart of the news: AI. It is developing at breakneck speed and has great potential to reshape the economy. What do you think is, and will be, the impact of AI on the defense sector?

Patrice Caine: The deployment of AI in the defense sector is already a reality and is now taking on more of an operational than prospective characteristic for the industry. Let me give you two examples of technologies where AI has already had a significant impact: sensors and decision-support systems.

Let us talk first about sensors, such as radar and sonar. Currently, the level of performance of our radar systems enables us to detect very small, very slow-moving objects, such as prowling munitions or drones. But it is difficult and time-consuming for a human operator to differentiate them from other flying objects, such as birds. The introduction of AI provides real added value in terms of interpretation: It can quickly and reliably determine the nature of these objects and identify those relevant to air surveillance. This is an extremely important advantage when it comes to protecting ourselves against this type of threat, which has increased significantly in recent years. These functions are already present in some of our radars.

A second use case relates to "Command and Control" decision-support systems. The use of these systems includes preparing for missions consisting of highly complex operations, for example, an aerial reconnaissance mission. This phase, in particular, involves making decisions on aspects such as flight trajectory, altitude, speed, the number and configuration of aircraft, and take-off time. It involves resolving an extremely complex combination of factors to be able to arrive at the best possible decision, the one that will meet the objectives while ensuring pilots' safety and making the best use of resources. AI algorithms have demonstrated that they add real value by quickly finding the best possible compromise—and then leaving it up to the operators to accept or reject what the AI proposes.

But let's be clear: Whether we're talking about sensors or support systems for decision-making, AI does not question existing technologies. In some cases, its contribution can be a real game changer, but it works complementary to systems that are, in themselves, already highly advanced and have proven their worth.

The integration of AI-based technologies nevertheless presents a number of challenges, including that of exportability. Obviously, for security reasons, a system that has been trained on operational data from live action would be excluded from being exported, as we do not own such data, and it contains classified defense information. Moreover, it would be inappropriate to use the same training data for all use contexts. The interpretation of a sensor's results must be adapted, particularly to the circumstances in which it will be deployed. To meet this dual challenge, we pretrain our algorithms using industrial and synthetic data, while fine-tuning is carried out using data from the end customer.

McKinsey: How do you reconcile the length of time it takes to structure the development

and implementation of defense projects and platforms with the need for the rapid deployment of architecture and software capable of technological acceleration?

Patrice Caine: We proceed by successive extensions, by modules. Let's take the example of a platform such as the Rafale. When we introduce AI into a reconnaissance pod,[1] we take care to make as little impact as possible on the Rafale's weapons system. We integrate this additional capability into the pod to assist the pilot without impacting the rest of the platform. Of course, this imposes very strong design constraints in terms of space and energy consumption. In this respect, it is less complex to integrate AI on a ship, for example, where it is possible to take data hubs on board designed to retrieve onboard information and process it.

McKinsey: What, in your view, is the difference between the incumbent defense companies and large tech players that are increasingly open to hosting defense applications or agile start-ups that have more recent experience with defense issues?

Patrice Caine: In the defense sector, even more than in other sectors of the economy, the need to be anchored in operational reality is crucial. In my view, there are four key elements that need to be mastered in order to be credible.

First, to harness the potential of AI, one must have a high level of mastery in both the digital and physical fields. It is vital to understand the underlying physics of defense technologies. This is particularly true where sensors are concerned. Here is a concrete example: To me, it seems extremely complicated to develop algorithms for underwater acoustics without knowing exactly how sonar works. How does an acoustic wave make a ceramic resonate? How does this ceramic react to produce an electrical signal from this acoustic wave? How do you convert an electrical signal into an analog signal to deduce the nature of the object detected? To enhance the performance of a sensor by using AI, knowledge of digital technology alone is not enough. It's the combination of highly specialized expertise in digital technology and the physical sciences that makes it possible.

Second, it is necessary to have a good understanding of the concepts behind the use of the technology. In the same example of submarine sonar, it is essential to know what operators are trying to detect and what they are trying to understand when they are in the field. In-depth knowledge of these needs is required to successfully combine theory with diverse and complex operational realities. A company such as Thales benefits from decades of close collaboration with defense forces. This is a considerable asset when it comes to developing AI that is truly useful to them.

Next, it is essential to be able to understand issues related to embeddability. On a combat aircraft, the computing power available is often limited due to the physical space available and the electrical power capacity. And, for reasons of security and

[1] A laser designation pod is airborne equipment that enables an aircraft to detect and designate targets on the ground.

'In the defense sector, even more than in other sectors of the economy, the need to be anchored in operational reality is crucial.'

—Patrice Caine, chair and CEO of Thales

stealth, it would be unthinkable to have a constant connection to the cloud. Add to this the constraints of electromagnetic radiation or even thermal resistance (military equipment must be able to operate between below 40°C and over 90°C). These are major technical challenges for new entrants and pure tech players.

The fourth point concerns cybersecurity. AI provides an additional capability with high added value, but it also represents a proven source of vulnerability, which we must be able to guard against. A few pixels altered in an image during a cyberattack can lead to errors in the interpretation by an AI algorithm. Imagine if this led to a tank being identified as a civilian vehicle and the consequences that could have. Thanks to our 6,000 cybersecurity experts, a company such as Thales has the capacity to protect its AI against these attacks. But few companies in the world have this type of capability at their disposal.

Combining physical and digital sciences, having a good understanding of the concepts of deploying the technology, mastering the constraints of embeddability, and being able to protect against cyberattacks—the number of credible players able to meet these four challenges simultaneously is very small. In this respect, the large historic tech companies such as Thales have a head start.

What I'm saying is slightly less true regarding decision-support systems, which are more about software than the hardware. The barriers to entry are, therefore, a little lower. Even so, this type of system has between 10 million and 20 million lines of code. You must first be able to master the operation of a gigantic piece of software before you can envisage integrating AI into it.

McKinsey: The topic of leadership often comes up when talking about defense matters. What is the role, not just of AI but of innovation in general, in terms of leadership for defense players? More specifically, what will allow European defense technology players to maintain their leading positions? And what will make a difference?

Patrice Caine: I'm convinced that, after several years in which a great deal of attention has been focused on digital technology, disruptive innovation in the coming decades will be driven by the physical sciences. Coming back to AI: We mustn't forget that large language models (LLMs) can only be trained using existing data and knowledge. How can we create something truly revolutionary on the basis of what already exists? On the other hand, in the physical field, we are identifying major disruptions ahead. I see the physical sciences getting even with the digital sciences, and in this field, quantum technology is the next big revolution.

The first quantum revolution was an upheaval, even though it is not necessarily widely known. It led to the development of atomic clocks that gave rise to GPS and even lasers, MRIs, and transistors. The second revolution will take us a step further by taming the extremely puzzling characteristics of matter at the elementary level.

McKinsey: You talk of a quantum revolution. How will it materialize in the defense sector? What are the most promising use cases, and when do you see them becoming available?

> **'To harness the potential of AI, one must have a high level of mastery in both the digital and physical fields.'**
>
> —Patrice Caine, chair and CEO of Thales

Patrice Caine: First of all, I'd like to make it clear that I'm not talking about the development of the quantum computer. Thales is not involved in that race, as building computers is not one of our specialties. As for the rest, no one knows when this quest will succeed. However, we are working in areas which we are more certain will give rise to viable technologies that can be industrialized in the medium term.

In particular, the second quantum revolution will give us access to radically higher performance in the field of sensors. We're not talking about incremental improvements but improvements by a factor of between 100 and 1,000. The technologies involved already exist and have proven their worth, but the challenge now is to take them from prototype to the industrial stage and then to build the economic models.

For example, quantum sensors could have a major impact on inertial navigation systems.[2] Today, without recalibration, the most efficient of these drift by around a kilometer on a journey between Paris and the East Coast of the United States. With a cold atom inertial unit, based on quantum technologies, it shifts from a difference of kilometers to a difference of meters, an improvement of a factor of 1,000. This is of interest to civil aviation, but it is especially of great interest to the defense sector. In the case of a nuclear submarine, for example, such a system will create the ability to avoid having to surface to carry out recalibrations—a major operational advantage! So, I'm deeply convinced that the initial use cases will more likely come from the defense sector.

Let's take another example, that of SQUIDs and SQIFs.[3] These technologies make it possible to dissociate the size of antennas from the frequency of the signal to be transmitted or received. The potential impact on the defense industry is enormous. Currently, to communicate at very low frequencies (particularly with submarines), antennas several hundred meters long are required. With these new devices, antennas the size of a fingernail will be able to perform the same function. You can imagine the advantages, particularly in terms of stealth.

McKinsey: In this new era, talent is essential, whether it's engineers or tech talent. What are the implications of these technological innovations in terms of talent acquisition? In one of our recent articles, we highlighted the challenges faced by European players when they encounter a shortage of skilled workers in a highly competitive labor market, making attracting and retaining talent a major challenge.[4] How is Thales competing with the big tech players in terms of attracting talent?

Patrice Caine: When it comes to talent, Thales has the undeniable advantage of being a strong brand with exciting projects for young engineers across all verticals. What's more, we combine a high level of expertise with concrete social benefits. Aeronautics enthusiasts who join us, for example, have the possibility of contributing to improving the environmental performance of aircraft. Others join us because they want to help protect their country's sovereignty or help combat cybercrime.

Another one of our strengths is the opportunity offered to our talent to change their discipline or area of expertise during the course of their career, for example, from the world of defense to that of aeronautics, from space to cyber, et cetera. Our employees can also change their technical discipline from physical to digital sciences or a combination of both. However, in actual fact, many of them become so passionate about their field that they often don't wish to change.

Our positioning also gives us the advantage of working in long cycles and balancing volatility caused by an increase or decrease in activity, which helps us build loyalty and avoid losing skills. However, we remain focused on this issue.

[2] An inertial navigation system is a navigation instrument that allows aircraft to position themselves autonomously (without relying on satellite positioning).
[3] A SQUID (Superconducting Quantum Interference Device) is an extremely sensitive sensor that uses the quantum properties of superconductivity to detect very small variations in magnetic fields. A SQIF (Superconducting Quantum Interference Filter) is a device designed to filter electromagnetic signals, using quantum interference to let pass or block certain frequencies.
[4] "Europe's gray-to-green workforce transition in aerospace and defense," McKinsey, October 2023.

‘I see the physical sciences getting even with the digital sciences, and in this field, quantum technology is the next big revolution.’

—Patrice Caine, chair and CEO of Thales

Continuing to attract qualified talent over the long term is a big challenge, as our employees are our main resource.

McKinsey: When it comes to attracting and retaining talent, we see that new generations are paying more attention to environmental and social aspects, placing meaning at the heart of their career plans. How are you responding to this trend?

Patrice Caine: When I joined Thales 22 years ago, environmental or ethical issues were less central to the recruitment process. Today’s young talent is much more focused on the social purpose of our business. This has led us to think and formulate our role differently. Today, we express it in terms of a triple ambition: to help make the world safer, greener, and more inclusive. Everything we do relates to at least one of these objectives.

Our defense, security, and cybersecurity activities enable our clients to protect their populations, their institutions, and their physical and digital infrastructure. It’s not always well-known, but Thales is currently one of the biggest global players in terms of the security of applications and digital data. In aeronautics, we are contributing to the efforts to reduce the sector’s carbon emissions, in particular by optimizing flight paths.

Finally, by playing an active part in the fight against the digital divide, we are helping to build a more inclusive world. For example, we have developed the SATRIA satellite, which connects Indonesia’s 13,000 islands to the internet at an affordable cost. We also contribute to providing all human beings on the planet with a secure legal identity, a prerequisite to being able to vote, travel, or access social services.

Patrice Caine is the chair and CEO of Thales. **Alexandre Ménard** and **Hugues Lavandier** are senior partners in McKinsey’s Paris office.

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Comments and opinions expressed by the interviewee are their own and do not represent or reflect the opinions, policies, or position of McKinsey & Company or have its endorsement.

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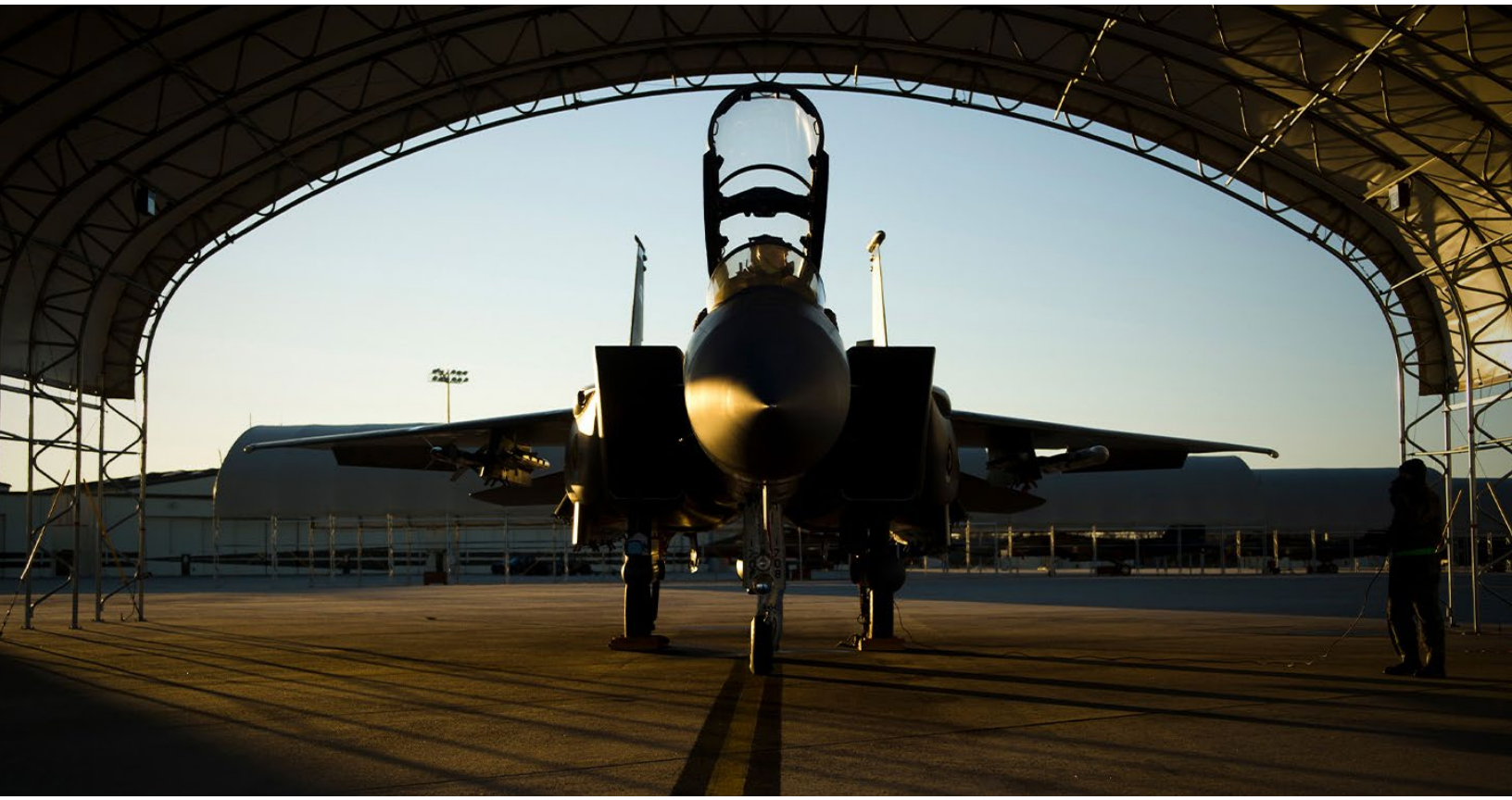
Aerospace & Defense Practice

Improving military aircraft sustainment to strengthen Europe's defense

With European NATO countries seeking to rapidly expand their defense capabilities, we explore how maintenance, repair, and overhaul providers could improve operations to enhance mission readiness.

by Christian Langer, Daniel Riefer, and Giacomo Gatto with Katharina Wagner



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In response to the changing geopolitical environment, European NATO countries have increased defense budgets, a significant share of which are expected to go to new equipment.[1] As munition stocks grow and existing equipment ages, mission readiness—the ability to deploy military assets for their intended use—is an increasingly important priority for countries. This, in turn, is likely to boost demand for maintenance, repair, and overhaul (MRO) services. But it will be no simple matter for industry stakeholders to meet this growing demand in an era of tightening operations and maintenance budgets, supply chain constraints, and talent shortages.

In this article, we build on a proprietary survey of military MRO experts in the air domain to explore how MRO providers can improve their operations to generate a mutually beneficial environment for MROs, OEMs, and military operators (see sidebar, "Our analysis"). We also consider how MRO providers who do not currently operate in this space could broaden their service offerings, not only to capture additional value but also to contribute to the defense industrial capacity in Europe.

Increasing equipment stocks: What does this mean for MRO partners?

Since the invasion of Ukraine in 2022, European NATO countries have announced increases in defense budgets amounting to an additional cumulative €700 billion to €800 billion by 2028—an increase of more than 60 percent compared to their pre-2022 baseline.[2] The largest share of this additional budget is likely to be allocated to equipment acquisitions to help replenish Europe's low stocks. Countries are already making new purchases—for example, in the air domain, Germany purchased 35 F-35 aircraft for approximately $8.5 billion in 2022.[3]

Across the 15 European countries with the largest air forces, 26 percent of all in-service aircraft were purchased before 1990.[4] With aging equipment in service for longer, it requires significantly more MRO services. Adding to this challenge is an expected increase in the complexity of fleets as new aircraft transition in, along with a shortage of trained personnel in the aerospace and defense industry.[5] As countries seek to maximize the return on their defense spending, increasing the availability of military air platforms in a cost-effective way will become crucial.

However, our survey data indicates that turnaround times in military MRO still lag behind those for commercial aircraft. By taking a proactive stance in the changing geopolitical environment, MRO providers, whether they already serve military platforms or not, could meet growing customer demand and thereby contribute to European security.[6] Both new players and existing military operators could improve their efficiency through strengthening processes and adopting digital solutions—thereby enhancing operations.

The effect of aging equipment and decreasing MRO budgets

More than half of the industry experts surveyed expect aging and heavily used aircraft to be the top drivers of future MRO demand growth as older platforms will require more intensive—and expensive—MRO (relative to the original platform cost) as they approach the end of their intended lifespan.

However, while European NATO countries are allocating a greater share of the budget to equipment acquisitions, the operations and maintenance (O&M) budget for existing equipment is relatively stable, increasing by only one percentage point.

[1] "Defense expenditure of NATO countries (2014–2024)," NATO Public Diplomacy Division, June 2024; "EDA defense data 2023–2024," The European Defense Agency, December 4, 2024.
[2] "Innovation and efficiency: Increasing Europe's defense capabilities," McKinsey, February 28, 2024.
[3] "Special fund: Bundeswehr can buy 35 F-35A for around 8.3 billion euros," Federal Ministry of Defense (Germany), December 14, 2022.
[4] "Fleets analyzer," Cirium Aviation Analytics, January 2025.
[5] David Vergun, "DOD addresses recruiting shortfall challenges," US Department of Defense, December 13, 2023.
[6] For more information, see Cindy Levy, Matt Watters, and Shubham Singhal, "A proactive approach to navigating geopolitics is essential to thrive," McKinsey, November 12, 2024.

Our analysis

In the fourth quarter of 2024, we surveyed 30 experienced military MRO professionals to explore opportunities to improve MRO for European NATO countries in the air domain. While these findings likely also apply to other military sectors, we focused our survey and analysis on aviation.

The respondents—the majority of whom operate in Europe—represent manufacturers and OEMs, MRO providers, suppliers of subsystems and spare parts, and representatives of the government customer. Military aircraft MRO is typically provided by an ecosystem of players across the private sector and government-related entities, including in-house capabilities of the armed forces, privately-owned companies, and, in some cases, commercial providers servicing aircraft operated by defense organizations.

From 2015 to 2020, European NATO countries' O&M spend was about $1.4 for every dollar spent on equipment; in the 2023 to 2028 period, this ratio is expected to be closer to $1.0 for every dollar spent on equipment, despite the average aircraft age already having increased from 23.0 years in 2014 to 25.8 years in 2024.[7] Improving mission readiness with this lower ratio would only be feasible if required maintenance for new aircraft is significantly lower during their lifecycle, or maintenance experiences a step-change in efficiency.

Commercial MRO capabilities could be applied to military

A comparison between military and commercial MROs shows considerable performance differences, indicating that military MRO providers could look to their counterparts to potentially increase their effectiveness and efficiency.[8]

According to the air-domain MRO experts we surveyed, military aircraft spend an average of 40 to 50 days per year undergoing scheduled maintenance, compared to 25 to 35 days for commercial aircraft—with some cases exceeding this average significantly. An additional 30 to 40 days a year are spent on unscheduled maintenance in comparison to commercial aircrafts' 10 to 20 days. MRO turnaround times for military aircraft often exceed the planned number of days: Our experts surveyed estimate that the planned turnaround time for the C-Check equivalent for military platforms is exceeded, on average, by 10 to 40 percent.[9] However, it should be noted that in addition to differences originating from the bespoke nature of military equipment, such as the complexity of cabin maintenance or the challenges associated with defense-specific equipment, there are also obvious mission-related differences that make a direct comparison between commercial airline operations and defense aircraft missions challenging.

However, lessons from commercial MROs can still be incorporated into military MRO planning to maximize availability. These include taking full

[7] "Fleets analyzer," Cirium Aviation Analytics, January 2025.
[8] This refers to privately owned military MROs and commercial MROs doing MRO for military aircraft.
[9] The C-Check requires an aviation maintenance technician to perform a deep inspection of the majority of the aircraft's parts. Aviation maintenance technicians will perform certain tasks during C-Checks, such as examining structures (load-bearing components on the fuselage and wings) and functions for corrosion and damage, checking the operation of the DC bus tie control unit, or lubricating all fittings and cables. Data include all types of military aircraft, that is, rotary and fixed wing, combat and noncombat, and drones.

advantage of an aircraft's downtime, reducing turnaround times of standard checks, and improving on-time-performance (OTP) of checks:

— MRO providers could optimize work packages to balance green time and ground time. This means comparing scenarios of performing tasks prematurely (giving away green time but bundling MRO activities) versus adding additional ground events (maximizing green time but reducing aircraft uptime).[10]

— MRO providers could increase productivity to reduce turnaround times of standard checks. They could learn from best practice commercial MRO providers to increase density (the number of work package hours performed per hour) and enhance labor productivity which is typically analyzed by looking at the "hands on metal" (HoM) of the qualified technicians.[11] Based on expert interviews, we learned that productivity in defense is often more than 20 percent lower than in commercial settings. HoM could be improved by increasing operational steering.

— The experience and process standards of commercial MRO providers could help military MROs improve the OTP of their checks by focusing on aircraft leaving a check at the planned time. An OTP of over 90 percent is considered best in class.[12]

In recent years, the commercial aviation market has seen even more volatility and unpredictability. Many commercial MROs have, therefore, gained relevant expertise to address these challenges, namely, supply chain disruptions, increasing costs of spare parts and raw materials, and a competitive talent market. However, these issues are becoming increasingly relevant for the military MRO sector as well and thus present an opportunity for commercial MRO providers to step into this space. By expanding their business into defense, commercial MRO providers could turn their expertise into a value-generating, competitive advantage.[13]

How MRO providers could improve efficiency

The experts in our survey identified four root causes as having the greatest impact on effectiveness and efficiency in military MRO (Exhibit 1). These, and potential measures to address them, are:

Spare part availability

The most cited reason for impeded efficiency is spare part availability, often affected by supply chain disruptions or insufficient inventory planning. To overcome this challenge, MRO providers could include flexibility in collaboration agreements, with an improved split between partners. Collaboration with other MROs could improve their data platforms to establish an "early warning system," achieved by monitoring supply chains (such as tracking change requests and procurement anomalies to identify issues) while also training staff in scenario and risk analysis.

Additional service provider involvement

Another cause of inefficiency cited is when additional technical expertise needs to be pulled in during maintenance from the airframe or engine OEMs—for example, when advice is needed on heavy structural findings. To ensure shorter waiting times and limited disruption, MRO providers may reassess their working relationships with OEMs. In best cases, response times and service levels are contractually agreed with the OEM during the initial purchasing process.

Unexpected findings

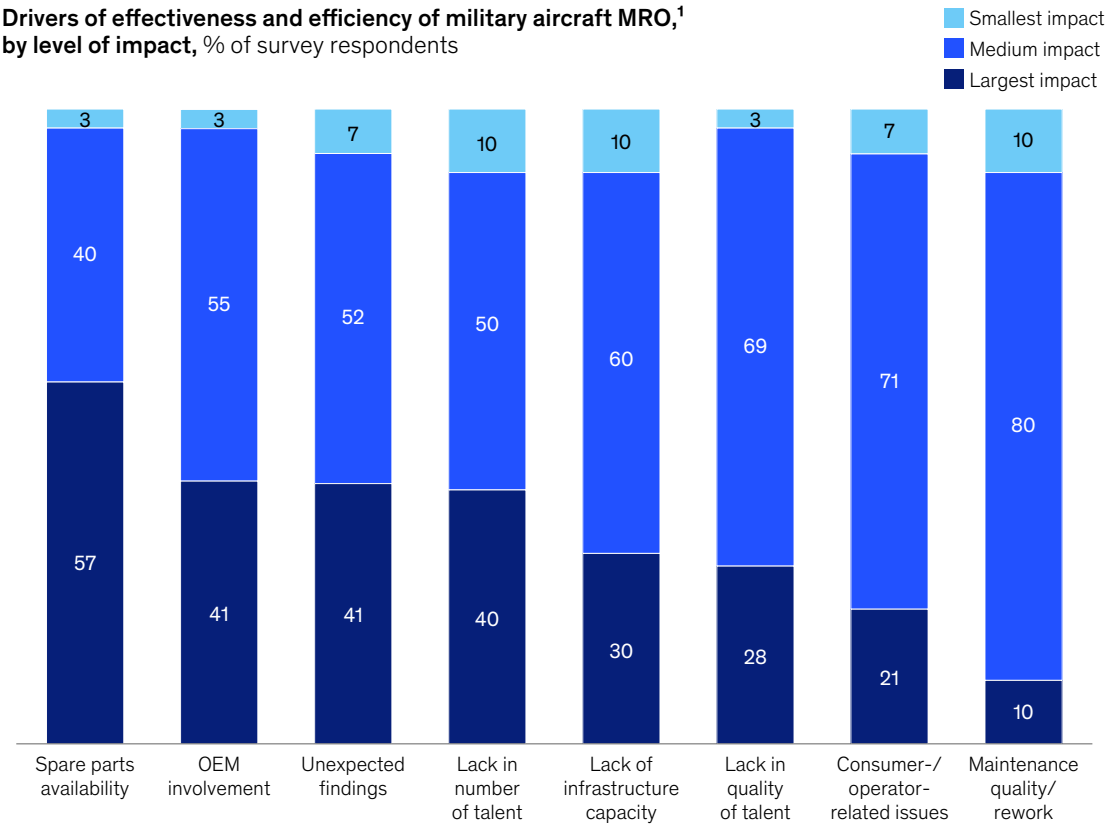
In maintenance, unexpected findings are common and can lead to inefficiencies. These include increased waiting and process times due to additional coordination requirements

[10] Green time describes the remaining operational life of an aircraft (or engine or component) prior to any required overhaul, while ground time describes the time the aircraft is unavailable for service, that is, unproductive aircraft time.
[11] HoM reflects how much of the technicians' available time in a shift they can spend on value-adding work at the aircraft instead of preparing work, searching for materials or tools, filling out documentation, et cetera.
[12] Based on expert interviews.
[13] Cindy Levy, Matt Watters, and Shubham Singhal, "A proactive approach to navigating geopolitics is essential to thrive," McKinsey, November 12, 2024.

Exhibit 1

Availability of spare parts could have the greatest impact on effectiveness and efficiency of military aircraft maintenance, repair, and overhaul.

Drivers of effectiveness and efficiency of military aircraft MRO,[1] by level of impact, % of survey respondents



Note: Figures may not sum to 100%, because of rounding.
[1]Maintenance, repair, and overhaul.
Source: McKinsey Defense MRO Survey Study (n = 30)

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(say, with the customer); unexpected demand for resources, such as spare parts or materials, critical capabilities, or machine availability; and the postponement of relevant nonsafety concerns, leading to an accumulation of issues and schedule overruns, for example, in base maintenance. Improving practices for managing unscheduled maintenance can improve these inefficiencies. Commercial MROs have established best practices and technologies: They use stochastic models and predictive maintenance linked to inventory management, which can reduce waiting times and increase equipment turnaround times. Military MRO providers could adopt similar solutions.

Lack of talent

The aerospace and defense industry is struggling with a workforce shortage, largely due to an aging workforce and recruitment challenges.[14] Many commercial MROs have recognized these talent challenges, taken steps to overcome them, and could advise military MROs on talent strategies, as

[14] *Aviation talent forecast,* CAE, 2023; Brooke Weddle, Giulietta Poltroniere, Hugues Lavandier, and Andy Voelker, "The talent gap: The value at stake for global aerospace and defense," McKinsey, July 17, 2024.

well as explore collaborative setups. For example, commercial MROs have designed recruiting programs to attract new talent by improving their employee value propositions, enhancing monetary and qualitative conditions to attract suitable candidates, and sourcing talent from new locations. Similarly, they have addressed retention challenges through improved career journeys, offering clear development paths and new capabilities, and incentivizing long-term loyalty. However, it should be noted that commercial MROs are more flexible in crafting talent paths and adjusting salaries and nonmonetary perks compared to military MRO providers.

By applying the suggested levers to improve military MRO, European NATO countries could potentially reduce the investment needed in new aircraft and increase the speed at which they reach their defense capability goals. For example, in a hypothetical calculation, increasing equipment availability by 10 percent would be equivalent to gaining 40 additional aircraft.

The role of digital in improving MRO efficiency

Given the potential of new technologies to improve operational efficiency and effectiveness across all industries, we asked the MRO experts for their perspectives on digital solutions in military aircraft MRO. (For further information on gen AI in aircraft MRO, see "The generative AI opportunity in airline maintenance.")[15]

They considered predictive maintenance to be the most impactful technology (Exhibit 2). Since AI collects and analyzes asset condition data to identify patterns and algorithms that can predict when failures may occur, predictive maintenance can help maximize asset operability for military MRO providers and allow components to be replaced or repaired before they fail.

Half of the respondents whose organizations have adopted digital reported that revenues increased by over 5 percent and engineering productivity by over 10 percent. More than a quarter of respondents indicated they have realized around a 10 to 20 percent reduction in maintenance costs, enabled through digital.

Improved military MRO could benefit industry stakeholders

Enhancing military MRO capabilities could be a mutually beneficial opportunity for industry stakeholders, including MRO providers, OEMs, and operators or customers, such as ministries of defense (MoDs).

MRO providers: Based on our survey, we learned that air forces have reduced their in-house MRO spend by approximately 5 percent over the past ten years, with both OEMs and commercial MRO providers benefitting. Commercial providers could further expand their market share by broadening their service offerings for the military market and applying advanced capabilities—securing new and potentially countercyclical revenue streams and even opportunities to design and test new solutions or products. Market-entry strategies could be tailored around specific aircraft platforms where MRO providers have the deepest capabilities or for countries that have sufficient fleet size and MRO budget and are open to engaging with new entrants. Actively competing for this business, however, may require commercial MRO providers to consider partnerships with another market incumbent, a joint venture, or M&A activities.

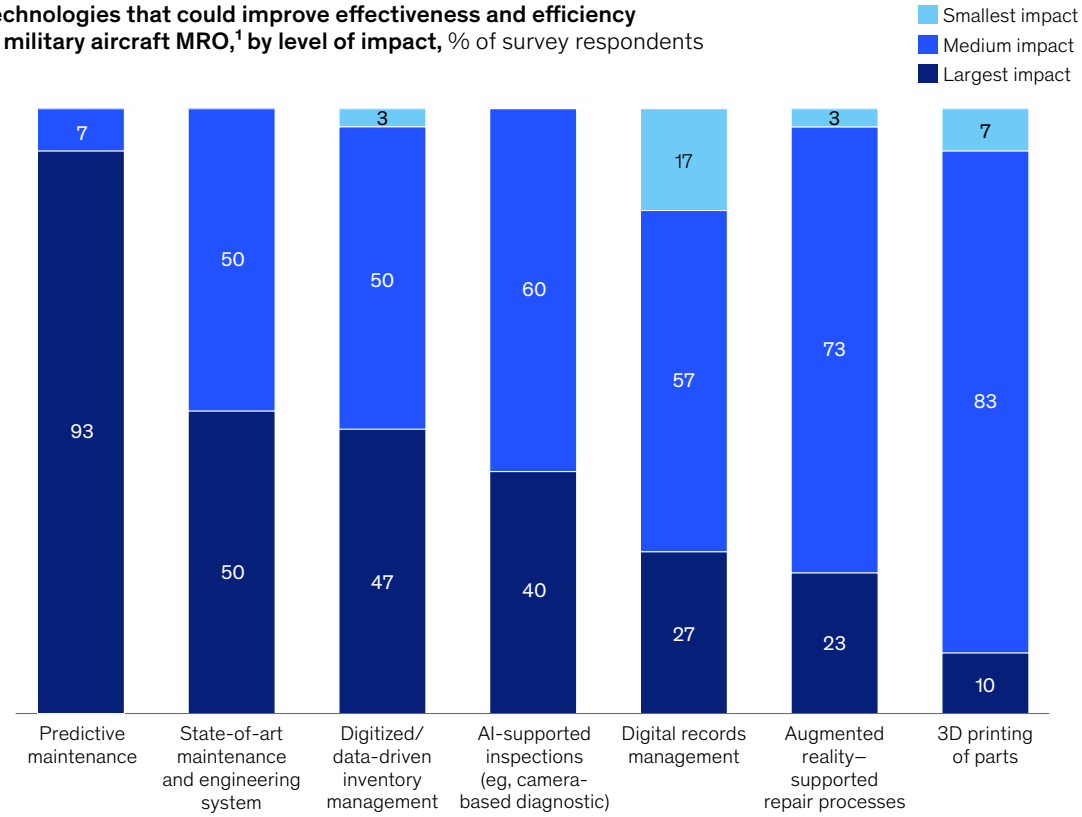
OEMs: Airframe, component, and engine OEMs are already providing MRO services to operators but could consider strengthening their capabilities as described above. Depending on the service contract, this may improve profitability or competitiveness, particularly considering new market entrants or the expansion of commercial MRO providers. OEMs benefit from capitalizing on proprietary aircraft and engine data, which are required to train predictive and preventive maintenance solutions. Partnerships with commercial MRO providers could accelerate capability buildup or unlock capacity expansion.

[15] "The generative AI opportunity in airline maintenance," McKinsey, April 8, 2024.

Exhibit 2

Predictive maintenance could most improve effectiveness and efficiency in defense maintenance, repair, and overhaul.

Technologies that could improve effectiveness and efficiency of military aircraft MRO,[1] by level of impact, % of survey respondents



Note: Figures may not sum to 100%, because of rounding.
[1]Maintenance, repair, and overhaul.
Source: McKinsey Defense MRO Survey Study (n = 30)

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Both MROs and OEMs: They could build new cornerstone capabilities that are expected to grow in demand over the next decade (for example, heavy vertical lift or air-to-air fueling). They could improve their coverage of types of systems—such as unmanned aerial vehicles and onboard avionic systems with advanced capabilities—which would require more efficient MRO services than currently predicted for sophisticated platforms. Additionally, they could develop solutions to provide services at decentralized, movable, and concealed hubs for armed forces that may need to adapt to new threats. This would mean deploying OEM personnel at a base that is neither a home nor a frontline one, enabling maintenance operations to be concentrated across platforms, thus increasing efficiency.

Operators: Some operators have already improved their MRO capabilities or achieved cost reductions through increased competition. Operators could further incentivize capability buildup through availability-based contracts (moving from cost-plus to performance-based) or transfer some control of their maintenance personnel and infrastructure to OEMs or MROs to free up capacity or optimize costs.

With the changing geopolitical landscape, European NATO countries are looking to rapidly increase their defense capabilities—effective MRO is a cost-efficient way to improve the availability of mission-ready systems. In the face of decreased military O&M budgets, MRO providers in the military air domain, as well as new providers, could capture this opportunity by taking steps to improve their operational efficiency. That could optimize fleets, reduce costs, and contribute to Europe's security.

Christian Langer is a partner in McKinsey's Hamburg office; **Daniel Riefer** is a partner in the Munich office; **Giacomo Gatto** is a partner in the London office; and **Katharina Wagner** is an associate partner in the Berlin office.

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Aerospace & Defense Practice

A different lens on Europe's defense budgets

European NATO countries are looking to ramp up their defense budgets—potentially adding much more direct in-country readiness per euro.

by David Chinn and Jonathan Dimson
with Josie Lambert and Timothy Chapman

February 2025

European NATO countries' defense spending has long fallen short of the organization's target of 2 percent of GDP, set in 2014.[1] In the decade since, it has averaged only 1.6 percent. However, geopolitical tensions have caused European NATO countries to reevaluate their defense capabilities. European defense spending is on the rise, standing at an average of 2.2 percent of GDP in 2024.[2]

Estonia and Latvia have announced commitments to spend 5.0 percent of GDP, and Poland plans to reach 4.7 percent in 2025.[3] Other countries are publicly discussing increasing their defense spending to 3 percent or even as much as 5 percent.[4]

What is the potential impact of these proposed increases? Our analysis focuses on the top spenders among European NATO countries: ones that each spent $10 billion or more on defense in 2024, according to NATO estimates (exhibit).[5]

NATO has a standard definition of defense spending, agreed by all NATO allies and regularly reviewed, most recently in early 2024: "Payments made by a national government specifically to meet the needs of its armed forces."[6] Looking into the individual country breakdowns, this figure typically includes spending that, while important, does not contribute directly to conventional and hybrid deterrent and combat capabilities. This may include funding for nuclear deterrents (in France and the United Kingdom), pensions from historic conflicts and other spending on retired personnel, donated material (for example, to Ukraine), and spending on community engagement (such as museums).

To understand the relative impact of additional spend, we have defined "conventional in-country defense spend" as what is left after subtracting these areas of spend, which typically account for about a fifth of the total defense budget in European NATO countries.

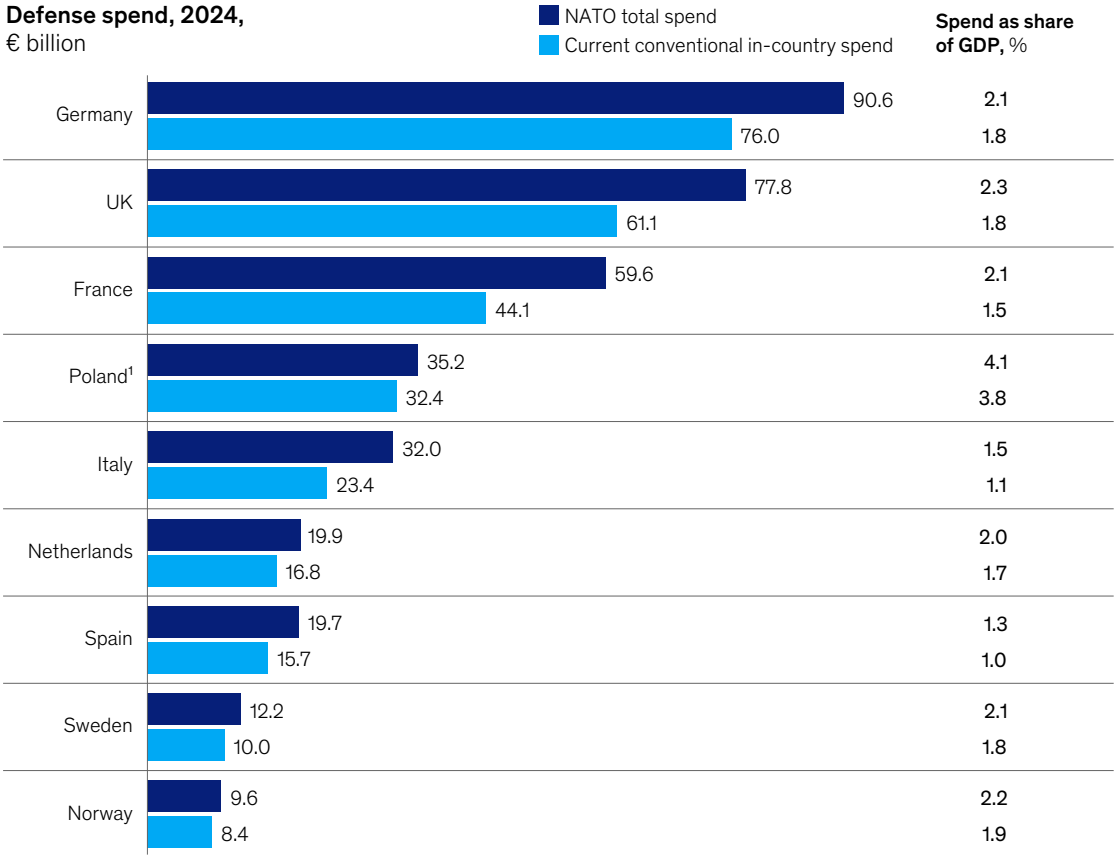
While this naturally results in a lower share of "core" defense spend of GDP than the broader NATO definition, anticipated additional spending will likely be channeled into rebuilding stockpiles and to new and more modern equipment such as uncrewed and autonomous capabilities, although there may also be additional commitments to Ukraine.

This implies a proportionally higher impact per additional euro spent on these areas. For example, our calculations estimate that if total defense spending in a given country were to rise from 2.2 to 3.0 percent of GDP (an increase of 36.0 percent), this could translate into a 47.0 percent increase in spending on conventional or hybrid deterrence and combat-related defense. Taking into account innovation leading to more sophisticated and effective systems, increased spending could generate much more than a 47 percent increase in defense outputs and readiness.

[1] "NATO spending by country," World Population Review, accessed February 2024.
[2] "Defense expenditure of NATO countries (2014–2024)," North Atlantic Treaty Organization, June 17, 2024.
[3] Gergely Szakacs and Karl Badohal, "Poland leads NATO on defence spend—but can it afford it?," Reuters, October 22, 2024.
[4] Jonathan Beale, "Britain must train citizen army, military chief warns," BBC News, January 24, 2024; "Russia may be able to attack NATO as early as 2026 or 2027 says Duda," Polish Press Agency, March 19, 2024; "Remarks by NATO Secretary General Mark Rutte at the European Parliament's Committee on Foreign Affairs and Subcommittee on Security and Defense," NATO, January 13, 2025; Liudas Dapkus, "Lithuanian president backs Trump's NATO defense spending goal amid ongoing Russian threat," AP, January 31, 2025.
[5] "Defense expenditure of NATO countries (2014–2024)," North Atlantic Treaty Organization, June 17, 2024.
[6] "Defense expenditure of NATO countries (2014–2024)," North Atlantic Treaty Organization, June 17, 2024.

Exhibit

Of the top spenders in NATO Europe, typically four-fifths of budget is on conventional in-country spend.



[1]Accurately sizing Poland's support to Ukraine is not possible, as it is not declared for security reasons.
Source: Countries' annual government budgets; Kiel Institute; NATO

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David Chinn is a senior partner in McKinsey's Tel Aviv office; **Jonathan Dimson** is a senior partner in the London office, where **Josie Lambert** is an associate partner; and **Timothy Chapman** is a consultant in the Wroclaw office.

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