NATO
OTAN
Science & Technology Organization (STO)

Science and Technology Trends 2025–2045

Volume 1

Contents

Forewords

Now more than ever, geopolitics and strategic decision-making are impacted by, and even driven by, science and technology (S&T). As this trend intensifies, it is vitally important that NATO and Allies understand how decisions made today affect future options, opportunities, and preparedness. To do this, as leaders, we must assess the evolving science and technology environment and Macro Trends against the backdrop of the current era of heightened strategic competition. Taking a 20-year outlook, this report offers an opportunity to better understand these complex relationships. As these trends unfold, it will be increasingly vital that political and military decision-makers not only learn from relevant technical experts but also work closely with trusted partners across society. Ensuring the Alliance benefits from science and technology advancements to the greatest extent possible will also require us to give priority to ethical and legal safeguards, global partnerships, and collaboration both with the private sector and within the scientific community. This whole-of-society approach will enable leaders to assess future risks, opportunities, and choices as they prepare for future scenarios and work to minimise future shocks for the over 1 billion citizens our Alliance defends.

Radmila Shekerinska
NATO Deputy Secretary General

Science and technology is the bedrock of our modern society, ensuring our prosperity and driving our progress. As the body tasked with meeting the collective science and technology needs of the Allies and partners, it is incumbent upon the Science & Technology Organization to provide evidence-based strategic advice for NATO leadership. Given the increasing importance of science and technology for strategic decision-making, it is vital to build on existing technical knowledge and understand the context in which scientific and technological developments are occurring. The overview of interdependencies between scientific and technical areas and their economic, geopolitical, and social effects and enablers provided by this report offers useful context for understanding our current and future geostrategic environment. The six S&T Macro Trends described in this report therefore empower NATO and Allies' decision-makers to consider the choices before them and how they can best prepare the Alliance today to face future challenges. Continued knowledge-building and investment in science and technology will strengthen NATO's and Allies' ability to outperform the competitors of today and tomorrow and ensure that we remain robust, resilient, and ready to respond to any threat.

Dr Bryan Wells
NATO Chief Scientist

Introduction

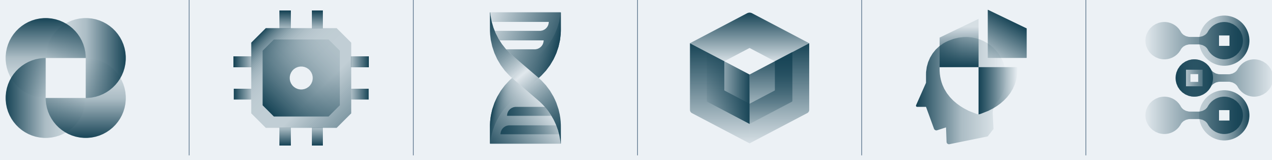
This Science & Technology (S&T) Macro Trends Report provides an overview of the socio-technical trends that will shape the technology landscape from 2025 to 2045. It analyses links between emerging and disruptive S&T areas and their macro-economic, geopolitical, and societal effects and enablers.

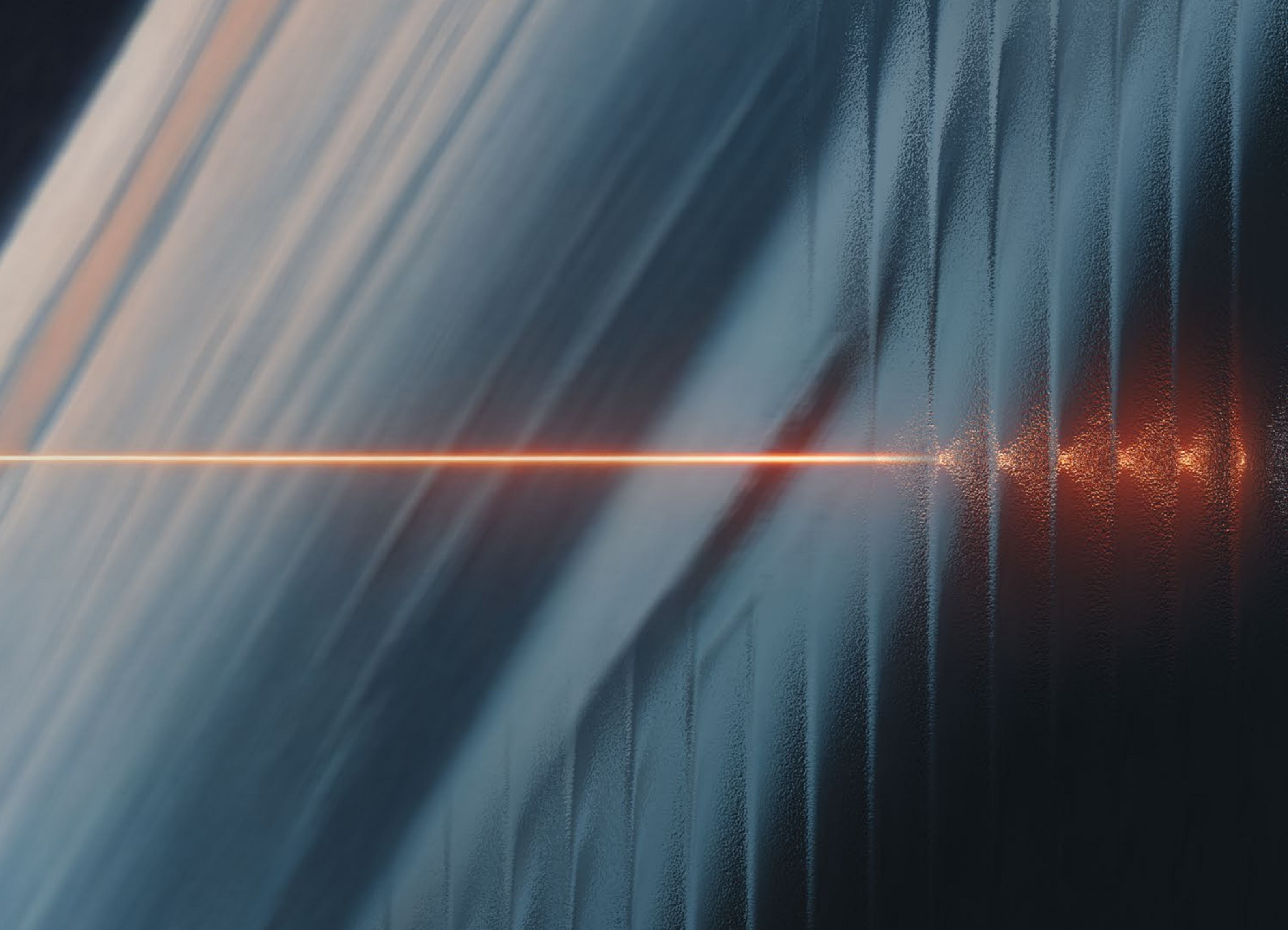
This Public Release volume represents the latest iteration of the NATO Science & Technology Organization's (STO) flagship research report and builds on the previous version, the S&T Trends Report 2023-2043 published in March 2023. In alignment with previous S&T Trends Reports, this volume aims to build understanding on the impact of S&T on the Alliance's political decision options, defence capabilities, military operations, and enterprise functions.

As a response to the increasing linkages and dependencies between technology and geopolitics, this publication complements existing foresight work across NATO by offering an S&T perspective on trends that will affect diverse aspects of the Alliance over the next 20 years. While targeting a senior leadership audience, this report also aims to be accessible to a wide range of readers, including practitioners from within and outside of the S&T environment.

In offering insights into how S&T shapes geopolitical priorities and vice versa, this report offers a perspective for senior decision-makers on how to respond to challenges on (and over) the horizon by making strategic choices now.

Evolving Competition Areas	Race for AI and Quantum Superiority	Biotechnology Revolution	Resource Divide	Fragmenting Public Trust	Technology Integration & Dependencies





Executive Summary

Each of the S&T Macro Trends describes a distinct global trend that is *uniquely impacted by* and *distinctly impacts* S&T. These six trends are shaping and/or will shape NATO's strategic landscape and influence how emerging and disruptive technologies (EDTs) continue to evolve. They will also impact how Alliance governments and societies respond to and develop future S&T policy. The following trends are anticipated to define the S&T landscape from 2025-2045, with differing impacts and timelines expected for each.

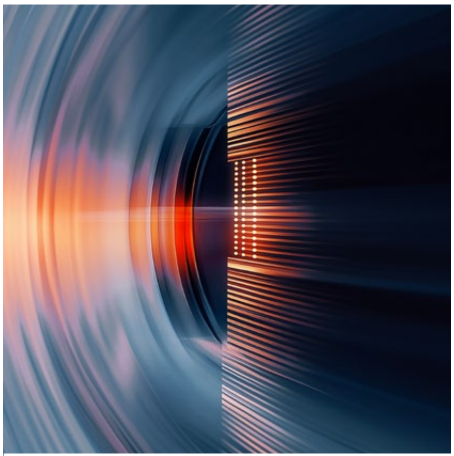
MACRO TREND 1

Evolving Competition Areas

As global strategic competition intensifies, S&T advances will shape and transform the nature of competition, in traditional domains and in non-traditional ones – for example, cyber, space, hybrid and information, and in geographical regions such as the High North. In turn, the continued hybridisation of warfare and heightened importance of multi-domain operations (MDO) are expected to fuel further reliance on S&T across all domains.

Key judgements

- Emerging technologies offer leaders a spectrum of strategic choices to be made now to ensure that the Alliance is fit for the future operating environment.
- Critical technology areas will shape the future of geopolitical competition and, simultaneously, geopolitical competition will fuel future S&T development.
- The continued hybridisation of warfare has not only made shocks from tactics such as economic coercion more likely, but has also heightened the importance of the cyber and space domains in future contests and conflicts.



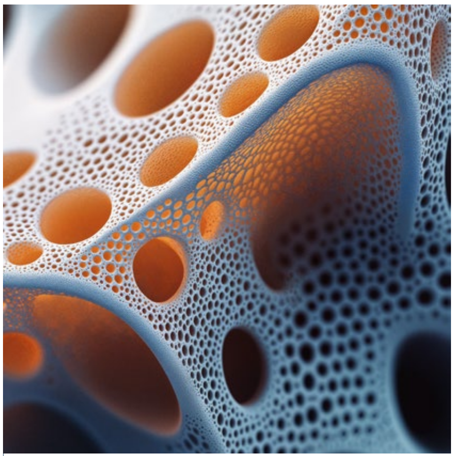
MACRO TREND 2

Race for AI and Quantum Superiority

Artificial Intelligence (AI) and quantum not only represent technology areas that will transform a diverse range of industries in the next 20 years, but they are also areas in which competition between dominant actors will accelerate over time. An essential and long-term aspect of this trend will be the challenge of finding, training, and retaining talent.

Key judgements

- Digital transformation (including access to large quantities of quality data, as well as storage and dissemination tools) will remain essential as AI and quantum technology continue to develop.
- Talent acquisition, training, and retention will be a key battleground for technology competition.
- Like-minded nations will need to pool expertise and resources to win this race.



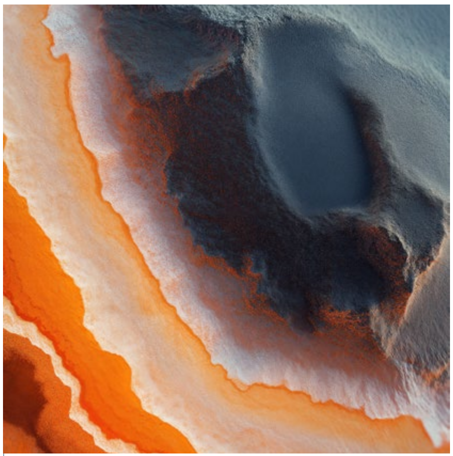
MACRO TREND 3

Biotechnology Revolution

The next revolutionary technology cycle will be driven by synthetic biology. In addition to continuing developments in related technology areas (e.g., biodata and biosensors), this trend will bring issues such as research security (safeguarding sensitive research) and regulation to the forefront.

Key judgements

- Synthetic biology and related technologies will have a disruptive, revolutionary impact within the next 20 years, in both the civilian and military realms.
- While the potential benefits from increased biotechnology use are substantial, especially for healthcare, the risks of harmful uses are also enormous. This necessitates careful consideration of security and defence implications, including the protection and sharing of research.
- Research safeguards need to align with our shared values and norms.



MACRO TREND 4
Resource Divide

S&T advancement serves both as a driver of deepening resource divides and as a potential enabler of economic development via AI-enabled solutions, bio- and green technology, and novel/advanced materials. Economic resilience and security as well as NATO's global partnerships will become increasingly crucial in relation to this trend. Techno-nationalism is also expected to be further prioritised by leaders who view technological capability as increasingly integral to economic, societal, and national security needs.

Key judgements

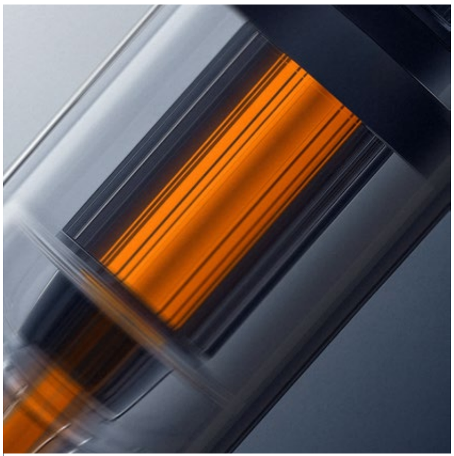
- Climate change will impact the Alliance's shared access to critical resources for S&T innovation.
- Upcoming shocks, especially but not exclusively stemming from climate change, will exacerbate existing tensions between nations that can more easily recover from such shocks and those that cannot.
- Future technology advancement and adoption will act as both a solution to these growing tensions as well as an accelerator of them.

MACRO TREND 5
Fragmenting Public Trust

Trust in science, institutions, and governments is vulnerable to further undermining and fragmentation, and technology acts primarily as an accelerator of these challenges, especially via AI-generated information threats. As a result of these developments, topics such as strategic communications, digital sovereignty, the need for trustworthy S&T solutions, and improved technology education are expected to increase in importance within the next 20 years.

Key judgements

- Global leadership is needed to encourage the responsible use of EDTs.
- Technology, especially AI, is being used to decrease public trust (in governments, institutions, and science), and the future impact of these developments will be further complicated by rising political polarisation.
- In the long term, tech-fuelled solutions may offer tools for combatting disinformation and misinformation, but in the short term, strategic communications, legal/regulatory mechanisms, and technology education will be increasingly vital.



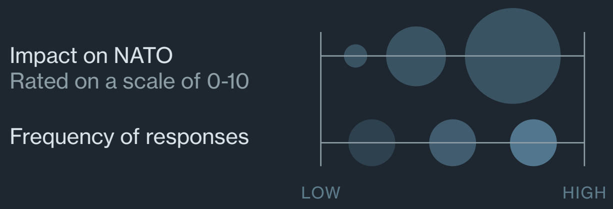
MACRO TREND 6
Technology Integration & Dependencies

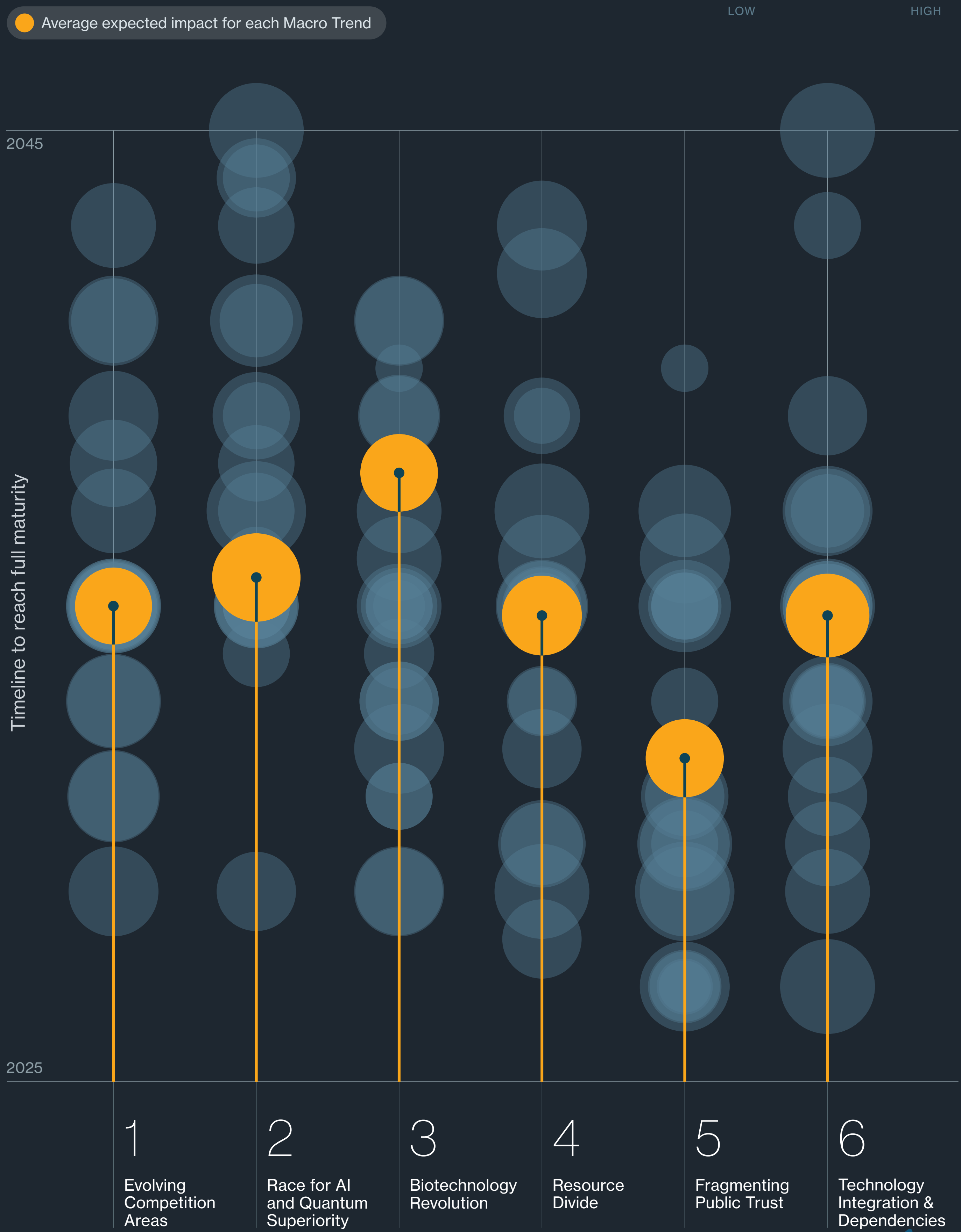
While S&T advancements will continue to provide solutions to complex challenges, access to these solutions will be unequal. For those with cutting-edge technology, differences in Concepts of Operations and regulation will pose challenges for interoperability and standards. Meanwhile, as innovation is increasingly driven by the private sector, new challenges for civilian-military integration will emerge, and the long-term effects of increased dependency on S&T across civilian and military domains may bring unexpected consequences.

Key judgements

- Future S&T capabilities need to be interoperable by design.
- Interoperability will become more critical than ever for Allies in the next 20 years, yet new challenges to achieving it will also arise as disparities in technology access, usage, and regulations become more pronounced.
- Economic cooperation is needed with like-minded nations and private sector partners.
- Increasing dependencies on private actors for critical defence needs will become a greater challenge as S&T becomes increasingly essential for a wider range of military operations.

S&T Macro Trends
Timeline & impact





Cross-cutting issues

Within these six S&T Macro Trends, several key themes cut across the S&T and geopolitical areas discussed in the following report. Four primary issues are identified as being particularly significant for all Macro Trends. These are:

- Challenged Rules-based International Order (RBIO)
- Climate change
- Global partnerships
- Increased role of the private sector

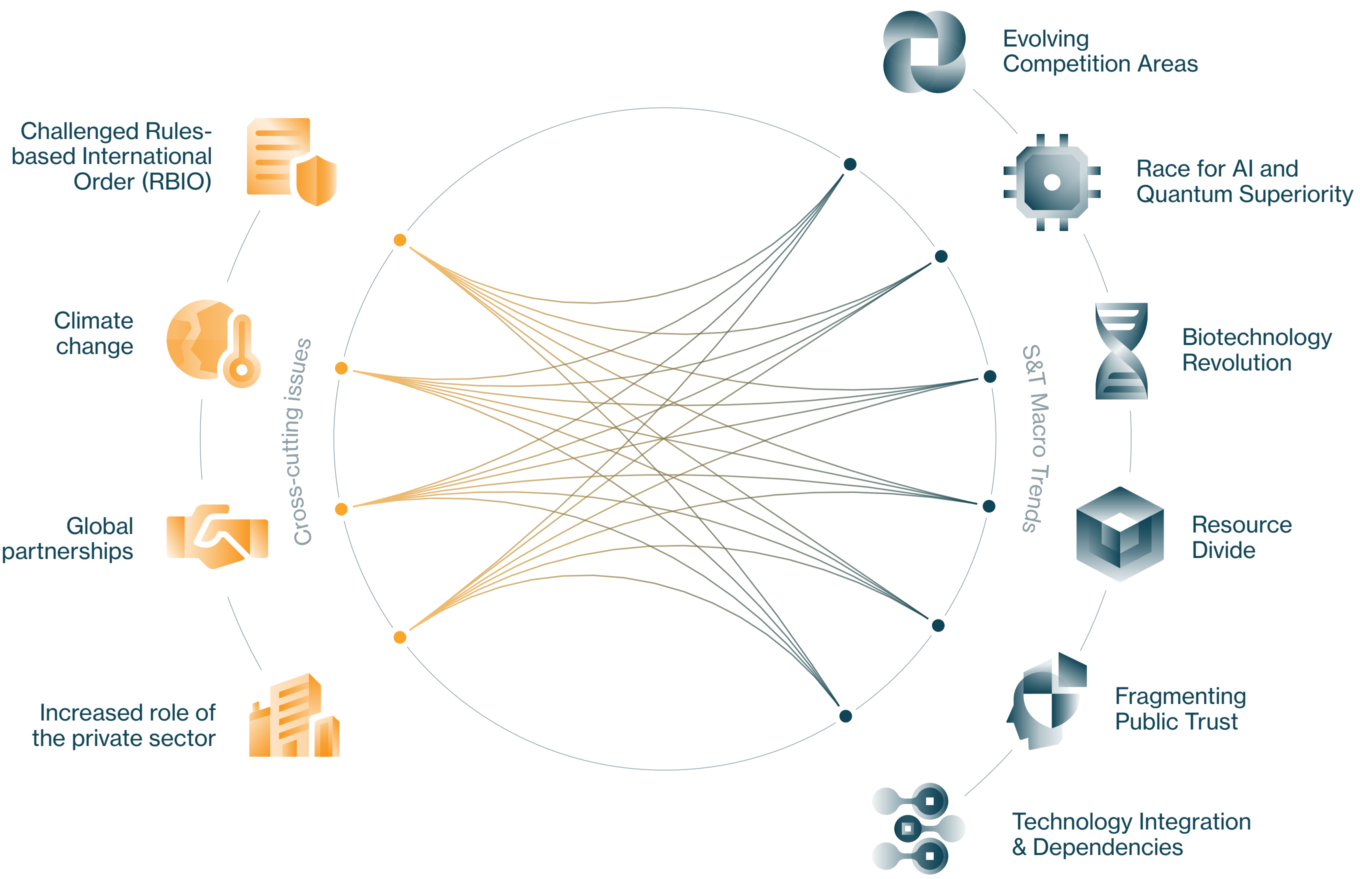
Each represents a driver and/or result of multiple Macro Trends, hence these four issues are simultaneously enabling future S&T advancement and/or will be significantly affected by future S&T development. The cross-cutting issues provide a thematic lens through which to view the S&T Macro Trends and their combined impact, and are therefore highlighted in the trend implications.

Considerations regarding the promotion of scientific collaboration while simultaneously safeguarding sensitive research or ensuring 'research security' is also highly relevant for several Macro Trends. Research security refers to the protection of scientific research – especially that which has defence and security applications – from undesirable foreign state (or non-state) access, influence, or espionage, with the aim of protecting national security and achieving decisive advantage from technology across all instruments of power. These concerns are vital to consider when assessing future S&T development. However, research security was not identified as a primary cross-cutting theme across all six trends.

Report structure

In addition to the key judgements outlined above, this report assesses the six S&T Macro Trends by explaining the background, implications, state of play, and choices for leadership related to each trend.

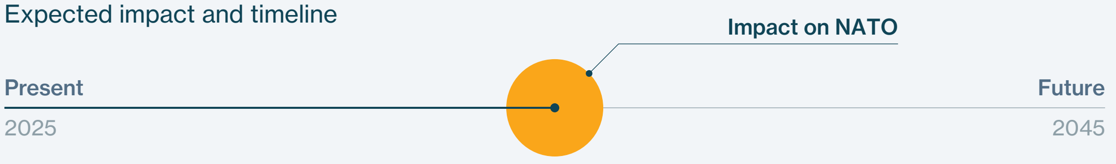
Cross-cutting issues for the S&T Macro Trends



Macro Trend 1

Evolving Competition Areas

Expected impact and timeline



Key judgements

Emerging technologies offer leaders a spectrum of strategic choices to be made now to ensure that the Alliance is fit for the future operating environment.

Critical technology areas will shape the future of geopolitical competition and, simultaneously, geopolitical competition will fuel future S&T development.

The continued hybridisation of warfare has not only made shocks from tactics such as economic coercion more likely, but has also heightened the importance of the cyber and space domains in future contests and conflicts.

1.1 Background

As stated in the NATO Strategic Concept (2022), the current security environment is characterised by “strategic competition, pervasive instability and recurrent shocks.”[1] In this environment, **EDTs are gaining strategic importance and becoming key arenas of global competition**. As global competition intensifies, S&T advancements will shape and transform the nature of strategic competition, including in traditional domains and non-traditional ones – for example, hybrid and information warfare or contests in the High North. In turn, the continued hybridisation of warfare (i.e., the combined use of traditional military aggression with tactics such as coercion, influence operations, or sabotage) and heightened importance of multi-domain operations (MDO) will fuel further reliance on S&T across domains, since technology offers vital links between military systems and operations.

Experts widely accept that great power competition is on the rise and shows no sign of abating in the short term.[2] While current trends do not necessarily result in the eruption of additional kinetic conflicts, it is especially critical to monitor the full spectrum of friendly-to-confrontational interactions between great powers and their allies at a time when direct confrontation between powerful (nuclear-armed) nations appears a greater danger than it has been for the past three decades.[3] Viewing this trend through the S&T lens explains how critical technology areas are likely to shape the future of competition as well as how geopolitical competition may fuel future S&T development.

1.2 Implications

Strategic competition is a key driver of S&T development, and at the same time, S&T advancement allows for new areas of competition. This is especially true for the cyber and space domains, where below-threshold attacks are expected to significantly increase in the future. Furthermore, the likelihood of action taken in the cyber or space domain to spur a direct, kinetic conflict is also increasing. Given that everything from the global stock market to GPS relies on space assets, this domain is of particular concern as space becomes more congested and contested.

Continuous technology advancements have also created opportunities for both state and non-state actors to engage in more diverse forms of conflict – for example, in the cyber domain or through other non-kinetic, hybrid, or grey-zone attacks. Therefore, conflicts in non-traditional domains as well as below-threshold attacks are highly likely to become more commonplace in the next 20 years. Additionally, the fact that innovation, including defence innovation, is primarily driven by the private sector will allow super-empowered individuals to play a role in shaping the future of strategic competition. These developments pose significant challenges for attribution, norm-setting, and crafting proportional responses.

Compounding these challenges, the exponential increase in AI integration could transform standard methods for conflict prevention, leading experts to doubt whether traditional crisis communication mechanisms can sufficiently address coming risks.[4]

Conflicts in non-traditional domains [...] are highly likely to become more commonplace in the next 20 years.

1.3 State of play

Technology has always been central to determining victors in all forms of competition and conflict. However, the current landscape offers more options than ever due to both the existence of additional military domains and evolving applications for technologies in military contexts. Today, advantages from technology are increasingly determinant of battlefield success,[5] and these dynamics are generally understood by strategic decision-makers. Taking the United States and the People's Republic of China as examples, the past 2 years alone have demonstrated a notable uptick in US initiatives to prevent China from gaining a technological advantage, as policymakers in both nations clearly consider innovation to be a key factor of economic and military superiority.[6]

Advantages from technology are increasingly determinant of battlefield success.

Space

The space domain is widely considered to be an increasingly contested environment in which competition for geopolitical and military supremacy is expected to play out, a challenge for which no international consensus exists.[7] While space has long been an enabler of all other military domains, from communications and weather forecasting to tracking adversaries and providing position, navigation, and timing (PNT), its increasing applications have led to greater reliance on its assets over time, making it a critical arena not only for power projection but also operational effectiveness. Space is also characterised by rapid transformation[8] due in large part to increasing access to technology and, as a result, access to space itself.

The increased strategic importance of space and related dependencies for military activities has naturally led to the space domain becoming more militarised over time – for example, through reinvigorated efforts to develop anti-satellite weapons and counter-space capabilities, such as conducting cyber-attacks or jamming/spoofing satellites. In the longer term, accelerated proliferation of earth-to-space (especially anti-satellite) weapons, directed energy weapons, and more sophisticated counter-space capabilities enabled by emerging technologies is not difficult to imagine, especially if international norms and regulations for what operations can be conducted in space are not updated to address the risk of a potential space arms race.[9] These developments are already illustrating the potential for a substantial uptick in space contest and conflict, even if it remains below the threshold of kinetic warfare.[10]

The exponential increase in space accessibility – via the commercialisation of space and proliferation of civilian usage and, looking further forward, predicted increases in the use of hypersonics and in-space propulsion technologies – will further congest the space environment. Furthermore, as space becomes more congested with commercial and other actors, the potential for miscalculation, mistakes, in-space collisions, and escalating tensions will only heighten in the coming years.

Cyber

The cyber domain is often cited as an equally important arena for near- and medium-term competition[11] as many international actors continue to favour and, due to continued technology advancements, have more options for below-threshold and non-kinetic aggressions. Although shifts in this domain tend to be difficult to track, in part due to attribution challenges, it is clear that the importance and impact of cyber conflict should not be underestimated. Even in scenarios that are largely defined as conventional warfare, cyber plays a crucial role for all sides. For example, the Russian Federation conducted a cyber-attack against Ukraine prior to its full-scale land invasion of Ukrainian territory in 2022, with the aim of disrupting command and control (C2) capabilities at a critical moment for the Ukrainian military.[12] Increasingly sophisticated cyber technologies will continue to fuel the hybridisation of warfare, which is likely to create more frequent disruptions caused by more precise targeting of critical and civilian infrastructure and financial systems.

The hybridisation of warfare

The continued hybridisation of warfare extends beyond traditional military domains, and technological advancements are shaping these developments as well. For example, the combined

use of AI with robotics and autonomous systems already enables militaries to choose from more diverse types of operations and effects, especially below-threshold activities. Advanced technologies not only enable more and more precise attacks, but also are increasingly difficult to detect and attribute.[13] The challenges and opportunities posed by these developments are likely to increase in importance not only as a result of global competition, but also at the operational level, as MDO are more widely deployed. Military experts anticipate an increase in MDO in the near and medium term, due to a growing need for militaries to synchronise efforts and achieve real-time integration across numerous domains simultaneously.[14]

Technological developments are also increasing opportunities for hybrid warfare tactics such as economic coercion and the spread of information threats (more on the latter in Macro Trend 5). Regarding economic coercion, it is recognised that technology is a major factor regarding nations using export controls to exert influence, as seen for example with recent US policy shifts on semiconductors.[15] More broadly, recent national, international, and intragovernmental initiatives[16,17] focused on economic security and supply chain resilience have been fuelled by several factors, including increased great power competition, Russia's war of aggression against Ukraine, and the COVID-19 pandemic. However, these efforts also stem from the increased importance of technology and critical dependencies that offer opportunities for coercion, influence, and exploitation. As competition increases, there has also been an uptick in the weaponisation of economic dependencies or 'weaponised interdependence'.[18]

Economic security will therefore require more than de-risking supply chains or safeguarding critical infrastructure. Consistent commitment to prioritise technology development and fostering innovation and investment is also necessary. Additionally, responses to these challenges must involve cooperation among diverse international actors to align economic security priorities with shared strategic objectives.[19,20]

Technological developments are also increasing opportunities for hybrid warfare tactics.

Regional partnerships

Regional divides act as both an enabler of global competition and a result of it. Experts predict that, in addition to more frequent global shocks, growing strategic competition may also encourage further regionalisation. In addition to economic and technology-related factors such as the aim to decrease dependencies or de-risk, this trend will likely also be affected by climate change, migration, demographic changes, and rising authoritarianism. Smaller nations in particular are likely to be affected as more frequent economic, climate, security, and geopolitical disruptions will heighten the importance of having reliable and stable trade regimes.

Therefore, smaller economic actors may be forced to rely on partners who not only offer the cheapest solutions but those who appear to be most resilient against coming shocks. One possible result could be that the influence of economic blocs such as BRICS (originally composed of Brazil, Russia, India, China, and South Africa, but has since expanded its membership) will grow. Developments like this would challenge the influence of institutions such as the International Monetary Fund and World Bank and likely contribute to further instability.[21]

Growing discontent in the southern hemisphere or 'Global South', including parts of Africa and the Middle East, Central and East Asia, and Latin America, is also likely to impact global competition. Many nations in these regions hope to rebalance global power dynamics and encourage more equitable divisions of prosperity, security, and technology. These aims are made significantly more difficult by climate change, which disproportionately affects these same areas.[22] Simultaneously, these are also the nations in which competition for global influence will likely intensify most as traditional global powers attempt to deepen existing ties or build new alliances.[23] In this context, the importance of existing international partnerships would increase exponentially. However, these relationships could also become less predictable if new alliances are potentially determined by ideological and political values or short-term economic security and technology needs rather than long-standing trade agreements or geography.[24]

1.4 Choices for leadership

As global strategic competition intensifies, unpredictability and uncertainty are also on the rise, making it difficult to anticipate which shocks to prepare for and when. Decision-makers will benefit from considering multiple future scenarios, possibly using advanced immersive simulation and modelling opportunities to better understand the choices available. However, no matter the future contest or conflict scenario, it is clear that traditional notions of deterrence and escalation must adapt to the increasingly technology-dependent defence environment.

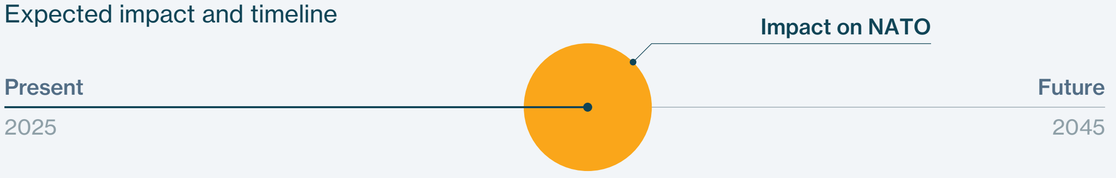
The fundamental dependence of civilians and militaries on space assets represents a crucial vulnerability that is only increasing over time.

Leadership will also need to address the growing importance of space. Although all military domains rely on technology, the fundamental dependence of civilians and militaries on space assets represents a crucial vulnerability that is only increasing over time. In the civilian realm alone, space-based systems are integral to more than 50% of critical infrastructure and services in members of the Organisation for Economic Co-operation and Development (OECD).[25] As the importance of space resources and technologies grows, leaders should consider options for building resilience and responding to future tensions.[26] Looking forward, serious efforts must also be dedicated to investigating how international legal frameworks can be leveraged to mitigate the growing risk of space conflict.[27]

Macro Trend 2

Race for AI and Quantum Superiority

Expected impact and timeline



Key judgements

Digital transformation (including access to large quantities of quality data, as well as storage and dissemination tools) will remain essential as AI and quantum technology continue to develop.

Talent acquisition, training, and retention will be a key battleground for technology competition.

Like-minded nations will need to pool expertise and resources to win this race.

2.1 Background

Although AI and quantum are fundamentally very different S&T areas, their technologies will be distinctly impactful and disruptive across a very diverse range of sectors. Therefore, nations with cutting-edge AI and/or quantum capabilities will have an advantage when it comes to withstanding future shocks and answering on-the-horizon (and over-the-horizon) challenges. While other technology areas are similarly wide-ranging in their effects, for example automation or 'autonomy', AI and quantum are less predictable and more disruptive in terms of their long-term effects across various sectors, including the defence sector. Hence, it is especially important to assess the likely future impact of these two technology areas.

Nations with cutting-edge AI and/or quantum capabilities will have an advantage when it comes to withstanding future shocks.

AI and quantum not only represent technology areas that will transform a diverse range of industries in the next 20 years, but they are also areas in which competition between dominant actors is likely to accelerate and intensify within this timeframe.

Advancements in a key technology area in one nation may not always come at the expense of advancements in another nation. However, leading competitors – in particular, the US and China – will remain incentivised to maintain the technological advantage or 'edge' in areas where they already dominate, requiring further specialisation in those target areas. Simultaneously, global competitors will also attempt to curb any monopolies on innovation implementation in rival nations. This race will be driven by the private sector, hence government-industry relations will be influential in determining the outcome.

2.2 Implications

AI and quantum technologies support advanced, high-value-added private-sector capabilities for which the consequences of losing the advantage include challenges such as national security risks, the loss of well-paid jobs, and barriers to re-entry into the market.[28] Data access, curation, storage, and quality also represent fundamental issues that will directly impact the future development of both AI and quantum. Additionally, finding, training, and retaining the necessary talent will be a crucial long-term challenge of this trend as both competition and the need for specialised skills rises.

In terms of research and development (R&D), Generative AI will transform current methods for conducting research and achieving innovation breakthroughs – for example, through significantly enhanced data analysis. If Artificial General Intelligence is developed, its effects will be even more revolutionary. R&D will also be indirectly affected by AI and quantum development. Further advancements in AI and quantum will require significant amounts of data and energy, as well as access to scarce elements such as gallium and germanium. These needs will be further complicated as climate change continues to affect energy supplies and access to scarce resources. This will likely drive future R&D efforts to create bioengineered novel materials and alternative, 'greener' power supply options to support future energy needs for technology development. Any actor that can successfully develop future AI and quantum technologies at a lower cost will certainly benefit from advantages.

AI and quantum advancement will also impact the security and defence landscape. Future cutting-edge capabilities will likely be available for public use rather than created solely for military applications, often referred to as 'dual-use' technologies. This means that future technology advantages will not only be available to powerful state actors but also super-empowered individuals and adversarial non-state actors such as criminal and terrorist organisations.

2.3 State of play

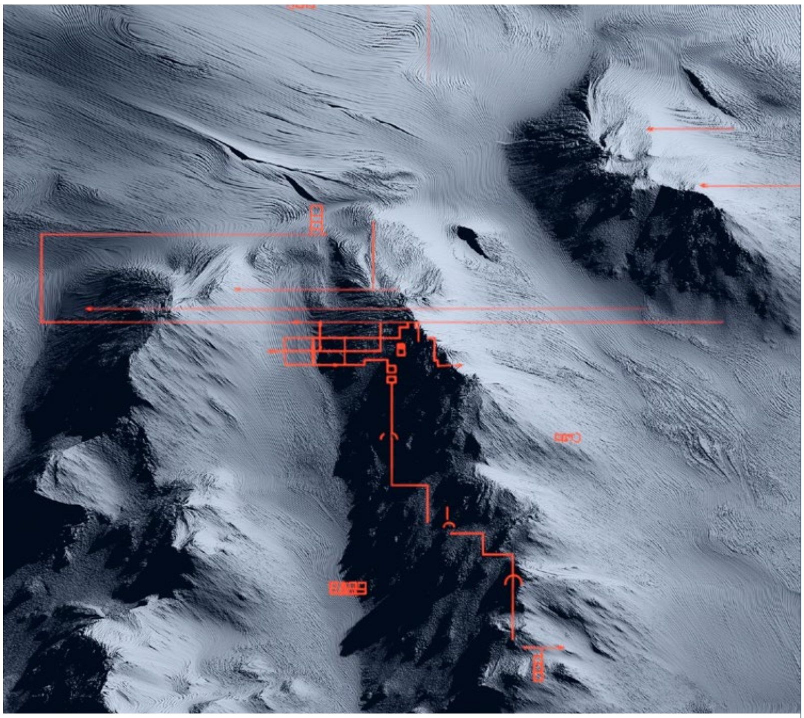
AI development, applications, and innovation are substantially more mature than the range of quantum technologies. Using scientific excellence as one metric, the 2024 Nobel Prizes for both chemistry and physics were awarded to breakthroughs in which AI played a central role.[29,30] Quantum, on the other hand, has not been widely implemented. For quantum computing specifically, one challenge for future integration stems from the fact that this technology relies on fundamentally different and more complex principles than traditional computing. Therefore, utilising the power of quantum computers requires users to carefully formulate problem sets that will enable the computer to fully leverage its unique properties (e.g., significantly increase processing power and speed compared to classical computing). Hence, it will likely take several years for quantum computing to be fully realised. Obstacles to the further development and 'scaling up' of other quantum capabilities will also depend on the availability of enabling technologies, including robust supply chains and infrastructure.

Artificial intelligence (AI)

AI is already having a profound effect on efficiency and productivity across a broad range of industries, in particular manufacturing, healthcare, and finance.[31,32] As AI technologies become more sophisticated, products and services increase in quality and accuracy while cutting down on labour costs and creating new opportunities for emerging markets.

However, it is the combined use or 'convergence' of AI and other S&T areas that will bring the most revolutionary impacts. For example, the combined use of AI and autonomy is already transforming decision-making processes and enabling real-time insights. These capabilities are particularly applicable for prediction and optimisation needs in the finance and healthcare sectors.[33] In healthcare, future combinations of AI and quantum computing have the potential to transform biotechnology (further discussed in Macro Trend 3) by, for example, enabling more advanced genomic analysis and more efficient, personalised medical interventions.

In the military context, AI provides strategic planning and tactical decision support, enhances intelligence, surveillance and reconnaissance (ISR) capabilities, improves cyber network monitoring and defence, and more. While some use cases are well-established, such as the combined use of AI and autonomous (unmanned) systems for gathering intelligence, new and creative applications of AI for military use are also rapidly evolving. For example, the US Army recently developed a smartphone application that uses AI to quickly identify military equipment in combat areas.[34] Due to growing applications, AI use has surged within the past year. Although the full range of applications remains difficult to predict, experts agree that AI's uses will further expand and its effects will continue to be disruptive across many industries.[35,36] Expectations for future AI-fuelled battlefield advantages include enhanced C2 and improved, persistent situational awareness. These will be made possible by future advancements in AI, in particular as the next generation of AI technologies is more informed by human-centric design principles and achieves greater human-machine symbiosis.



Quantum

Quantum technologies currently include four distinct technology application areas: sensing, processing (computing), communication, and navigation.

Quantum computing is predicted to be similarly disruptive compared to AI. Although not currently as widely used, quantum computing is already predicted to significantly impact all key economic sectors in the next decade due to its ability to drastically accelerate processing capabilities.[37] While quantum sensing, quantum communication, and quantum navigation are further ahead in terms of research, experts suggest that reliable quantum computing capacity will be available by 2029.[38] Others project that quantum technologies will be worth trillions of dollars by 2035, with sectors such as life sciences, finance, and transportation likely being impacted the earliest.[39] Current and foreseeable applications of quantum computing include advancements in cryptography, drug delivery, and environmental monitoring. Looking longer term, quantum key distribution is expected to have an enormous impact on data transmission, by enabling fully secure lines of communication. Quantum sensors could enable the detection of underground structures, submarines, and nuclear weapons. Additionally, quantum accelerometers are expected to allow for navigation where GPS is denied.[40,41]

60%

of top AI institutions are based in the US.

Similar to AI, the full potential of quantum will be realised through its combined use with other S&T areas. For example, future quantum sensors are expected to be deployable in space, which would significantly improve military ISR capabilities. The combination of quantum and autonomous systems is also being explored, as quantum technology will drastically enhance sensors as well as data collection, processing, and exploitation, which would increase the safety and efficiency of autonomous missions.[42]

Leading nations

Given the transformative impact of these technologies across multiple industries, nations that have access to enabling materials as well as the best research and workforces in these areas will have a significant advantage when it comes to economic resilience, security, and growth. Leading nations will therefore benefit from an advantage regarding their ability to solve complex future challenges and withstand shocks. Currently, the US and China are the two most notable players when it comes to research, development, innovation, and implementation of AI and quantum technologies. The dynamics between these leading countries have changed markedly in the past decade and are expected to evolve significantly in the next.

S&T investment

The latest available data demonstrates that the US spends the most on overall R&D globally ($806 billion in gross expenditures in 2021) and the largest share in relation to GDP (3.48% in 2021), but China is close behind ($668 billion, 2.43% of GDP in 2021).[43,44] This is historically unusual, since as recently as 2009 US R&D spending was more than twice that of China's.[45] Through comprehensive, long-term government strategies and targeted investments, China has positioned itself to be a leading global innovator.[46]

AI investment & education

The US is still generally considered the world leader in AI technology and innovation. Substantial government and private sector investment led to a boom in AI start-up companies and job openings in the US in recent years, and these investments are expected to continue increasing.[47] US entities also continue to attract the vast majority of AI talent, including the most elite AI talent worldwide (those in approximately the top 2%), and it remains home to 60% of top AI institutions.[48]

Nevertheless, China's AI workforce and innovation ecosystem should not be underestimated, as the Chinese government and private sector are strategically investing in developing and deploying AI capabilities.[49] Although data is not as widely available compared to the US, assessments of government, university, and industry reports suggest that China is investing substantially in the development of AI education, the future AI workforce, and in recruiting Chinese talent currently employed abroad in AI-focused jobs.[50] Government investment in higher education has also drastically increased in the past decade and, as a result, top Chinese universities now have comparable budgets to those in the US.[51] Several metrics illustrate the fact that China's overall higher education ecosystem is now highly competitive if not dominant – for example, China is predicted to award almost double the amount of science, technology, engineering, and mathematics PhD degrees as the US starting in 2025.

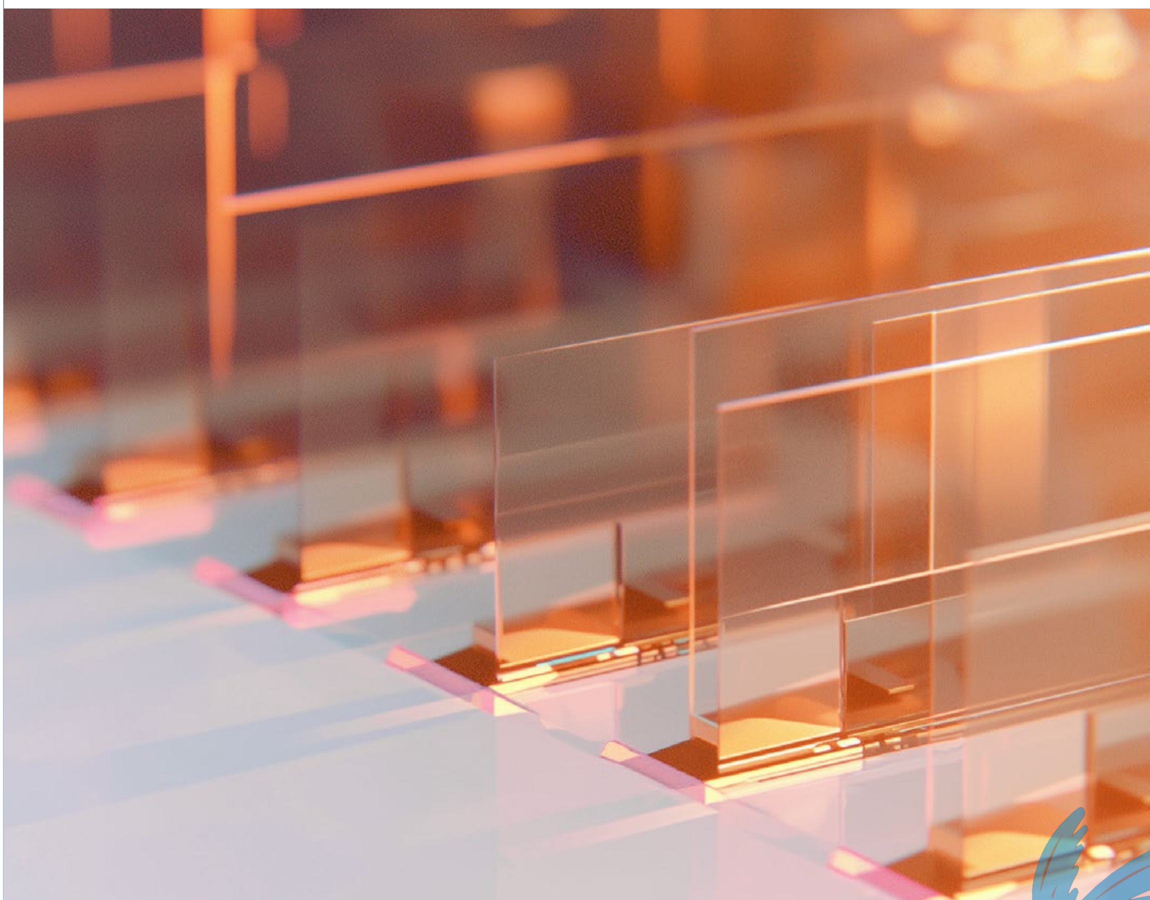
Available data indicates that China could be on the path to surpassing the US as the leader across quantum technology areas.

Even if the US remains dominant in AI technology and innovation, data points to a coming shift in AI research dominance. The US has historically led in AI across five out of six key research areas (advanced data analytics, advanced integrated circuit design and fabrication, adversarial AI, machine learning, natural language processing), with China being the historical leader in AI algorithms and hardware accelerators. However, from 2019-2023, China surpassed the US in terms of highly-cited research publications in all five categories in which the US previously dominated. For cumulative publications, the US has also trended mostly downward across all six categories. Despite this, the US shows higher numbers for most recent employment affiliation in all five categories in which it is the historic leader. Regarding country of education for top researchers, China trains a higher percentage of undergraduates in all 6 categories, while the same is true for the US at the graduate level.

Quantum investment & education

Determining the leader in overall quantum technology and innovation is more challenging compared to AI, in part because quantum development and application remains nascent, but also due to the fact that details of government investment and research initiatives in the leading nations remain closely guarded.[52,53] However, available data (including publication output and highly-cited authors/publications) indicates that, similar to AI, although the US is the historic leader across most quantum technology areas, China could be on the path to surpassing these capabilities, if it has not already. According to data collected on the education and career trajectories of highly-cited researchers, the vast majority of them are currently employed by US-affiliated entities (in all four quantum technology categories measured except for post-quantum cryptography), even though the percentage of highly-cited authors who completed undergraduate studies in China is significantly higher across all areas. European Union countries have a higher employment rate for top researchers compared to China in all four categories, including post-quantum cryptography.

While high US investment, especially from the private sector, and a robust education ecosystem certainly contribute to the competitiveness of future workforces, these metrics alone are not enough to predict innovation excellence for the next 20 years. China continues to put enormous effort into transforming its education and innovation ecosystems and has successfully overturned many previous assumptions in both areas – for example, that it only produced copycat research, or that its top companies could only succeed when dependent on foreign partners.[54] Additionally, nearly all Chinese research is targeted to achieve specific national security goals, hence the majority of research is formulated with defence in mind. While some scholars suggest that freer approaches foster the creativity needed for breakthrough innovations, the fact that the Chinese system provides direct, practical benefits for its military cannot be overlooked.



2.4 Choices for leadership

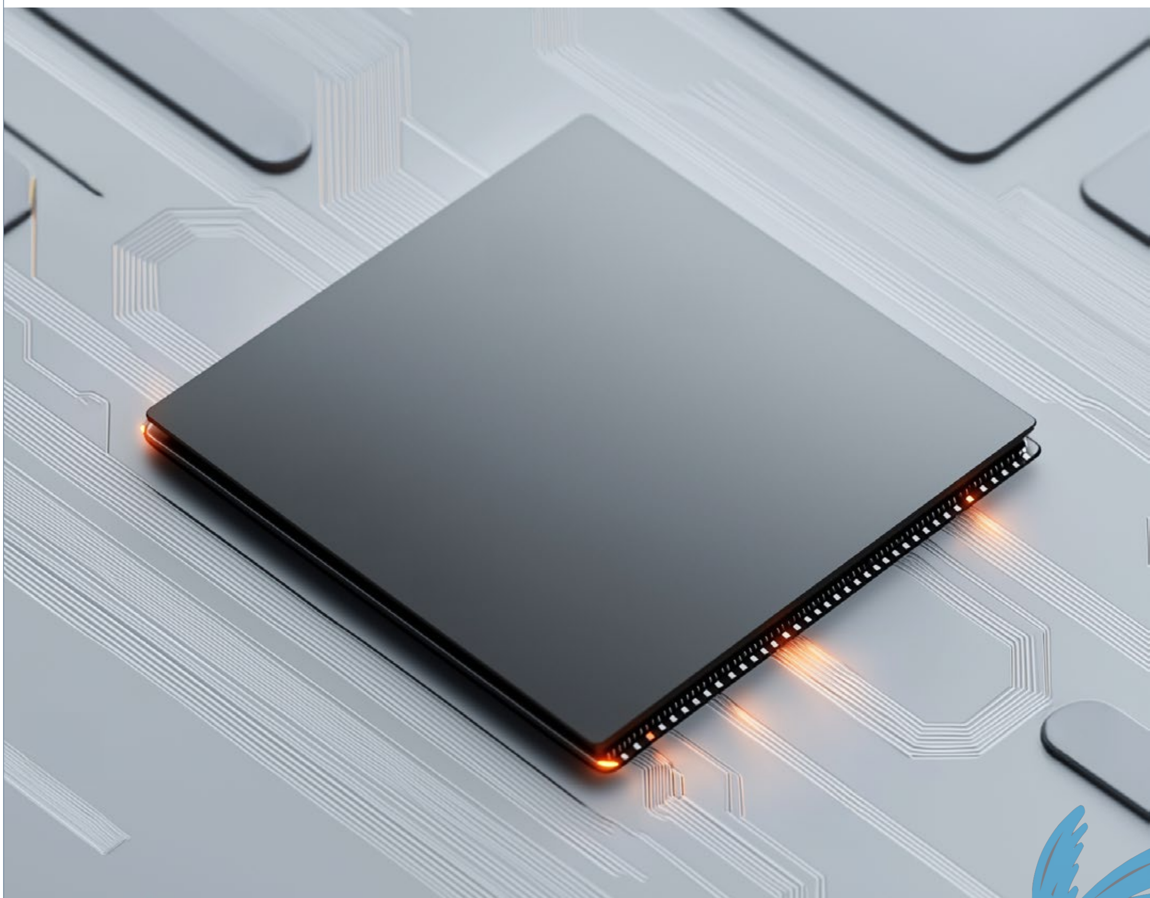
Despite their different stages of development, significant advancements are expected in both AI and quantum in the next 20 years, and the unique impacts of each technology area on various sectors will be both wide-ranging and revolutionary. While these trends are not solely applicable to AI or quantum, these technologies are primed to become the fiercest areas of competition over the next two decades.

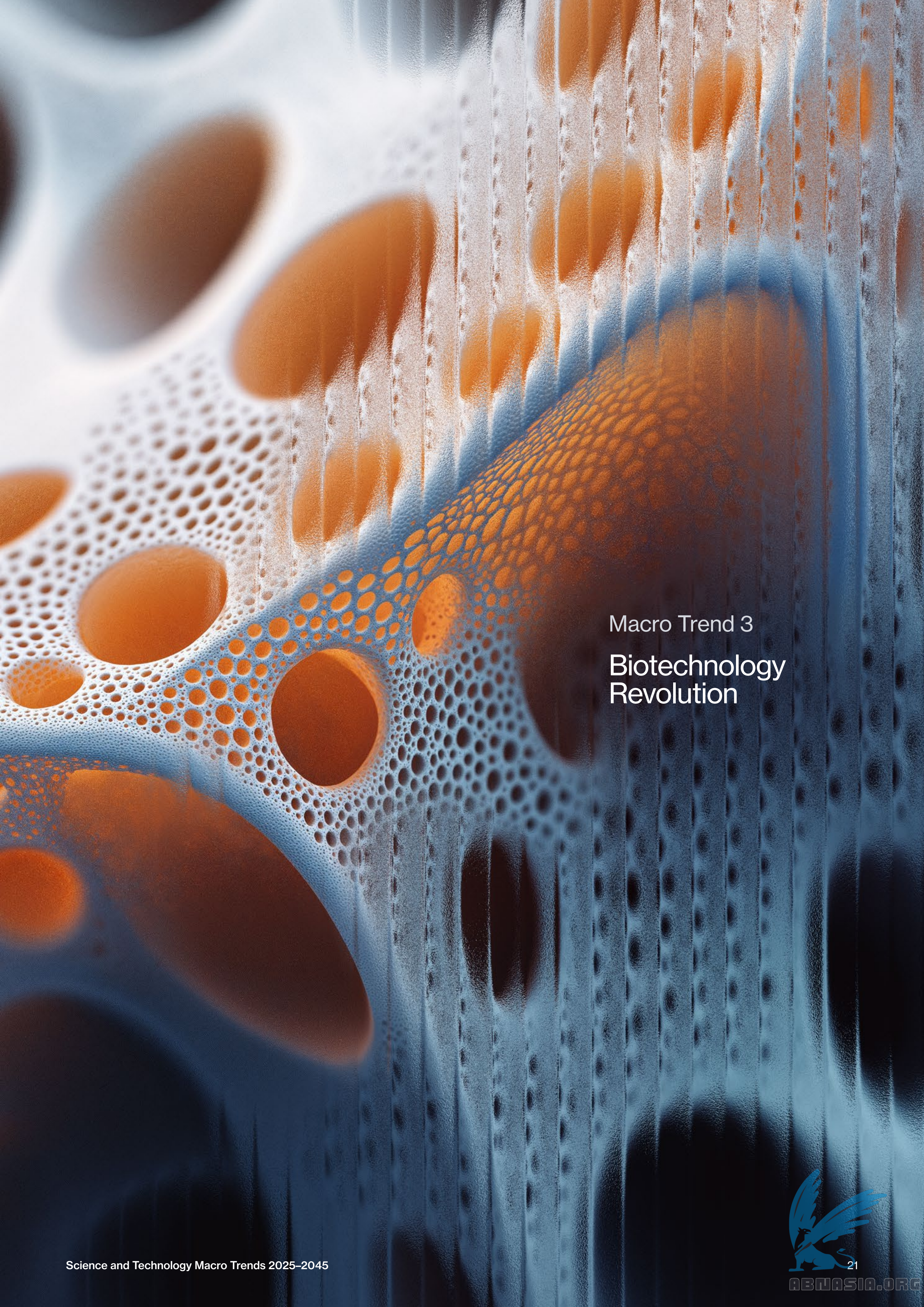
One proactive step that leaders can consider is the development of a national quantum strategy. In recent years, several Allies have developed strategies for AI outlining aims such as ensuring responsible use of related technologies, harmonising innovation efforts, and capitalising on economic benefits of future advancements. However, many Allies have not announced strategic plans or outlooks for quantum technologies.

Allies could also consider greater S&T collaboration in AI and quantum, including investing in their national education and innovation ecosystems. Given the complexity and pace of development of these technologies, pooling resources among like-minded nations is the only way for Allies to be ahead in the competition for technology leadership. Allies should therefore examine ways to enhance S&T collaboration with partners. Current frameworks for NATO-partner engagement are already well-equipped to foster further ties, including in the S&T space. For example, the Individually Tailored Partnership Programme (ITPP) provides unique roadmaps for NATO-partner relations, including cooperation milestones and future activities. ITPPs serve as the foundation for NATO's relationship with Australia, Japan, New Zealand, and the Republic of Korea, among others. S&T cooperation is expected to remain a key focus with these partners, especially Australia and Japan, including through NATO's Science for Peace and Security Programme (SPS) and numerous activities in the STO's Collaborative Programme of Work (CPoW). As NATO and Allies' partnerships in the Indo-Pacific and elsewhere continue to develop, it will be necessary to strike the appropriate balance between encouraging open, collaborative research among diverse institutions and safeguarding discoveries with revolutionary national security implications.

> [AI and quantum] are primed to become the fiercest areas of competition over the next two decades.

Leadership will also need to consider the trade-offs involved in the race to achieve and maintain AI and quantum superiority. Further AI and quantum advancement will only be achievable if access to large quantities of quality data can be assured, in addition to data storage and dissemination tools. At the same time, future AI- and quantum-related processing will require an enormous amount of energy. These and other implications regarding future technology development trade-offs should be carefully assessed, keeping in mind considerations related to climate change.





Macro Trend 3

Biotechnology Revolution

Expected impact and timeline

Impact on NATO

Present
2025

Future
2045

Key judgements

Synthetic biology and related technologies will have a disruptive, revolutionary impact within the next 20 years, in both the civilian and military realms.

While the potential benefits from increased biotechnology use are substantial, especially for healthcare, the risks of harmful uses are also enormous. This necessitates careful consideration of security and defence implications, including the protection and sharing of research.

Research safeguards need to align with our shared values and norms.

3.1 Background

As reflected in the S&T Trends Report 2023-2043, the next revolutionary technology period will be driven by synthetic biology. Synthetic biology, a closely related subset of biotechnology, is the exploitation of biological processes for specific purposes, especially genetic manipulation and the re-engineering of organisms. In the NATO context, biotechnology includes both bio-engineered novel materials and human enhancement technologies.

In addition to continuing developments in related technology areas (e.g., biodata, biosensors), this emerging trend will bring issues such as safeguarding sensitive research or 'research security' and regulation to the forefront of policymaking. Emerging areas of research such as the relationship between climate change and chemical, biological, radiological, and nuclear (CBRN) threats also necessitate increased awareness in relation to future biotechnology development.

3.2 Implications

[Biotechnology] is now widely considered to be crucial for future economic security.

Biotechnology is poised to improve many aspects of society, from agriculture to environmental science to healthcare, hence it is no surprise that this technology is now widely considered to be crucial for future economic security.[55] In the healthcare sector in particular, major discoveries in how synthetic biology can be used to solve complex medical challenges have been made in the past years, through gene editing and therapy, rapid responses to infectious diseases and epidemics, personalised medicine and response to genetic diseases, and more.[56] Bio-informatics and biomaterials will become more pivotal for future medical advancements, for example via personalised medicine and advanced orthopaedic solutions.[57] Bio-energy sources are also expected to improve responses to environmental challenges such as greenhouse gas emissions and waste management.

In terms of military applications, biosensors (especially combined with nanotechnology) offer cutting-edge solutions for combat casualty care and CBRN defence.[58,59] Looking longer term, the agricultural sector is expected to benefit even more from biotechnology breakthroughs such as genetically-engineered alternatives for traditional food sources that are more resilient against the effects of climate change (e.g., droughts).[60,61] These applications could be the key to combatting rising food insecurity levels across the globe.

However, the potential benefits of increased use of biotechnology are balanced by its high likelihood of causing economic, geopolitical, and social disruptions, in large part due to issues surrounding security and ethics.[62] Advancements in synthetic biology are likely to increase the risk of biological and chemical weapons becoming more accessible through the potential utilisation of gene-editing technologies to alter existing agents for harmful use or create new hazardous agents. Given the rapid and often unpredictable nature of development in these areas, governments face serious challenges with regard to updating and adapting regulatory frameworks to address these developments.[63] The combination of synthetic biology used with other emerging and disruptive technology areas is also likely to create opportunities to use synthetic bioweapons for targeting specific individuals or groups. Additionally, the combined use of synthetic biology with other developing S&T areas will compound already substantial privacy, ethical, and regulatory concerns.[64]

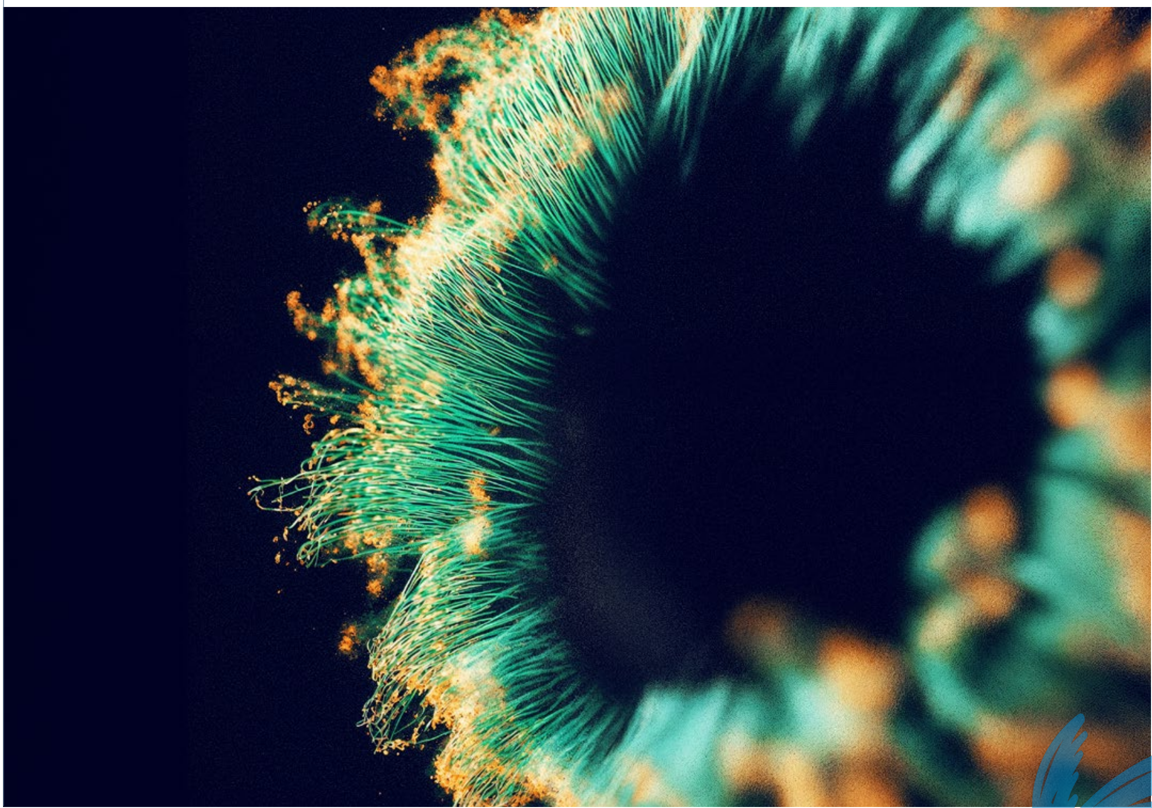
The moral, ethical, and legal implications of future biotechnology use are particularly complex. While the overall benefit to healthcare cannot be overlooked, certain biotechnologies pose unique concerns, and this is particularly true of implantable technologies. Neural implants, for example, could offer a solution for improving neurological conditions such as epilepsy.[65] However, the long-term effects of neural implants on physical and psychological health remain largely unknown. These concerns are also relevant in the military context. If future soldiers are equipped with specialised devices that enhance cognition, strength, or other abilities, it will be necessary to understand their long-term impact on individuals. Furthermore, the use of such devices may cause wider repercussions – for example, jeopardising unit cohesion. Additionally, as biodata tracking becomes more accessible, protecting personal (biological) information will become increasingly challenging. Moral, ethical, and legal questions regarding genetic intervention are not easily answered, and how Allies integrate these capabilities into their civilian and military systems will likely differ significantly across nations.

3.3 State of play

$20 trillion

The value that synthetic biology and related biotechnology markets could reach or exceed globally by 2030.

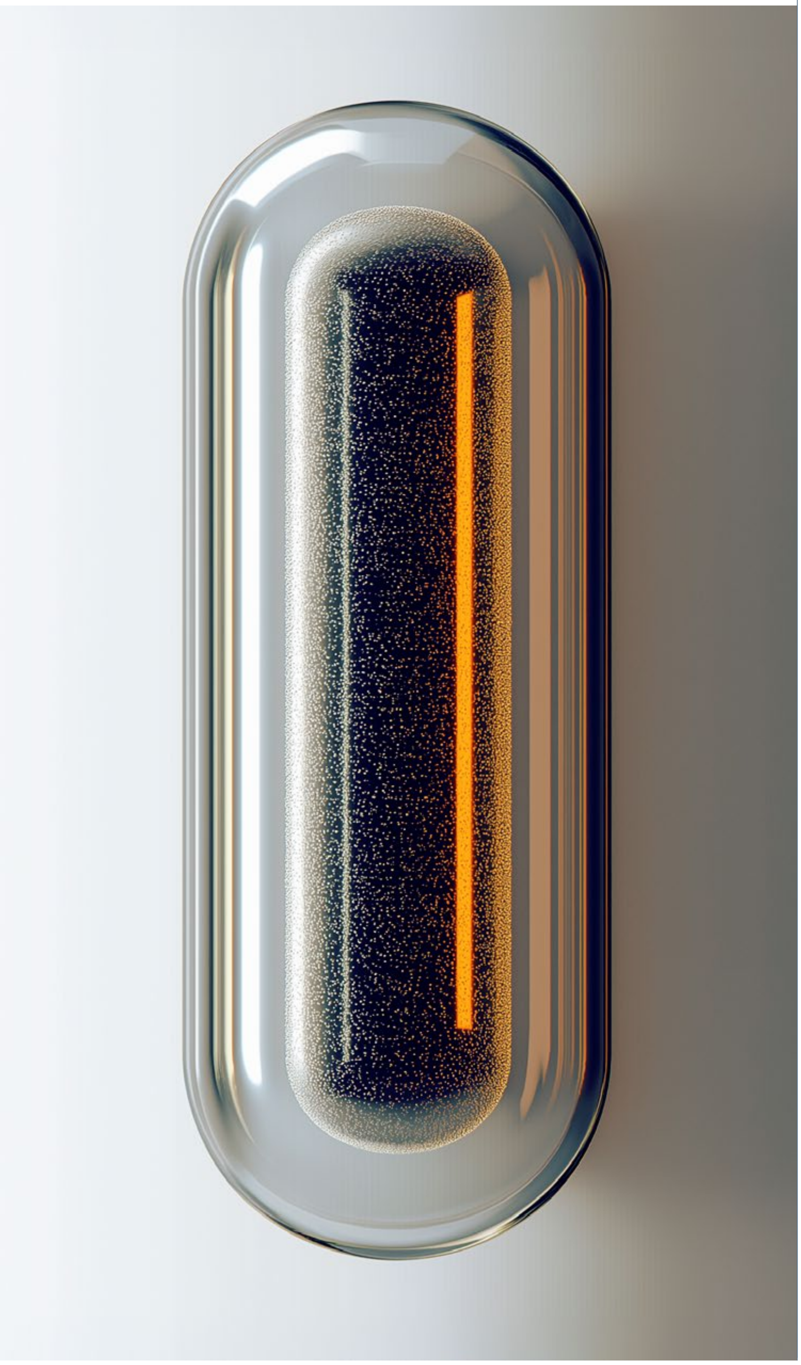
Experts predict synthetic biology developments will accelerate in the next 10 years, based on the following factors: additional applications expected for synthetic biology across diverse sectors, expected increases in funding for related R&D, the declining cost of DNA sequencing, and expected future innovations in the science behind biotechnology.[66] The overall use of biotechnology for the production of goods and services, known as the ‘bioeconomy’, could reach or even exceed $20 trillion by 2030.[67] As one example, biosensors have brought several recent breakthroughs, including for monitoring foodborne pathogens and heart failure as well as targeting breast cancer,[68,69,70] and potential uses beyond the health sector are increasing due to advancements in other S&T areas such as AI and nanotechnology.[71,72,73] The combined application of AI and synthetic biology has also increased significantly in the past year, being applied to protein design, targeted drug delivery, and combatting drug-resistant diseases.[74,75] The convergence between synthetic biology, AI, and autonomy has also enabled faster research, analysis, and experimentation for bioengineers. Additionally, AI could be applied to CBRN defence and biosecurity risks, as AI and machine learning could improve detection mechanisms and safety protocols by quickly identifying potential threats.[76]



In the long term, synthetic bioweapons have the potential to become as harmful as nuclear weapons.

Although numerous beneficial applications for biotechnology exist, the potential for harmful use must also be considered. Technology areas such as AI, advanced manufacturing, 'big data', and CRISPR technologies (Clustered Regularly Interspaced Short Palindromic Repeats, which are used to selectively modify the DNA of living organisms), could potentially contribute to the proliferation of bioweapons.[77] For example, the use of AI tools trained on biological data together with CRISPR gene-editing technologies can allow for precise genetic modifications and the creation of novel pathogens that are resistant to current countermeasures or antidotes.[78]

In terms of privacy, ethical, and regulatory concerns, the use of synthetic biology together with other technology areas poses risks as well.[79] For example, utilising AI will enable more rapid discovery of novel compounds while at the same time raising additional questions regarding biodata and data privacy as well as potential inaccuracies or accidents based on incomplete or inaccurate data.[80]



In the long term, synthetic bioweapons have the potential to become as harmful as nuclear weapons; however, the regulatory frameworks surrounding bioweapons are much less robust. Compared to the Treaty on the Non-Proliferation of Nuclear Weapons and the Chemical Weapons Convention, the Biological Weapons Convention is considerably weaker: it not only lacks a verification regime, but also does not explicitly prohibit the *use* of biological weapons.[81] The rate at which biotechnology discoveries are being made together with the fact that potential future bioweapon manufacturing will likely not require the financial backing of a powerful state or large organisation will further complicate the creation and implementation of appropriate legal and ethical safeguards.[82] Some countries have acknowledged this future challenge – for example, in 2024, the US published AI chemical safety recommendations, which offer guidance on combatting AI-fuelled chemical and biological threats. These recommendations also propose safeguards for accessing high-risk scientific databases and standards for how to respond to dangerous information produced by AI-enabled tools.[83]

Climate change & CBRN

Regarding linkages between climate change and biological threats, the effects of climate change will further compound the already substantial threat of increased biological weapons usage. Chemical and biological agents are extremely sensitive to environmental changes, such as humidity, increasing temperature, and wind.[84] Furthermore, a warming atmosphere is likely to enable access to potentially dangerous biological agents due to thawing permafrost and ice loss at the Earth's poles. Additionally, unpredictable extreme weather events increase the likelihood of incidents involving the release of toxic industrial materials. This potential increase in the accessibility of hazardous materials could lead to a lower barrier of entry for biological weapons development if in the future it is no longer necessary for adversaries to develop dangerous substances in a lab. If safeguards are not put in place, some commentators have stated that it is not difficult to imagine a world in which homemade bioweapons become commonplace.[85] Additionally, habitat degradation and loss are increasing contact between humans and wildlife, which raises the risk of spreading zoonotic diseases and new epidemics.

Safety measures for mitigating and combatting these risks are further complicated by climate change. As the Earth's temperature rises, current protective equipment will not be usable in extremely hot climates. Changing temperatures and unpredictable evaporation timelines will also make decontamination efforts significantly more challenging. Traditional CBRN countermeasures and predicting the spread of dangerous airborne agents are also becoming more difficult due to less predictable weather and dispersion patterns. As a result, space assets that support weather forecasting will become ever more crucial for tracking potential outbreaks.

Leading nations

The US is widely considered the global leader in biotechnology, with a biotech industry that is supported by currently unmatched levels of R&D investment. The US also holds the dominant global position with regard to biotechnology patents, which is further safeguarded by a robust intellectual property framework and innovation ecosystem.[86] However, as numerous nations have stepped up R&D spending and other investments that support biotechnology, there are many other nations to assess when projecting developments for the next 20 years. The United Kingdom is a recognised hub for biotechnology innovation, which is growing due to recent progress in life science start-ups and patent applications, which encouraged increased government investment.[87] The UK has consistently ranked third in global medical science citations (following the US and China),[88] and data points to substantial future job creation and growth in the biotechnology sector specifically.[89] Germany is a global leader in pharmaceuticals, with its industry placing fourth (after the US, China, and Japan).[90] In addition to substantial national R&D investments, Germany's small and midsize companies as well as its research institutions have contributed to global breakthroughs in both biotechnology and drug discovery.[91] Switzerland is a historic powerhouse in bio-pharmaceuticals and saw a record amount of private investment in the biotechnology industry in 2023.[92] Looking ahead, China and India are both expected to increase their biotechnology capacity in the next decade, potentially rivalling or surpassing not only traditional regional powerhouses, such as Japan, but other industry leaders as well. India has shown notable progress in biofuels, for example, and is predicted to overtake China in biofuel publications shortly, having already surpassed the US' output.[93]

90%

of biotechnology patents are held by the US and EU.

Up-to-date information on China's biotechnology patent holdings is difficult to obtain, but data from 2020 indicates that it still trailed the US and EU, holding just 10% of global biotechnology patents.[94] However, the fact that the Chinese government has publicly identified biotechnology as being critical for competitiveness – for example, through clear prioritisation in its 14th Five-Year Plan[95] – it is reasonable to expect future progress in this area.[96] India has also made recent breakthroughs, particularly in bio-manufacturing, and in 2024 its government announced a policy for BioE3 (Biotechnology for Economy, Environment and Employment) aimed at fostering further growth.[97]

3.4 Choices for leadership

The enormous potential benefits of increased biotechnology use as well as its serious risks pose a unique challenge for policymakers, scientists, and industry. An interdisciplinary approach that prioritises international scientific collaboration, safeguarding sensitive research where necessary, will be essential for harnessing the power of synthetic biology advancement.[98]

Proactive steps toward achieving responsible progress could be the establishment of global standards for biosafety and ensuring that necessary safeguards are implemented, especially in labs where researchers manipulate dangerous pathogens.[99] Further investment in biodefence and CBRN defence is also highly necessary.[100] Broad-scale international collaboration will also certainly be needed to ensure the safe and sustainable development of synthetic biology through appropriate ethical, legal, and security oversight.

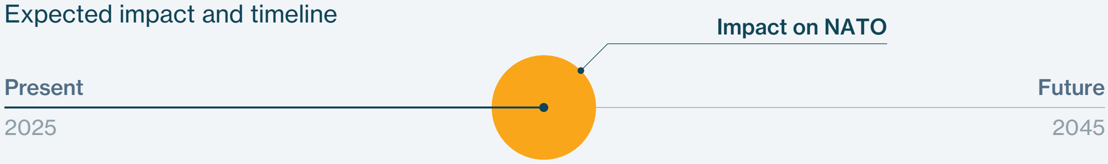
In the NATO context, important work has already been completed regarding standard- and norm-setting for emerging technologies. NATO's Biotechnology and Human Enhancement Technologies Strategy[101] and revised Artificial Intelligence Strategy[102] offer examples of how governments and militaries can promote principles of responsible use (PRUs) in S&T areas where the risks of misuse are significant.

Regarding CBRN threats, leaders should recognise that current defence capabilities are designed to respond to an environment that no longer exists, due to not only an evolving threat landscape but also due to climate change. Future-proofing CBRN defence will be extremely challenging since our environment is continuously and rapidly changing, but a failure to do so will leave Allies dangerously unprepared.[103] Collaboration within the NATO scientific community – including mainstreaming climate change considerations in a broader range of S&T work – will be an essential aspect of combatting these threats. Furthermore, it will be increasingly important to align national R&D efforts with norms and values shared by Allies and partners in order to encourage further progress as well as the ethical use of scientific breakthroughs.

Macro Trend 4

Resource Divide

Expected impact and timeline



Key judgements

Climate change will impact the Alliance's shared access to critical resources for S&T innovation.

Upcoming shocks, especially but not exclusively stemming from climate change, will exacerbate existing tensions between nations that can more easily recover from such shocks and those that cannot.

Future technology advancement and adoption will act as both a solution to these growing tensions as well as an accelerator of them.

4.1 Background

While resource divides have existed since the establishment of societies, modern technological development has played a significant role in pushing this trend to the forefront of geopolitics. Technological development has impacted resource scarcities (e.g., by fuelling increased demand for critical materials) as well as resource inequities (e.g., by widening gaps between more and less prosperous nations). In order to anticipate how technology will continue to shape the demand and supply of resources, both positively and negatively, it is necessary to understand the complex political and economic context in which this trend has emerged.

4.2 Implications

Heightened competition for critical resources and the race to acquire technologies that provide alternatives to or reduce dependencies on those resources will be driven by several factors. These include locally- or regionally-specific effects of climate change across the globe, anticipated increases in climate-related migration and conflict, and decreasing social mobility across multiple regions. Increasingly sophisticated S&T not only serves as a driver of a widening resource divide, but also a possible innovative enabler of development. For example, vulnerabilities related to energy security, critical infrastructure, and logistics supply can be mitigated through AI solutions, biotechnology and green technologies, or the use of alternative/novel materials.

Economic resilience and security, as well as efforts to develop circular economic practices, will become even more crucial for managing and distributing resources over the next 20 years. In this environment, Allies have the opportunity to build collective resilience by sharing resources and learning from the best practices of 32 nations.

Building resilience for the future will also likely affect NATO's partnerships, hence underscoring the importance of deepening and broadening the Alliance's relationships across the globe.

Technology inequalities

While these innovative solutions will likely be critical to responding to future global challenges, it is also worth noting that their benefits are not likely to be equally distributed. Historically speaking, access to emerging technologies has rarely been equitable on a global scale. Considering the modern geopolitical context, future technology solutions aimed at fostering resource access could easily result in greater benefits for the least vulnerable economies, unless policies to more equally distribute positive effects are put into place. At worst, less advantaged nations could end up suffering consequences of misused or under-regulated technologies (e.g., geoengineering) unless safeguards exist for regulating how powerful nations and private sector leaders are able to test and utilise emerging technology solutions.

It will be crucial to monitor how technology adoption affects less powerful economies.

As technology becomes more widely integrated into economic, political, and social toolkits, it will be crucial to monitor how technology adoption affects less powerful economies. Taking AI as an example, if AI technology continues to be rapidly integrated in diverse facets of modern economies yet cutting-edge tools remain inaccessible or under-utilised in others, these parallel developments would further exacerbate income, wealth, and power inequalities.[104] How technology is adopted and regulated across the globe will determine whether digital gaps will widen or whether historically underdeveloped countries will also have the opportunity to benefit from technology-driven tools to increase economic productivity and growth.[105]

The future of work

Resource divisions and uneven effects of resource scarcity and climate change across the globe will also affect the future of work. As extreme weather events occur with increasing regularity, normal working patterns in diverse sectors will have to be adjusted. Workers employed for manual labour will find it more difficult to complete their tasks as temperatures continue to rise. These trends are already apparent in Central Africa and the Persian Gulf,[106] but other regions will be affected in the future.

In addition to environmental trends, technology trends are expected to remain a primary factor in shaping the future of work, in particular regarding required skills and the remuneration offered. Experts predict that technology adoption will continue to fuel business transformation over the next 5 years or more, with greater access to digital tools and integration of new and emerging technologies expected to fuel net economic growth. Additional areas of expected growth include digital commerce[107] and, to a lesser extent, technology-enabled circular economy practices, which offer a possible solution to overconsumption.[108]

4.3 State of play

Recent years have shown a resurgence of the notion that the world is divided into two camps, nations that mostly benefit from the current political and economic order and nations at a comparative disadvantage. Voting records from the United Nations' Resolution "Towards a New International Economic Order" roughly demonstrate the two sides, with the vast majority of Allies voting against it together with NATO's Indo-Pacific partners.[109] While the numerous nations spanning across Africa, Latin America, the Middle East, and Southeast Asia certainly cannot be viewed as homogeneous, the trend toward a growing perception of common grievances against traditionally more powerful states is notable. These tensions are further exacerbated by climate change, with decision-makers noting that wealthier states contribute to nearly half of worldwide emissions while less wealthy ones are most affected by the related repercussions.[110]

Within this context, the availability of critical resources is decreasing, both in terms of access to basic necessities and the scarcity of rare-earth minerals. If current trajectories are not altered, experts project that by 2050, overconsumption will require the equivalent of three times the Earth's resources to sustain its population.[111] In addition to overconsumption, factors such as climate change (e.g., extreme weather events, environmental degradation), new and protracted conflicts, population growth, and urbanisation also contribute to this trend. Basic needs such as food, water, and energy are becoming more difficult to supply, especially in nations across the Middle East, Sub-Saharan Africa, and South Asia. So far, the global food crisis shows little sign of decelerating in the next 10-15 years.[112] In 2023, the number of displaced persons related to food insecurity reached over 90 million.[113] While water scarcity is less acute, it is predicted to become as severe as food insecurity, and experts project that half of the world's population could be living in areas facing water scarcity by as early as 2025 and, as a result, over 700 million people could be displaced by 2030.[114]

Scarce materials

Demand for rare materials and minerals (e.g., lithium) is accelerating due to economic growth, especially in wealthy nations. The growing need for maintaining technological advantage has further compounded this situation, since rare substances are often essential for manufacturing cutting-edge technology. While access to new or previously undiscovered critical materials sometimes occurs – for example, the discoveries of rare-earth reserves in 2023 and 2024 in Sweden and Norway[115] – the overall trend remains negative. Scarce resources are increasingly controlled by only a few nations, and demand continues to rise, in particular due to technology development. For this reason, some experts suggest that the emergence of resource cartels could occur in the next several years. Drivers of this potential trend would likely be further dependence on critical materials, including those needed for manufacturing technologies for green energy transition. The possible creation of such cartels would also likely further intensify already high strategic competition and significantly affect the nature of global partnerships.[116] For example, China issued a regulation that put the mining and trade of rare-earth materials under national control, which took effect in October 2024.[117] If these trends continue, the ability to develop technology without scarce materials and engage in more circular economic practices will become vital.[118]

Novel materials have the potential to provide alternatives for substances that are currently vital for technology development.

Technology solutions

Emerging technologies will be crucial for combatting climate effects, including in especially vulnerable regions, as well as offering alternatives for critical materials and vital resources. Synthetic biology (discussed in Macro Trend 3) offers one example, as it has enormous potential to revolutionise agriculture. Biotechnologies can offer solutions to several underlying problems related to food scarcity and insecurity. For example, biology can be engineered to create foods with enhanced nutritional value and longer shelf life; microbial food production can enable faster, environmentally friendly production; and genetically modified crops can provide a higher tolerance against environmental disruptions.[119,120] Additionally, the combination of AI and space technologies offers more accurate ways of tracking weather events through the use of satellite imagery together with AI-powered remote sensing technologies.

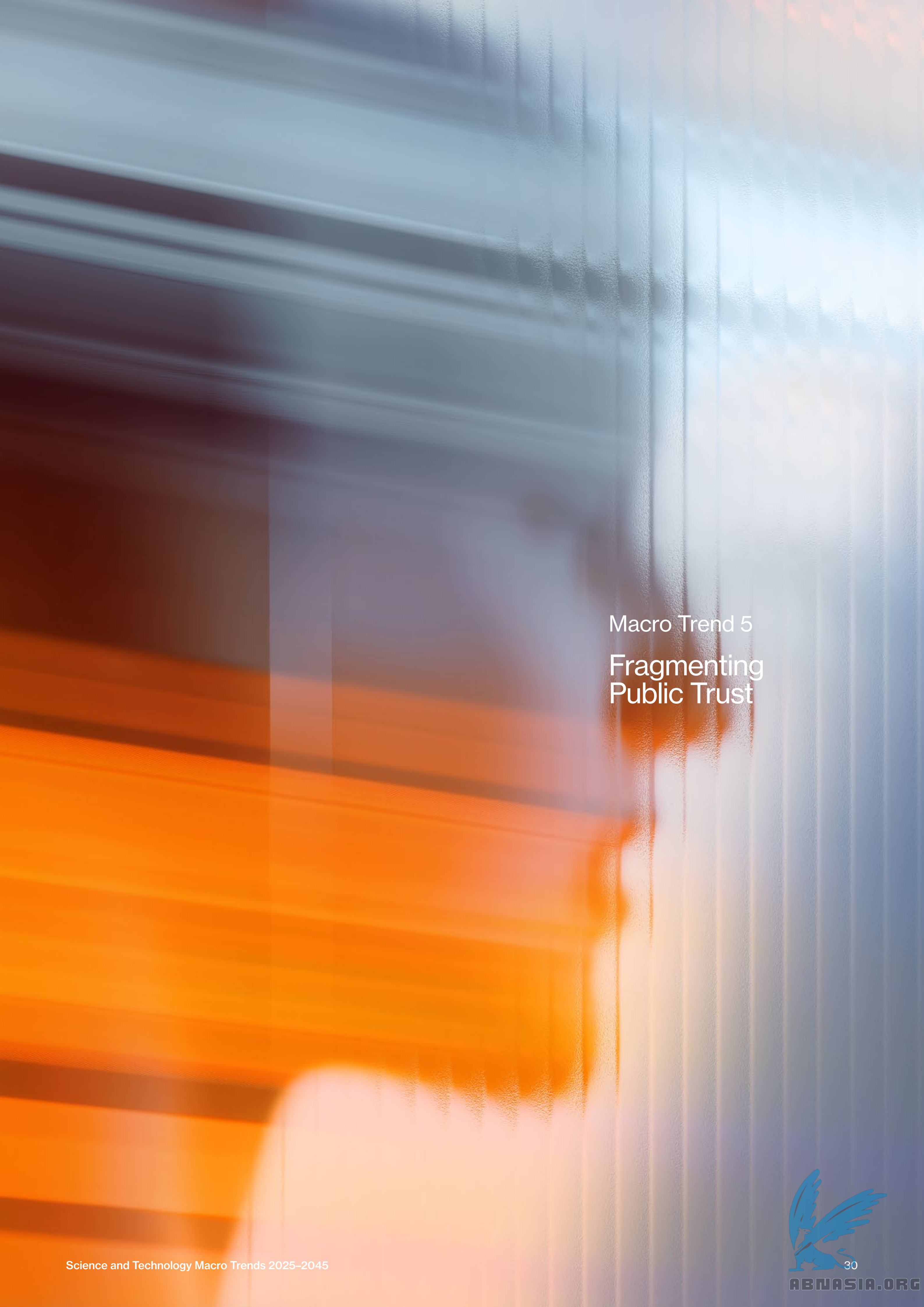
Regarding the scarcity of rare-earth minerals, novel materials have the potential to provide alternatives for substances that are currently vital for technology development. Looking further ahead, technology areas such as carbon capture, green hydrogen development, and possibly solar geoengineering will likely see increased use over the next 20 years. While geoengineering has for many years been disregarded due to legitimate concerns regarding ethics and unintended repercussions, interest in this topic from the private sector and academia has recently grown.[121,122]

4.4 Choices for leadership

While global shocks and their precise repercussions are difficult to predict, it is highly likely that climate-related tensions, migration, and even conflict will increase in the next 20 years. Preparing for these developments will require action on multiple fronts.

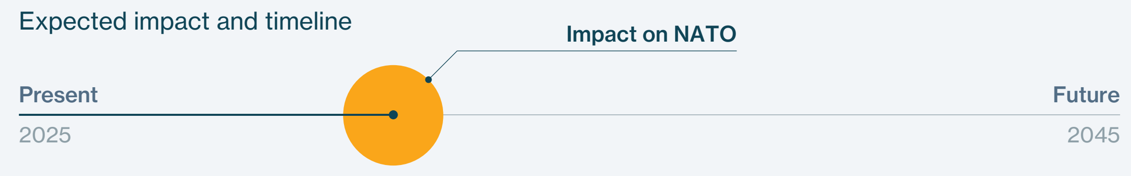
In response to these trends, Allies could consider engaging in technology diplomacy in order to develop norms and bridge growing resource divides. This could involve international collaboration on technology development that enables supply chain resilience, enhances recyclability, or encourages the use of novel materials as substitutes for rare minerals. Denmark's 'TechPlomacy' initiative and Germany's Strategy for International Digital Policy provide different examples for how nations may get involved.[123,124] Technology diplomacy and collaboration efforts should also consider that international cooperation on technology norm-setting will become increasingly crucial over the next 20 years.

The Alliance's efforts to strengthen energy security should also be further bolstered. For example, increased utilisation of the NATO Energy Security Centre of Excellence could encourage increased prioritisation of energy-secure solutions for future operational needs.



Macro Trend 5

Fragmenting Public Trust



Key judgements

Global leadership is needed to encourage the responsible use of EDTs.

Technology, especially AI, is being used to decrease public trust (in governments, institutions, and science), and the future impact of these developments will be further complicated by rising political polarisation.

In the long term, tech-fuelled solutions may offer tools for combatting disinformation and misinformation, but in the short term, strategic communications, legal/regulatory mechanisms, and technology education will be increasingly vital.

5.1 Background

Trust in science, as well as in institutions and governments, is declining in many regions of the world. Currently, S&T development acts primarily as an accelerator of this emerging challenge, especially through generating and spreading misinformation (false information) and disinformation (deliberately false or misleading information) more rapidly with AI. As a result, issues such as techno-nationalism and digital sovereignty are expected to increase in importance. At the same time, the need for trustworthy, transparent S&T solutions and for technology education will only grow. Demographic shifts will also impact these developments, in part due to the fact that digital media is consumed differently across generations and regions.

In addition to creating more opportunities for hybrid warfare and economic coercion (discussed in Macro Trend 1) technological developments also enable the spread of disinformation, misinformation, and other harmful content online. Digitalisation and the popularity of social media and other online platforms have created the possibility of information dissemination and exchange to and from anywhere in the world. When prudently used and regulated, online platforms offer important tools for global exchange, socialisation, education, and more. However, without thoughtful regulation of platforms, emerging technology can be easily applied to enhance harmful impacts of online communication.

5.2 Implications

Emerging and evolving technologies – in particular, AI – can be manipulated and exploited to encourage instability by undermining truth.[125] Malicious campaigns aimed at influencing public opinion through spreading propaganda and false information do not represent a new trend. However, new challenges are emerging due to the use of technology to both create more believable harmful information and to rapidly and widely disseminate it. From election interference to deepfakes, technology advancements are not only making dubious material more believable but also enabling increased access to misleading information.

The increasing believability of technology-generated content leaves many individual users finding it difficult to determine what is real and what is fake. Compounding the problem, the speed with which information threats can now be generated poses extreme challenges for platform monitors, fact-checkers, regulators, and others who aim to encourage the dissemination of trustworthy content. Slow responses and lack of regulation serve to further undermine trust in institutions, exacerbating an already worrisome trend. Additionally, it is important to consider potential unintended effects of well-meaning regulatory initiatives. Taking recent research findings on misinformation warning banners as an example, data suggests that such warnings unintentionally cause readers to distrust accurate information.[126]

The increasing believability of technology-generated content leaves many individual users finding it difficult to determine what is real and what is fake.

Technology manipulation can also undermine well-meaning applications of AI. For example, incorrect or malicious data can be injected into AI models through 'backdoor' vulnerabilities in order to manipulate decision-making or compromise AI-enabled systems used for medical, manufacturing, finance, or other applications. These vulnerabilities require operators and decision-makers to carefully consider potential overreliance on AI-dependent systems. Technology solutions should not fully supplant critical thinking and decision-making skills, but rather complement them to enable greater efficiency and effectiveness.

These trends impact NATO both directly and indirectly. In terms of technology aiding the spread of information threats, data analysts have found that a significant portion of NATO-related posts on Russian-language social media platforms were automatically generated.[127] Indirectly, the continued undermining and fragmentation of public trust in institutions affects how individuals across the globe view the Alliance, which could impact NATO's ability to effectively reach its objectives. For example, being perceived as an untrustworthy actor could make building and deepening partnerships with other nations, as well as the private sector and academia, more challenging. Additionally, several Allies are struggling to meet military recruitment targets, and these challenges would likely grow if defence-related institutions such as NATO are viewed negatively in the future.

5.3 State of play

AI allows for an unprecedented spread of disinformation, due to the ability of Generative AI to rapidly produce information that closely imitates content created by humans, whether the original information was accurate or not. As Generative AI continues to develop, the content it creates is increasingly difficult to distinguish from human-generated information. The combination of AI and machine learning is also being further refined in the creation of deepfakes. Furthermore, recent studies show that large language models (LLMs) utilised by AI have the power to easily create highly persuasive text (including propaganda) and, where errors still exist, only minimal human effort is needed to adjust AI-generated content to make it appear fully human-made.[128] Hence, misleading and harmful content can easily be created and shared since, in most cases, it does not require cutting-edge or expensive tools to produce.

Political polarisation

While the full spectrum of disinformation applications and impact cannot be predicted, it is reasonable to expect the impact of this trend to be affected by global geopolitical polarisation (as discussed in Macro Trend 1) as well as domestic political polarisation and the emergence of authoritarian governments, all of which have increased in recent years. These trends are mutually reinforcing, as disinformation generates more distrust and encourages polarisation while, at the same time, political polarisation and fragmentation increase the likelihood of disinformation being spread and trusted.

> Online platforms were rife with so much false information regarding the COVID-19 pandemic that this effect was labelled the 'infodemic'.

Internet fragmentation

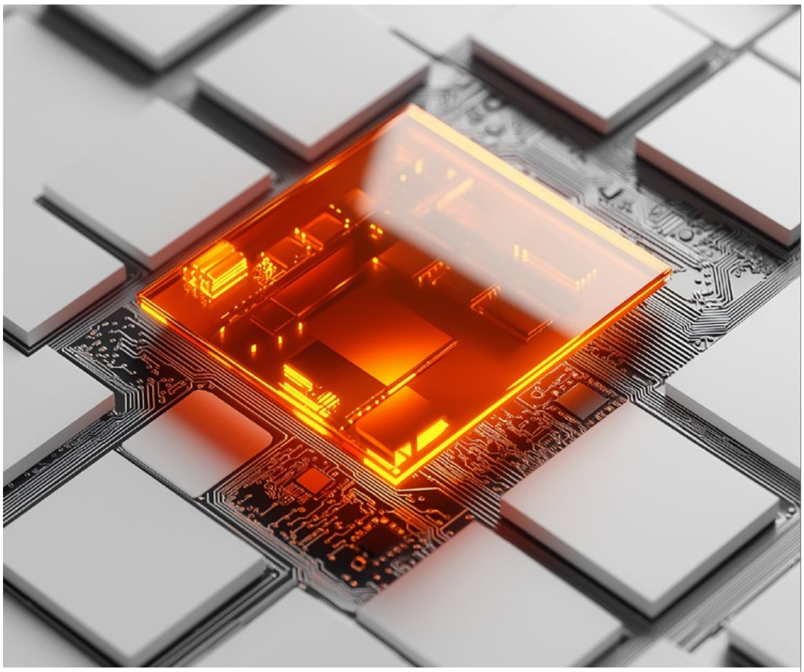
Some experts predict that the technology sector itself will become increasingly fragmented based on regional divides. Regionalised, isolated internet networks or the fragmentation of the internet in several controlled nets (or 'splinternet') may become more popular due to a variety of factors, including differences in technology adoption and standards in different regions, a possible decrease in available hardware options if industry power is further consolidated among few providers, or the desire for authoritarian governments to strictly control online media and political dissent. Should the splinternet become reality, this would likely enhance global geopolitical tensions and make it easier for false information to be disseminated and believed.

Trust in science

The combined effects of AI-enabled disinformation spread and a lack of regulatory oversight must be viewed in the context of increased global strategic competition. These developments, together with the potential for a more regionalised global economy, political landscape, and even internet, increase the likelihood of future fragmentation of public trust along technological, political, economic, and ideological dividing lines. Should this trend become reality, trust in empirical and scientific information would also be highly likely to decline.

Taking the COVID-19 pandemic as an example, data indicates that political beliefs and levels of trust in government significantly impacted individuals' level of trust in COVID-19 vaccines. Online platforms were rife with so much false information regarding the pandemic that this effect was labelled the 'infodemic'.[129] Regarding public health specifically, the availability of evidence-based scientific advice will remain vital in addressing future shocks, in addition to inclusive public health education.

Policymakers should also recognise that the factors that fuelled the infodemic trend remain key challenges today and are further empowered by advancements in Generative AI. Hence, future risks of similar trends should be assessed against a broader range of potential shocks, beyond just public health.



Technology solutions

Developing necessary regulation and safeguards will be no easy task. For AI specifically, tools for measuring basic features such as algorithm biases are still severely lacking, but the need to measure such effects is widely known. Other potential challenges and repercussions are often not monitored or, in some cases, they are not yet identified or understood. One challenge that is nearly certain to emerge is the ability of live AI chat functions to persuade human behaviour and decision-making, for which no current methods for measurement exist.[130] As researchers struggle to make sense of current and foreseeable risks, technology is rapidly advancing. For example, tech experts recently observed that AI chatbots are able to trick existing safeguards and produce dangerous information despite developers' attempts to prevent this.[131]

One challenge that is nearly certain to emerge is the ability of live AI chat functions to persuade human behaviour and decision-making.

Responses to these substantial and compounding challenges must be comprehensive and creative. The international S&T community offers crucial insights across numerous topic areas. For example, the International Panel on the Information Environment provides advice to government policymakers, industry, and civil society on threats to the information environment such as AI bias and algorithmic disinformation.[132]

From the technology and platform regulation perspective, it will likely be necessary to further integrate advanced AI and LLM tools to monitor, identify, and react to dangerous behaviours online. However, experts cannot currently predict whether those acting as defenders or attackers of online information safety will ultimately benefit from technology tools more in the long term.[133] Data-driven approaches must also be pursued when assessing possible solutions for mitigating risks of harmful information spread. Recent studies show that, contrary to popular belief, online searching intended to evaluate the truthfulness of false information actually increases the likelihood that the user will believe falsehoods.[134] These findings would also suggest that media literacy education needs to be reassessed, given that current trainings often suggest using search tools to verify false information. Media literacy education must also take into account the different challenges online users face depending on age and nationality rather than offering a one-size-fits-all approach.

Enacting larger-scale change, however, may prove the most complex, as the increasingly popular goal of achieving national digital sovereignty faces significant obstacles, such as increased private sector influence and competing national security objectives, in addition to domestic politics.[135]

5.4 Choices for leadership

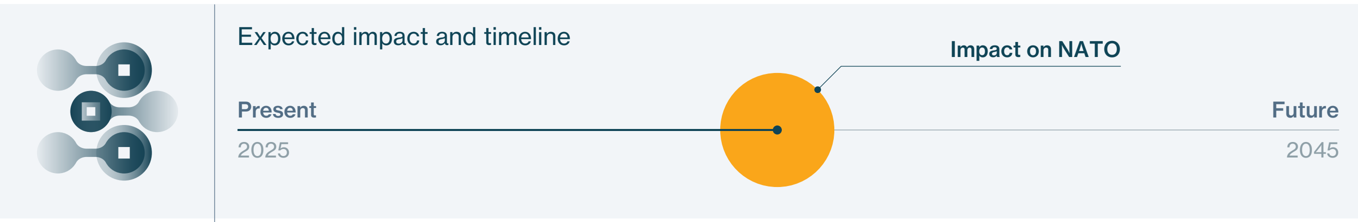
Research suggests that trust in science, institutions, and governments is highly vulnerable to further fragmentation. In order to combat these challenges, including AI-generated information threats, trustworthy S&T solutions must be pursued. This will likely require substantial investment in advanced AI and LLM tools to monitor, identify, and combat harmful information online, supported by regulation to ensure that monitoring requirements are executed responsibly. Additionally, the need for evidence-based media and technology education, including training in critical thinking, will significantly increase over the next 20 years.

To mitigate the continuing fragmentation of public trust in science and technology, senior leaders should continue prioritising strategic communication efforts, including pre-bunking and de-bunking false narratives. In parallel, senior leaders' support for responsible use of technology – for example, developing and implementing PRUs – will be essential. In order to foster trust, clear and consistent messaging of PRUs and other initiatives should remain a high priority. NATO leaders should also consider how best to reach out to international communities of experts who are addressing the technical aspects of the information environment.

It is also important to recognise that the weaponisation of certain technologies to create misunderstandings and mistruths can be achieved very easily and cheaply. While AI in particular has empowered the rapid spread of misinformation and disinformation, effective disinformation can instil doubt in a targeted audience without presenting a credible story or facts in response.

Macro Trend 6

Technology Integration & Dependencies



Key judgements

Future S&T capabilities need to be interoperable by design.

Interoperability will become more critical than ever for Allies in the next 20 years, yet new challenges to achieving it will also arise as disparities in technology access, usage, and regulations become more pronounced.

Economic cooperation is needed with like-minded nations and private sector partners.

Increasing dependencies on private actors for critical defence needs will become a greater challenge as S&T becomes increasingly essential for a wider range of military operations.

6.1 Background

Continued integration of emerging technology into R&D, manufacturing, transportation, communications, and other areas has the potential to rapidly accelerate scientific progress and innovation. From new avenues for space exploration through hypersonics and in-space propulsion to reimagining public health through applying quantum mechanics to vaccines, future S&T benefits will touch many lives and sectors. Increased economic and logistics benefits are already visible in several industries – for example, via the implementation of AI and advanced manufacturing. However, understanding the potential long-term risks and challenges caused by tech integration is also vital.

6.2 Implications

While S&T advancements will continue to provide solutions to complex challenges, access to these solutions will not be equal, even among NATO Allies and partners. For those with access to cutting-edge technologies, differences in usage and regulation will likely create challenges for interoperability and for aligning ethical and regulatory standards. Meanwhile, as innovation is increasingly driven by the private sector, new challenges for civilian-military integration are likely to emerge, and the long-term effects of increased dependency on S&T across civilian and military domains will likely bring unexpected consequences, both positive and negative. Additionally, enhanced reliance on dual-use technologies, synthetic environments (virtual and mixed-reality environments), and commercial actors is likely to reframe traditional concepts of deterrence and escalation.

As innovation is increasingly driven by the private sector, new challenges for civilian-military integration are likely to emerge.

In the NATO context, future defence capabilities will rely on the ability of planners, engineers, and operators to effectively integrate new technology solutions with legacy platforms. These efforts must also comply with NATO standards and international norms. Long-term dependencies on certain technologies must also be considered when aligning requirements with the NATO Defence Planning Process and developing collective capabilities through, for example, High Visibility Projects.[136] Alliance training and exercises will be vital for building understanding on future interoperability challenges and the complex interdependencies involved in coalition warfighting.

Private sector dependence

Since the private sector now drives the vast majority of defence innovation, a substantial amount of the technology that armed forces need to gain/maintain the necessary military advantage is dual-use. Hence, it is more likely that cutting-edge technology adopted by one military can be integrated by others. This may offer useful options for forces that seek to exercise and train together, but it also means that these technologies may be easily available to competitors or adversaries. Therefore, although Allies often benefit from the availability of quickly deployable and often

cheaper off-the-shelf capabilities from industry suppliers, overreliance on commercial entities for critical capabilities may create vulnerabilities in the event of near-peer conflict. Furthermore, growing dependence on the private sector for strategic defence capabilities may also reframe the way military leaders and political decision-makers have traditionally approached deterrence.

Social effects

In addition to military, economic, and geopolitical effects, it is also important to understand the potential long-term effects of technology integration and dependency on individuals. Research on technology dependencies and addiction in children and young adults suggests that overreliance on technology results in significant negative effects on psychological and physical health as well as social behaviour,[137,138] also considering the possibility of exposure to disinformation campaigns.[139] Regarding wearable and especially implanted technologies – for example, neural implants, advanced prosthetics, or AI-powered exoskeletons – the long-term health effects on human health, cognition, and identity remain largely unknown. As experts have pointed out regarding the use of AI, only the uses that are measured can be properly managed.[140] Therefore, creating mechanisms for monitoring and measuring how humans are impacted by future technology use is vital.

Creating mechanisms for monitoring and measuring how humans are impacted by future technology use is vital.

6.3 State of play

Across many technology areas, the short-term benefits are often clear while the potential long-term repercussions remain difficult to predict. Careful consideration of possible future scenarios must therefore be considered as S&T is further integrated into diverse aspects of everyday life.

The manufacturing industry offers one useful example of the positive and negative effects of technology integration. In this sector, tech-enabled tools – for example, the combined use of AI and additive manufacturing – are already transforming many companies' workflows and profit margins by significantly boosting productivity and efficiency. However, some bigger picture repercussions may be negative in the long term. For example, automated work is likely to not only displace many low-skilled workers but increase demand for highly skilled ones in addition to encouraging further market concentration, hence expanding the power of key industry actors.[141]

Looking at AI, this technology area already provides critical real-time decision support for military leaders in operational scenarios, allowing for rapid and data-driven decision-making. However, the technology behind AI solutions remains imperfect (for example, due to algorithm biases), which is why Allied militaries require humans to be 'in the loop' when it comes to decision-making. However, if decision mechanisms were to become over-reliant on AI in the future, this could have major unintended implications for battlefield escalation. Although industry actors are working to mitigate these risks through relying on human-centred design approaches, it is necessary to consider potential long-term vulnerabilities.

The role of the private sector

The private sector is gaining a more dominant position in the global economic and geopolitical landscape, as the technological solutions it provides are increasingly central for staying competitive in an unpredictable world where political and economic shocks are becoming more common. Relying on industry to provide tools for necessary initiatives such as digital transformation and prioritising sustainability in business operations is certainly necessary. For many nations, private actors also offer the only alternative to decrease dependence on states that have weaponised their control of energy supplies. For these nations, the private sector will be central to achieving long-term economic resilience and national security aims.

The private sector is gaining a more dominant position in the global economic and geopolitical landscape.

However, dependence on private entities is not without risk. Even defence innovation is no longer driven by governments, but rather industry leaders. As gaining or maintaining the technological advantage becomes increasingly important for policymakers, military decision-makers, and a diverse range of business owners and other professionals, global dependence on industry leaders will only increase. As a result, it is important to consider the possible repercussions and responses if profit-driven entities were to use coercive practices to further deepen dependencies on their products and services.

Some nations have endeavoured to mitigate risks stemming from the combination of private sector overreliance and weak regulatory frameworks, for example by curbing unchecked dissemination of emerging technologies. However, even actors such as the EU, which has spearheaded multiple initiatives to protect its economies and citizens from the negative effects of ‘Big Tech’ and other industries, still face the challenge of rapid S&T development outpacing regulation mechanisms. Many countries across the globe also continue to offer favourable tax environments to private entities without enacting parallel policies to regulate harmful practices.

Interoperability

Integrating technology into the military brings both challenges and opportunities. Militaries have long grappled with interoperability issues such as combining new and legacy systems and low- and high-tech systems. However, the current rapid rate of technology advancement and potential applications has intensified the challenge of keeping pace. Some experts are also quick to point out that high-tech should not be viewed as a substitute for quantity of capabilities. In some cases, having adequate quantity of low-tech capabilities is sufficient to achieve battlefield objectives.[142] This thinking is also evidenced by recent policy efforts, for example the US Department of Defense’s ‘Replicator’ initiative, which aims to acquire thousands of cost-effective (i.e., expendable) autonomous systems for rapid adoption and deployment (and also replacement).[143]

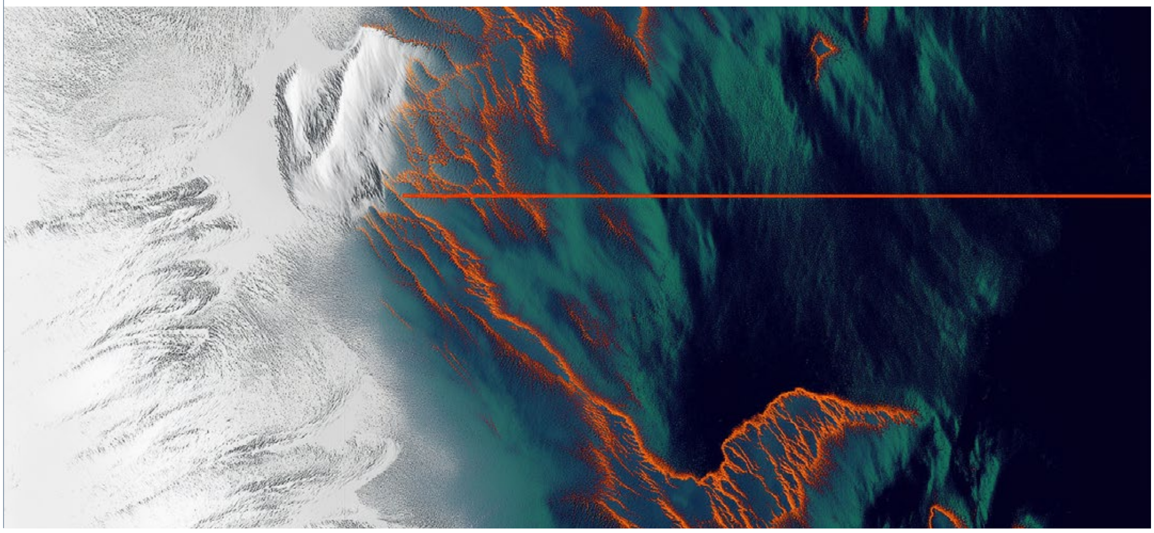
For NATO militaries, interoperability remains uniquely important, as the security of the Alliance depends on 32 militaries’ ability to exercise, train, and fight together. While having diverse forces and capabilities to draw on is certainly an advantage for Allies and partners, increasing technology adoption also poses interoperability challenges as militaries use different approaches and timelines. Nonetheless, integration will bring positive effects as well. For example, the rise of virtual and augmented reality or ‘metaspheres’ enables real-time military training in more realistic scenarios. When combined with increasingly advanced modelling and simulation techniques, this area could revolutionise the future of military training and increase access to distributed synthetic training, which provides soldiers the opportunity to immerse themselves in hyper-realistic virtual and mixed-reality training environments. Nevertheless, integrating new and emerging technologies in ways that are interoperable not only with legacy systems but the systems of fellow Allies and partners will be a key challenge over the next 20 years. If technical disparity between Allies results in disparity in Concepts of Operations, then Alliance interoperability could be severely challenged.

Information superiority

Accelerating investment in technology coupled with a rise in the use of electronic warfare has made information superiority even more important in the modern defence context. Due to the importance of data for cognitive, electronic, and conventional warfare, militaries will become more dependent on sensor technologies over the next 20 years.[144] Prioritisation of information superiority by military leaders has already created a substantial increase in investment related to advanced and networked sensors,[145] with future demand expected to continue growing. Advanced sensor capabilities will have a significant impact on future warfare, especially by providing more accurate data faster than ever via real-time data collection, including high-resolution images, and more comprehensive and precise monitoring. On its own, advanced sensing will enhance militaries' ability to maintain mission flexibility, allocate resources efficiently, and utilise more resilient communication systems. Paired with additional S&T tools such as AI, future sensing capabilities will also provide critical intelligence through advanced data processing as well as analysis and pattern recognition.

At the same time, a hyper-digitalised and connected battlespace also brings vulnerabilities and risks. For example, continued integration of complex military systems that rely heavily on space technologies for access to critical, time-sensitive information increases the likelihood that disruptions to space access and satellites will have catastrophic consequences.[146] These risks are also relevant for civilian communities, as networks that sustain critical infrastructure are also vulnerable to similar disruptions. As noted in Macro Trend 1, the current space environment is poised to become more susceptible to contests and conflict in the coming years.

Furthermore, persistent ISR will yield vast quantities of data, which could potentially create difficulties for processing and interpretation as well as causing dissemination bottlenecks. Such challenges could limit a commander's decision advantage even if the information they need has been collected.



6.4 Choices for leadership

Understanding the benefits and risks of technology – including their convergence and integration – will enable senior leaders to make future decisions regarding the necessary applications of S&T in civilian and military realms. Useful considerations include: the long-term effects of technologies on people, societies, economies, and militaries; the potential risks of critical dependencies (on technology areas and commercial actors); and likely future disparities between Allies and partners in the use and regulation of technologies. Carefully monitoring these effects will empower decision-makers to take actions today that will prepare NATO for the possible scenarios of tomorrow.

Leaders would also benefit from building awareness of how adversaries and challengers are exploiting and combining novel technologies. This knowledge would support a deeper understanding of how science and technology can be leveraged to grant strategic, operational, or tactical advantage.

When assessing the risks and opportunities of further technology integration, it will be necessary to bring political and military decision-makers together with voices from the S&T and R&D environment and trusted private sector partners. In addition to drawing from interdisciplinary expertise, a prioritisation of safeguards and regulation will also be needed in order to ensure that the Alliance's citizens and warfighters can benefit from future technology advancement as much as possible while maintaining resilience against catastrophic shocks.

Conclusion

These socio-technical trends will shape the strategic S&T landscape over the next 20 years. As such, these trends will not only impact scientific collaboration and research but will also affect the Alliance's political decision space, defence capabilities, military operations, and enterprise functions.

As S&T is integral to achieving both political and military objectives, building knowledge on these inter-relationships will enable the Alliance to be more strategically prepared and less strategically surprised. Therefore, this analysis aims to equip Alliance leadership with evidence-based suggestions about long-term military and political imperatives.

The overview of linkages between S&T areas and their economic, geopolitical, and social effects and enablers provided by this report offer useful context for understanding the world of today and tomorrow. However, in order to prepare for the future, it is incumbent upon senior decision-makers to consider the choices before them.

While some trends and related technology areas are already apparent today, others will take time to fully mature. Nevertheless, the decisions made by senior leaders now will impact the Alliance and its citizens for years to come. Careful consideration of future scenarios and their likely implications will be critical to ensuring that the Alliance will maintain its ability to act and react as these trends continue to unfold. Within this context, Volume II of the S&T Trends Report provides NATO leadership with classified recommendations for equipping the Alliance with the necessary S&T solutions to support future warfighting.

The choices outlined in S&T Trends Volumes I & II will shape NATO's and Allies' level of preparedness for future challenges as well as the extent to which they benefit from S&T advantages and solutions.

Abbreviations

ACT – Allied Command Transformation

AI – Artificial intelligence

BioE3 – Biotechnology for Economy, Environment and Employment

BRICS – Brazil, Russia, India, China, South Africa *(formally, the Federative Republic of Brazil, the Russian Federation, the Republic of India, the People's Republic of China, and the Republic of South Africa; as of March 2025, BRICS members include the Arab Republic of Egypt, the Federal Democratic Republic of Ethiopia, the Islamic Republic of Iran, and the United Arab Emirates)*

CBRN – Chemical, biological, radiological, nuclear

CPoW – Collaborative Programme of Work

CRISPR – Clustered Regularly Interspaced Short Palindromic Repeats

C2 – Command and Control

DNA – Deoxyribonucleic acid

EDT(s) – Emerging and disruptive technology/ technologies

GDP – Gross domestic product

GPS – Global Positioning System

ISR – Intelligence, surveillance, and reconnaissance

ITPP – Individually Tailored Partnership Programme

LLM(s) – Large language model(s)

MDO – Multi-domain operations

NATO – North Atlantic Treaty Organization

NCIA – NATO Communications and Information Agency

OCS – Office of the NATO Chief Scientist

OECD – Organisation for Economic Co-operation and Development

PNT – Positioning, navigation, and timing

PRUs – Principles of responsible use

RBIO – Rules-based International Order

R&D – Research and development

SPS – NATO Science for Peace and Security Programme

STO – NATO Science & Technology Organization

S&T – Science and technology

Methodology

The following trends were formulated on the basis of:

- scan of the STO Programmes of Work, including Research Task Groups, Technology Watch Cards, and recent STO publications;
- analysis of multiple surveys of STO's network of experts, conducted by the Office of the NATO Chief Scientist;
- research & analysis of open-source materials, including a thematic analysis of:
  - a wide range of national strategy documents:
  - strategic foresight analyses; and
  - think tank reports,

  conducted by OCS staff as well as AI-enabled tools;

In addition to open-source research, trend analysis was also conducted with the assistance of participants in the Science & Technology Trends Workshop and Young Voices Workshop in 2024.

Contributors

Jordan Sweeney, Daniel Bayliss, Fiona Butcher, Salvatore Calabro, Lucas Cox, Georgiana Dragomir, Ulf Ehlert, Alvaro Martin-Blanco, Sascha Simon

Acknowledgements

This publication would not have been possible without the valuable inputs to the research for this report from members of the NATO STO network of experts and the following organisations and offices:

Centre for European Reform (CER)

Defence Science and Technology Laboratory (Dstl)

European Cyber Security Organisation (ECSO)

European Commission Joint Research Centre (JRC)

Fraunhofer Institute

The German Marshall Fund of the United States, *Brussels Office*

Japan Ministry of Defense, Department of Technology Strategy, Acquisition, Technology & Logistics Agency (ATLA)

Leonardo S.p.A.

NATO Allied Command Transformation (ACT)

NATO Centre for Maritime Research and Experimentation (CMRE)

NATO International Military Staff, *Office of Chair, Military Committee*

NATO International Staff: *Executive Management Division; Defence Policy and Planning Division; Innovation, Hybrid and Cyber Division; Office of the Secretary General, Policy Planning Unit; Operations Division*

Netherlands Organisation for Applied Scientific Research (TNO)

Norwegian Defence Research Establishment (FFI)

Polish Air Force Institute of Technology

Polish Military University of Land Forces

PwC Belgium

Swedish Defence Research Agency (FOI)

Von Karman Institute for Fluid Dynamics

Production

Editing and design by Studio Miko: Phoebe Barker, Laurence Denmark, Martha Howlett, George Messer, Alistair Millen

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