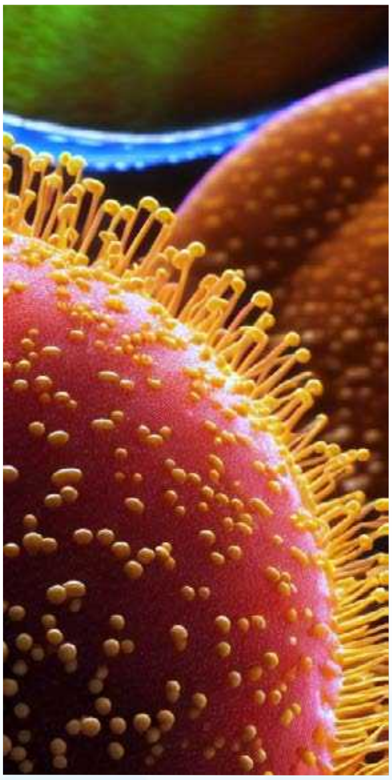
Science and Technology Organization

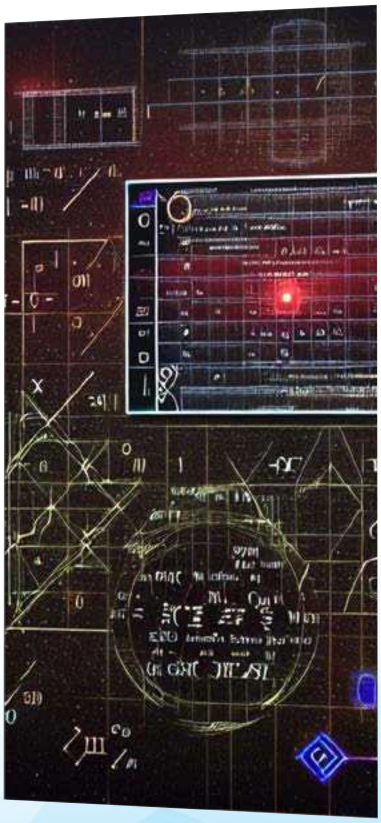
# Science & Technology Trends 2023-2043

**Across the Physical, Biological, and Information Domains**

NATO Science & Technology Organization

VOLUME 1: Overview





## ⚠ DISCLAIMER

*The research and analysis underlying this report and its conclusions were conducted by the NATO S&T Organization (STO) drawing upon the support of the Alliance's defence S&T community, NATO Allied Command Transformation (ACT), and the NATO Communications and Information Agency (NCIA). This report does not represent the official opinion or position of NATO or individual governments but provides considered advice to NATO and Nations' leadership on significant S&T issues.*

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# Foreword

NATO continues to strive for peace, security, and stability in the whole of the Euro-Atlantic area. Central to this task is maintaining, and sharpening, our technological edge. While we develop and adopt new technologies, we also strive to preserve the ethical, legal, and moral principles of the Alliance. This is what sets us apart from our competitors. We want to shape the standards and norms of emerging and disruptive technologies, and lead in the ethical use of these technologies in defence. Further, we must actively address the threats and challenges posed by such technological developments both now and in the future. To do so requires us to understand the evolving S&T environment. This report constitutes an essential and evidence-based understanding of future science and technology development, and will act as a foundation for our future technological, defence, and investment decisions.

*Mircea Geoană*
*NATO Deputy Secretary General*

This report assesses the state, rate, and potential impact on the Alliance of emerging and disruptive scientific and technological advances expected over the next 20 years. It updates and extends the previous ***Science & Technology Trends: 2020-2040***, reflecting the considerable geopolitical, technical, and scientific developments that have occurred over the last few years. This assessment is based on a review of selected national and international S&T foresight and futures studies, multi-national workshops, and technology watch activities conducted by the Science & Technology Organization. In addition, I gratefully acknowledge the collaboration and support provided by Alliance and Partner defence R&D communities, the NATO International Staff, Allied Command Transformation (ACT), and the NATO Communication and Information Agency (NCIA).

*Dr Bryan Wells*
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# Executive Summary - Volume 1

***Science & Technology Trends: 2023-2043*** provides an assessment of Science & Technology (S&T) trends and their potential impact on NATO military operations, defence capabilities, enterprise functions, and political decision space. This assessment draws upon the collective insights and research activities of the NATO Science & Technology Organization (STO), its collaborative network of over five thousand active scientists, analysts, researchers, engineers, and associated research facilities. These insights have been combined with an extensive review of the open-source S&T literature, selected national research programmes, NATO STO technology watch activities, (serious) research games, STO CPoW (Collaborative Programme of Work) activities, and NATO innovation endeavours. The report is split into two volumes covering the overall conclusions (Volume 1) and the detailed analysis (Volume 2).

This report builds upon, updates, and extends the previously published ***NATO Science & Technology Trends: 2020-2040***, following the same general structure and focus. In general, the conclusions and insights from that report have stood the test of time. Nevertheless, noteworthy developments have occurred in the broad technological and geostrategic environments, with COVID-19, Ukraine, climate change, a new Strategic Concept, and South-East Asia being of note. These changes have, in turn, driven relevant S&T developments and highlighted their implications for enterprise or military operations.

The report aims to assist current and future military and civilian decision-makers in understanding emerging and disruptive technologies (EDTs), thereby guiding NATO R&D portfolio management, innovation activities, and capability planning. It focuses on the following: • *Why* such EDTs are important to future Alliance activities; • *How* they are expected to develop over time; and • *What* will this mean to the Alliance from an operational, organisational and enterprise perspective?

Over the next 20 years, we assert that four overarching characteristics will define advanced military technologies. Technological developments will be increasingly *intelligent*, *interconnected*, *decentralised*, and *digital*. These, in turn, will lead to military capabilities that are increasingly *autonomous*, *networked*, *multi-domain*, and *precise*. Technology will be increasingly dual use, i.e. developed and drawn from the commercial sector. Emerging technology-enabled capabilities will increase the Alliance's operational and organisational effectiveness by enabling the NATO Warfighting Capstone Concept's five Warfare Development Imperatives (WDI): *Cognitive Superiority*; *Integrated Multi-Domain Defence*; *Cross-Domain Command*; *Layered Resilience*; and wide-ranging *Influence and Power Projection*. At the same time, such technologies will and indeed are presenting significant challenges to the Alliance, including operational, interoperability, ethical, legal, and moral concerns.

NATO has approved an established set of EDTs of interest, also referred to as priority technology areas. Defence Ministers agreed to the first seven EDTs in October 2019. For the previous S&T Trends report, the STO added an eighth area (*Materials*) for future consideration and development. In 2022, at the Madrid summit, these EDTs were formally expanded to include *Energy & Propulsion* and *Novel Materials and Manufacturing*. In keeping with the STO's mandate to continue to monitor and evaluate the broader technological landscape, this report also considers the status of recent developments in *Electronics & Electromagnetics (E&EM)* technologies. These S&T areas are either currently in nascent stages of development or are undergoing rapid revolutionary growth. The final list of EDTs considered in this report, along with the usual abbreviations or *shorthand* used (shown in bold), are:

- **Data**: *Big Data, Information & Communication Technologies*
- **AI**: *Artificial Intelligence*
- **RAS** (or **Autonomy**): *Robotics & Autonomous Systems*
- **Space**: *Space Technologies*
- **Hypersonics**: *Hypersonic Technologies*
- **Quantum**: *Quantum Technologies*
- **BHET** (or **Biotech**): *Bio & Human Enhancement Technologies*
- **Materials**: *Materials & Advanced Manufacturing*
- **Energy**: *Energy & Propulsion*
- **E&EM**: *Electronic & Electromagnetic Technologies*

Technological developments in *AI*, *Autonomy*, *Space*, some areas of *Data*, *Energy*, and *E&EM* are seen to be predominately (but not exclusively) disruptive in nature, as developments in these areas build upon long histories of supporting scientific and technological development. The focus of action in these areas revolves around their effective adoption and impact on other technologies. As such, significant or revolutionary disruption of military capabilities is either already ongoing or will have a considerable effect over the next five to ten years. Emergent areas are to be found in *Quantum*, *BHET*, *Materials*, and some aspects of *Data* (e.g. 6G technologies). Such developments are perhaps better defined as re-emergent as previous development cycles have significantly affected earlier technology revolutions. These will require substantially more development time (ten to twenty years) before their disruptive natures are fully realised as military capabilities.

Since the last report, several major EDT developments are worth noting, including:

- **Data**: The increased use of distributed ledger technologies, advanced analytics and visualisation, and the development of new networking and wireless technologies (e.g. 6G) are accelerating the need for a well-thought-out digital data backbone linking decentralised sensor and C2 nodes. This, in turn, is driving increased developments in the internet of things (IoT), edge computing, and new data architectures (e.g. mesh, fabric, lake, etc.).

- **AI**: Disruptive AI applications and the role of AI as an S&T enabler or catalyst of other EDT developments have been a significant factor in major developments across the physical, information and biological sciences and associated technologies. At the same time, the limits of AI practice are leading to the exploration of new, more robust and trusted methods, moving beyond deep learning and the development of the AIoT (Artificial Intelligence of Things).

- **RAS**: Developments in AI and energy storage are driving the development of increasingly sophisticated and robust autonomous systems. However, the most significant and impactful RAS development is its wide application and impact on current military operations and plans. Cost reductions, widespread availability, and creative use on the battlefield have driven RAS innovation.

- **Space**: Commercial enterprises and strategic competitors are accelerating the development of space technologies. The impact of sustained space-based communications (e.g. StarLink) in areas of hostilities is of special note. At the same time, counter-satellite research is of increasing concern, while on-orbit repair capabilities promise cheaper and longer on-orbit operations. New propulsion systems also promise to increase the use of non-near-Earth (cislunar) space and reduce launch costs.

- **Hypersonics**: R&D is being conducted on mixed-mode engines for broad military applications (e.g. crewed aircraft), deployment of operational hypersonic missile systems and development of effective counter-measures.

- **Energy**: Developments in Energy, responding to climate change, and security challenges, are driving increased military exploration and adoption of electric propulsion (air, land and maritime) and new battery chemistries for advanced energy storage. Research into large-scale global solar energy production and terrestrial and extra-terrestrial space-based small nuclear, thorium, and fusion reactors show considerable promise for safe and widely available energy production in the latter half of 2030 or early 2040s. It is important to note that AI and novel Materials have been and will continue to be critical enablers of such developments.

- **Biotech**: The near-miraculous rapid development of vaccines (such as that for COVID-19) and the potential development of engineered pathogens are of particular note. Advances in bio-manufacturing, synthetic biology and 3D bio-printing are accelerating.

- **Materials**: Research into room temperature superconductors, novel uses of graphene (and other 2D materials such as graphyne), and new semiconductor materials hold considerable promise for future technologies. The applications of additive manufacturing and bio-printing are exploding, disrupting current medical and logistics systems.

- **E&EM**: New non-silicon materials and semiconductor designs are pointing toward faster chips and specialised processors (e.g. neuromorphic for AI).

Truly disruptive effects will occur through technology convergence driven by combinations of EDTs and their complex relationships. The following synergies and inter-dependencies are projected to be highly influential in the development of future military capabilities:

- **Data-AI-Autonomy**: The synergistic combination of Autonomy, Big Data and AI using intelligent, widely distributed, and cheap sensors alongside autonomous entities (physical or virtual) will leverage innovative technologies and methods to yield a potential military strategic and operational decision advantage.

- **Data-AI-BHET**: AI, in concert with Big Data, will contribute to designing new drugs, purposeful genetic modifications, direct manipulation of biochemical reactions, new chemical and biological threats, and living sensors.

- **Data-AI-Materials**: AI, in concert with Big Data, will contribute to the design of new materials with unique physical properties. This will support further developments in using 2-D materials and novel techniques.

- **Data-Quantum**: Over a ten-to-fifteen-year horizon, quantum technologies will expand C4ISR data collection, processing, and exploitation capabilities through significantly increased sensor capabilities, improved PNT (positioning, navigation, and timing), secure communications, and computing.

- **Energy-Materials-AI**: New developments in energy storage, driven by novel materials such as graphene and exotic battery chemistry, as well as stronger lightweight materials and novel designs (e.g. massive castings, super-capacitors or 3D printing), will continue to drive electrification or the use of green fuels (e.g. hydrogen and biofuels) in military operations. AI to support these designs and material developments and optimise energy use will contribute to the *greening* of NATO forces.

- **Space-Hypersonics-Materials**: Development of exotic materials, novel designs, miniaturisation, energy storage, manufacturing methods, and propulsion will be necessary to fully exploit Space and Hypersonic environments by reducing costs, increasing reliability, improving performance, and facilitating the production of inexpensive task-tailored on-demand systems.

- **Space-Quantum**: Space-based quantum sensors, facilitated by Quantum Key Distribution communication, will lead to high-precision sensors suitable for satellite deployment. Increasingly commercial, smaller, lower power, more sensitive, and distributed space-based sensor networks enabled by quantum sensors will be an essential aspect of the future military ISR architecture in ten to fifteen years.


# 1. Introduction

**The Future**
"Be not troubled about the future. You will come to it, if need be, with the same power to reason, as you use upon your present business." — *Marcus Aurelius Antoninus* [1]

## 1.1 Context

Since the last Science and Technology (S&T) trends assessment [2], the world has seen a staggering amount of change and disruption. Over the previous three years, NATO, and the world as a whole, have been challenged by the withdrawal of NATO forces from Afghanistan, the pandemic of the century (COVID-19), the Russian-Ukrainian *special military operation*, significant climate disruption, inflation, increased tensions in the Asia-Pacific, authoritarianism, and disinformation. This strain has been compounded by the relentless drive of commercial S&T developments, especially in the areas of quantum, biotechnology, and AI. NATO faces a strained and fluid security environment, with existential challenges and threats from all strategic directions, including state and non-state actors, near-peer military forces, cyberspace, space, and cognitive warfare.

NATO is a unique consultative and collaborative military and political framework. A key enabler of its success for more than 70 years has been the NATO S&T community (the original NATO *innovation engine*), which has provided NATO with the intellectual and technological edge needed to ensure the Alliance's success across the enterprise, operational, and diplomatic spectrum. Maintaining this S&T edge means understanding and adapting to emerging and disruptive technologies (EDT). In turn, this means anticipating S&T developments and understanding their potential operational and strategic implications.

The NATO S&T community enables the application of state-of-the-art validated knowledge for defence and security purposes. It embraces scientific research, technology development, quantitative analysis, capability-based planning, experimentation, and a wide range of related scientific activities [3].

The NATO Science and Technology Organization (STO) plays a decisive role in supporting *innovation*; providing profound *insights* into alliance challenges; ensuring the *integration* of Alliance capabilities; and making available an *interconnected* network of science and knowledge workers capable of providing evidence-based *advice* to NATO, as well as alliance members and partners. At its core, the role of NATO's S&T community is to [3]:

> *"... maintain NATO's scientific and technological advantage by generating, sharing and utilising advanced scientific knowledge, technological developments and innovation to support the alliance's core tasks."*

***Figure 1.1:*** *1958 NATO Science Committee (CREDIT: NATO).*

The importance of S&T to NATO and the Alliance was institutionalised early in the history of the Alliance [4], first through Article 2 of the North Atlantic Treaty [5] and later through the work and report of the *three wise men* [6]. Building on that bedrock and the foundational work of Theodore von Kármán and the NATO Science Committee (Figure 1.1), the STO in its various incarnations has, over the past 70 years, helped NATO effectively employ a *strategy of technology* [7, 8], leveraging a decision and S&T advantage to significant intellectual, political, economic, and military effect. As noted by [9], *"... in an Alliance united in purpose, extensive and meaningful coordination, cooperation and collaboration of defence S&T adds significant value to national efforts, while establishing interoperability and the necessary overarching command and control."*

This S&T excellence has been a critical enabler of the technological edge that NATO has relied upon for more than seventy years. However, this advantage has been degraded in recent years due to various strategic, economic, social, and technical challenges. Regaining this edge will require NATO to engage with and leverage the talents, capabilities, and creativity of the entire Alliance and national innovation systems [10]. Alliance leadership has awakened to the innovation challenge. As noted by leaders during the 2021 NATO summit in Brussels [11]:

> *"The speed of technological change has never been higher, creating both new opportunities and risks in the security environment and to the way NATO operates. We are determined to preserve our technological edge and ensure Alliance interoperability to maintain the credibility of our deterrence and defence posture. We have recently taken important steps to that end, building on the Emerging and Disruptive Technologies (EDTs) Roadmap we agreed on in 2019. We have now adopted our strategy to foster and protect EDTs. This strategy outlines a clear approach for identifying, developing, and adopting EDTs at the speed of relevance, guided by principles of responsible use, in accordance with international law, and taking into account discussions in relevant international fora. Moreover, this strategy seeks to preserve our interoperability; safeguard our sensitive technologies; and actively address the*

*threats and challenges posed by technological developments by others, both now and in the future. Drawing on the extensive innovation expertise of all 30 Allies, we will further leverage our partnerships with the private sector and academia to maintain our technological edge."*

## 1.2 Purpose

*Science & Technology Trends (2023-2043)* provides context and a foundation for the NATO EDT strategy, Alliance capability development and NATO S&T programmes of work. The core objective is to increase the understanding within the Alliance of the potential for S&T outcomes to enhance or threaten Alliance military operations. As such, the report is an aid to decision-makers in considering the following:

- *Why* such EDTs are important to future Alliance activities;
- *How* they are expected to develop over time; and,
- *What* this means to the Alliance from an operational, organisational and enterprise perspective?

Anticipating the future security environment better than potential adversaries is one way the Alliance has maintained a competitive advantage. S&T foresight is a critical aspect of this preparation. It does not attempt to predict the future in detail (a difficult task at best and impossible at worst). Instead, it seeks to provide a context for anticipating technology's potential development and impact on the Alliance. This report will help guide the development of essential policies, standards and collaborative S&T development while supporting effective capability development.

Analyses of technology trends and the associated process of technology watch are critical steps to identify new militarily important technologies and communicate the potential impact of these technologies on NATO and national leadership. Those recognised technologies hold the promise to enable the development of disruptive military capabilities for Alliance (BLUE) and potential adversarial (RED) forces. The report assesses S&T trends in priority technology areas projected to impact NATO military operations, capability development and core enterprise functions over the next twenty years. These S&T areas are broad, have significant overlaps, do not cover all S&T development, and are expected to:

- Mature over 20 years;
- Be transformative or revolutionary; and,
- Be emergent or create generational shifts in S&T development.

The STO provides these assessments for NATO. As noted in the STO charter (2012) [3]:

*"To fulfil its mission, the STO will ... provide advice to NATO and Nations' leadership on significant S&T issues, including the identification of emerging technologies, and the assessment of their impact on defence and security."*

## 1.3 Approach

This report aims to reach a wide audience inside and outside of NATO and its partners. A frank and open discussion of potential opportunities and risks presented by technological developments over the next 20 years is essential if NATO is to deploy operationally effective military capabilities. As such, the report is based strictly on the following:

- Technology trends discussed in the open literature;
- A global perspective on technological progress;
- Available scientometric analysis and surveys of technical experts; and,

- Logical reasoning informed by Alliance S&T expertise and technology watch activities.

Candidate S&T trends, within the context of EDTs, were identified considering which scientific and technological developments:

- Are likely to be realised in a non-cost prohibitive manner within the next twenty years;
- Will present a significant challenge to Alliance forces (e.g. survivability, costs, interoperability, legal, etc.); and,
- Will significantly impact Alliance capability or planning decisions (i.e. decision-making, countermeasures, etc.)

*Science & Technology Trends: 2023-2043* supersedes the *Science & Technology Trends: 2020-2040* report [2]. Nevertheless, it draws heavily upon its foundations, structure, insights and lessons learned. As before, the report exploits a broad range of open-source reports, internal assessments, NATO EDT and innovation activities, technology reviews, serious games, quantitative analysis and futures studies to develop a comprehensive understanding of the future technology landscape. These sources include:

- Existing NATO S&T trend and future security environment studies, strategies, discussions and assessments;
- Technology watch activities conducted by the S&T Organisation, including existing Technology Watch Cards (TWC) (current as of October 2022), Chief Scientist Reports, serious (technology) games and Von Kármán Horizon Scans (vKHS);
- Meta-analyses and reviews of open source technology watch and futures research from defence, security and industry sources;
- Internal and external quantitative analysis of academic publications, patents and research activities;
- Surveys of the STO network, Panels and Group seeking insights into technological developments, readiness and maturity;
- NATO-sponsored EDT workshops and innovation system engagements; and,
- Alliance and Partners' EDT studies and research programmes.

Defence Ministers approved a canonical set of EDTs and an associated roadmap in October 2019. In 2022, the meeting of Alliance Heads of State and Government in Madrid authorised two more priority technologies for consideration, *Novel Materials and Agile Manufacturing* and *Energy and Propulsion*. In keeping with the STO's mandate to continue to monitor and evaluate the broader technological landscape, this report considers the status of recent developments in *Electronics & Electromagnetics (E&EM)* technologies, including developments in directed energy weapons. As such, ten EDTs are considered in detail in this report, each broken down into technology focus areas, highlighting specific areas of research and development (R&D). Volume 2 discusses this decomposition in further detail.

In reading this report, one should keep several caveats in mind:

1. The accurate and detailed prediction of S&T trends is a difficult task, although there is some evidence that such studies have been successful at anticipating S&T development within broad time horizons [12];
2. The ultimate objective of any such forecast is to be impactful in a manner that ultimately drives the development or understanding of useful technologies [13];
3. Technologies rarely evolve in a simple linear fashion, and complex synergies between EDTs are often as critical (if not more so) as the EDTs themselves;

***Figure 1.2:*** *NATO Defence Ministers (2019) (CREDIT: NATO).*

4. The list of EDTs provides *a* grouping of related technologies capable of technological disruption. The development of sub-technologies may be very different from the aggregate. Further, such a grouping is not unique, and one finds many such taxonomies in the literature (e.g. [14, 15, 16, 17, 18]. All such clusters, or taxonomies, are simplifications; however, this particular clustering of technologies has proven useful for Alliance purposes; and,

5. Technology has historically driven the changing nature of human conflict, but not conflict itself [19]. More broadly, *"technology is neither good nor bad; nor is it neutral"* (Krazberg's First Law of Technology [20]). In future conflicts, NATO will inevitably use new technologies, and it is necessary to define how that should occur before any crisis. This understanding provides an essential first step to supporting technology-policy decisions, potential capability development, and preparing defensive countermeasures. As such, *discussion of the possible application or impact of S&T should not be taken as an indication of current or future NATO S&T research efforts. Further, such a discussion represents the considered assessment of the authors and does not represent an official NATO position.*

## 1.4 Overview

Within the following chapters, an analysis is presented of identified and militarily relevant S&T trends, which may impact NATO capability development and operational challenges over the upcoming 20 years (2023-2043). The key data sources, methodology, and analysis used to conduct this assessment are described in the Methodology chapter of Volume 2.

The assessment is presented in three parts:

1. An overview is provided of the general nature of S&T development. Specific EDT areas are identified that are expected to impact significantly NATO from 2023 through 2043 (Chapter 2). These EDTs are presented separately, broadly considering the state and rate of development and the military implications. Tables and graphs simplify and summarise the more detailed analysis supporting this report. This overview is followed by a consideration of critical potential synergies between EDTs, as it is in the overlap between these developments that significant disruptions and innovation will occur;

2. The broad strategic context and drivers are outlined that will impact defence S&T development (Chapter 3); and,

3. Volume 2 has separate appendices, which provide a more detailed exploration of each EDT, drawing heavily upon STO research and technology watch activities. This section also includes *Conjecture*

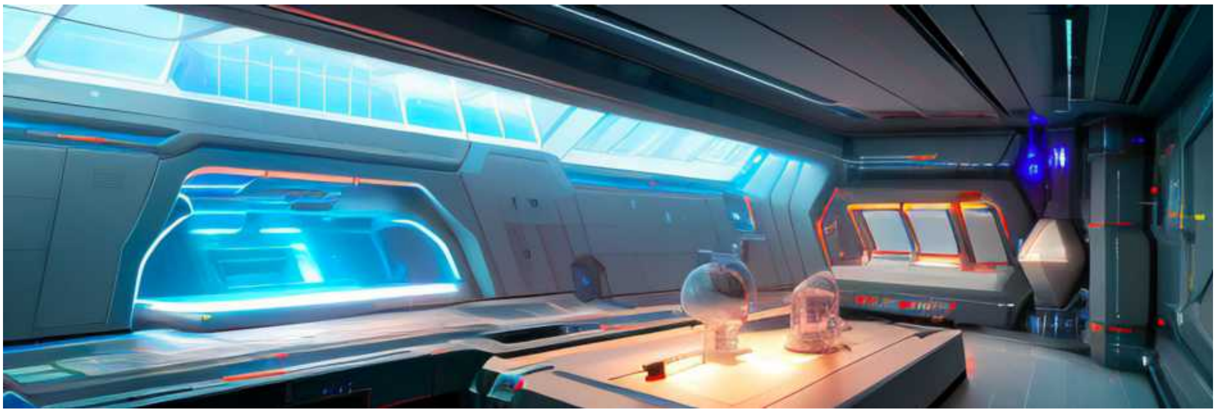
*Cards*, short vignettes that describe the potential future application of these technologies. They are included to help contextualise the potential impact of these technologies. In addition to these detailed assessments, Volume 2 also reviews the data sources and methodology used to generate this report.

The bibliography at the end of this document and Volume 2 provides an extensive list of useful references. These are also used throughout the body of the text where appropriate. When using the Adobe PDF version of the report, *clicking* on a numbered reference will take the reader to the relevant entry in the bibliography. If desired and available, *clicking* on the provided URL (i.e. web-link) will allow the reader to open the source reference directly for further study and exploration of the topic.

# 2. Science & Technology Trends

**Apprehension**
"Don't worry about what anybody else is going to do ... The best way to predict the future is to invent it. Really smart people with reasonable funding can do just about anything that doesn't violate too many of Newton's Laws!" - *Alan Kay* [21]

## 2.1 S&T Development



This chapter summarises the development of S&T, deemed essential to NATO, and seeks to answer the following:

- What do we mean by *emerging* or *disruptive* S&T?
- What are these emerging or disruptive technologies, or what disruptive scientific discoveries do we anticipate?
- What is the state, rate of development and projected impact of these technologies?
- What synergies do we need to pay particular attention to?

While intuitively, the terms emerging and disruptive may be self-evident, there is little consensus around the actual definitions for emerging and disruptive technologies (for example, see [22, 23, 24]). Nevertheless, for purposes of this report, we narrowly define technologies as:

- **Emerging**: Those embryonic technologies or scientific discoveries that are expected to reach maturity in 2023-2043; and are not widely used currently or whose effects on Alliance defence, security and enterprise functions are not entirely clear.
- **Disruptive**: Those technologies or scientific discoveries expected to have a major or revolutionary effect on NATO defence, security, or enterprise functions in 2023-2043.
- **Convergent**: Combinations of technologies that are integrated in a synergistic and novel manner to create a disruptive effect.
- **Sustaining**: Incremental improvements to existing technologies and resulting capabilities focused predominately on reducing size, weight, power, and cost (SWaP-C) or improving effectiveness.

Not all technologies or scientific discoveries are emergent or disruptive, nor is disruption driven solely by technology [25]. Further, not all emerging technologies will be disruptive; not all are emergent, and not all emerging ones will drive convergent technologies. For this report, we focus on those technologies assessed as most likely to be disruptive over twenty years, including those that have moved beyond the initial exploration phase but have not yet become widely exploited. Understanding the natural pattern of EDTs development is a prerequisite in understanding and assessing their potential effects on NATO and the Alliance. The methodology section of Volume 2 discusses this in more detail.

### 2.1.1 Defence S&T Context

One of the critical lessons (re)learned during the conflicts fought over the last two or more decades, especially during the *war on terror* and NATO operations in Afghanistan, is the essential human-centric nature of armed conflict. However, as noted in [26], one may take this (important) insight too far and assume that technology's role is diminished in modern warfare or that this human-centric perspective is independent of the technological ecosystem in which we all live and work:

> *"It has become in vogue for leaders to argue that one of the lessons of the past decade of war is that "technology doesn't matter in the human-centric wars we fight," as one four-star general put it to me. But that assumes a definition of "technology" as exotic and unworkable. To paraphrase the musician Brian Eno, technology is the name we give to things that we do not yet use every day. Once we use it every day, we do not call it technology anymore. Whether a stone or a drone, it simply becomes a tool we apply to a task."*

As this quote highlights, a risk in dealing with S&T developments is that one quickly becomes inured with such technologies and, therefore, greatly underestimates the impact they are or may be having (e.g. the rapid development of effective COVID-19 vaccines).

Over the last five years, technology's role in military operations and geopolitical influence has become increasingly more pervasive. There have been many revolutionary episodes in the development of warfare [27, 28], and it is well recognised that the current *seventh generation military revolution* [8, 29, 30] is being driven (once again) by rapid changes in the technological landscape. In a Clausewitzian sense, human-organised conflict (war in its most extreme case) is a fundamental clash of wills between large social groups (e.g. states, pseudo-states, communities, societies, etc.). During such conflicts, whether with peer competitors or asymmetric threats, technology is an *edge* [31] to be exploited and, in a nuclear-constrained world, displayed [8]. As democratised technology becomes even more central to human existence, it will also play an out-sized role in shaping modern conflict.

As noted in [32]:

> *"This next wave of innovation will stitch together the physical, digital, and bio-technical realms ... as a result, the character of warfare is changing. Already, we are in a new era of persistent cyber, economic, and information conflicts below the level of overt combat that risks bringing us closer to direct confrontation. Emerging technologies are changing the range and specificity of effects, enabling the microtargeting of individuals, and qualitatively changing the way we communicate, perceive our environment, and make decisions ... This approach centres around several focuses, including distributed and networked operations, human-machine collaboration, human-machine teaming, primacy in software-centric warfare and greater technological interoperability and interchangeability with allies and partners ..."*

Broad interest in such EDTs arises from the fear that such technologies may revolutionize aspects of our societies or provide an adversary with the means to change the balance of power. As noted by many authors in one form or another, *"Technology shapes warfare, not war ... War is a condition in which a state might find itself; warfare is a physical activity conducted by armed forces in the context of war"* [19]. Within broad strategic and geopolitical context (see Chapter 3), the nature of conflicts (warfare) is changing, with general agreement that the transforming technological environment is a significant factor [24, 32, 33]. This changing nature of conflict manifests itself in *hybrid war* [34, 35, 36], *hyper-war* [37], *memetic warfare* [38] or *next-generation conflict* [39]. In each, disruptive technologies are merged with existing technologies and military capabilities to create new ways and means of engaging in conflict. They rarely replace such existing technologies immediately but are integrated into existing plans, doctrine and operations.

In 2016, Klaus Schwab, Founder and Executive Chairman of the World Economic Forum, defined the fourth industrial revolution as one which *"creates a world in which virtual and physical manufacturing systems cooperate with each other in a flexible way at the global level"* [40]. Complex technological synergies and a fusion of the physical, biological, and information domains mark such revolution [41]. As noted by [42], this technological development is characterised by evolving and expanding immersive experiences, accelerated AI automation, and optimised technologist delivery. Thus, the technologies of the fourth industrial revolution underlie the development of the seventh military revolution.

Unlike the last 80 years, EDTs are no longer driven by the needs and interests of the Defence Sector nor by clear societal objectives [32]. Civil sector investments dwarf those of the defence sector, especially in such areas as quantum technologies, AI, bio-technologies and electronics. That is not to say that public sector investment is inconsequential but rather drives bespoke very high-risk technologies, such as exquisite and novel semiconductors technologies [43].

Another common theme for technology development is how impactful and pervasive the synergistic development of *AI-Data-RAS* has been. It is difficult to overstate this combination's impact on developing novel technologies. This raises the importance of *breadth* in technology development. Such breadth is as important as the actual pace of development. This breadth challenges prioritisation. EDTs cover everything from Quantum to Biotechnology, from Novel Materials to AI. This range makes prioritisation difficult, particularly as developments within a specialised area may vary widely. Yet at the same time, this tsunami of mutually reinforcing technological developments leads to combinatorial trends where *"these technologies can create new possibilities when they're used together"* [44].

Finally, a theme in this report that shall arise again and again is the increasing focus on human-machine interactions, including teaming, interfaces and symbiosis. The increasing scientific understanding of the human mind (driven in no small measure by advances in sensors, analysis, data and AI) will accelerate human-machine interfaces as a pervasive disruptor.

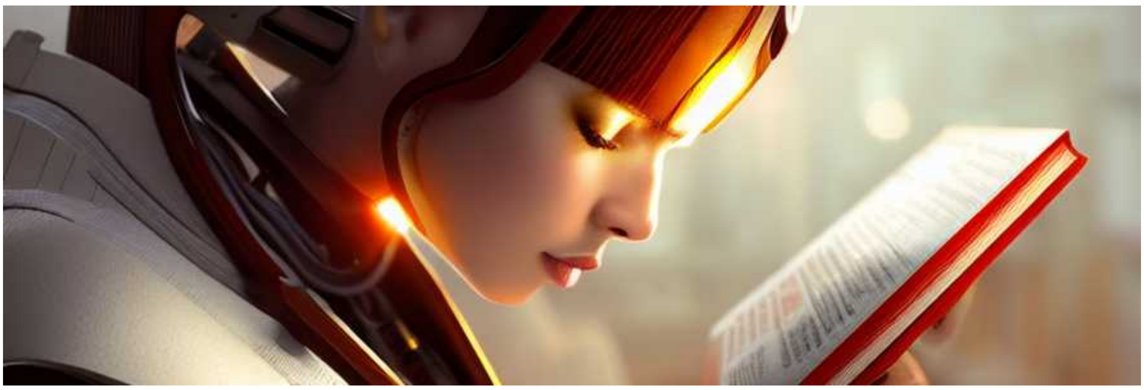
Historically, technology has driven the battlespace's changing (subjective) nature. Nevertheless, it has not fundamentally altered human conflict's (objective) nature. Innovative technologies are inevitably used in conflict, whether designed initially for such or not. At the same time, they may create entirely new operational domains (e.g. air, cyber & space) or reinvigorate old ones (land, sea & cognitive). Rapid changes in the technological landscape are driving the current seventh-generation military revolution.

Yet, organized human conflict (war in its most extreme case) remains a fundamental clash of wills between large social groups (e.g. states, pseudo-states, communities, societies, etc.). With the development of increasingly autonomous and AI-driven systems, the objective nature of warfare is changing. Modern military forces will need to adapt to operational domains increasingly dominated by AI and Autonomy and the technologies they enable, potentially redefining what is meant to impose one's will on an opposing force.

Transformation of Military forces will be increasingly dominated by the need to understand and successfully integrate technology-enabled capabilities (e.g. DOTMLPF-I) into the order of battle. Those with creativity and imagination will determine future military success in designing, developing, and operating information/autonomy-enabled technologies across the tactical-operational-strategic spectrum at all levels of technological sophistication. However, this does not necessarily imply the dominance of new and expensive technology. In this context, the old engineering adage of *"good, fast, cheap – pick two"* will continue to apply and may be used by adversaries on the battlefield to negate an expensive technological advantage.

The common factors that link these Fourth Industrial Revolution technologies are that they are all in some way, shape, or form: *intelligent*, *interconnected*, *decentralised* and *digital (I2D2)* in nature. Over the next 20 years, these four overarching characteristics can be expected to define advanced military technologies. In each, disruptive technologies are merged with existing technologies and military capabilities to create new ways and means of engaging in conflict. More specifically, we note that the future S&T landscape will be characterised (and at the same time driven) by the following qualities:

1. **Intelligent**:



Technologies will exploit integrated AI, knowledge-focused analytic capabilities, and symbiotic AI-human intelligence to provide disruptive applications across the technological spectrum.

(a) *Autonomy*: Artificial intelligence-enabled autonomous systems will be capable of independent decision-making. Such autonomous systems may be robotic, platform-based or (digital) agent-based.

(b) *Collaborative Intelligence*: The seamless integration of psycho-social-techno systems will support enhanced human-machine teaming and synergistic behaviours.

(c) *Knowledge Analytics*: Advanced analytical methods (including AI) exploring large data sets and exploiting advanced mathematics will provide unrealizable insights, knowledge, and advice.

2. **Interconnected**:

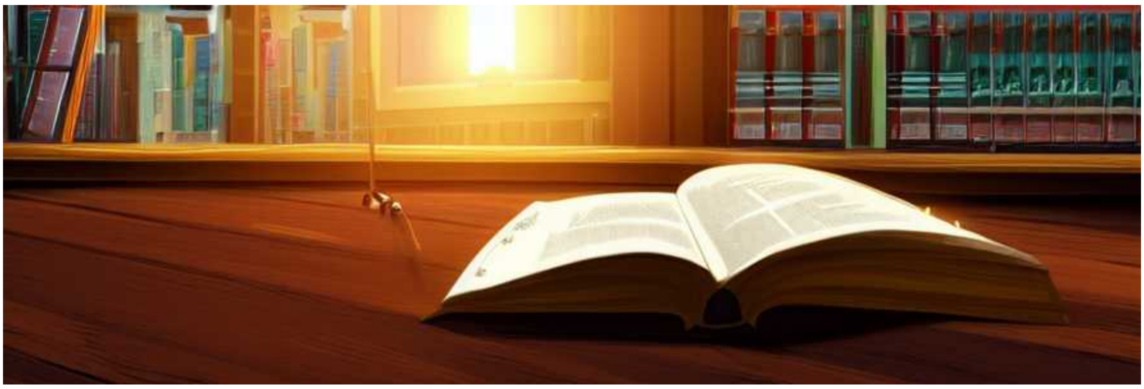
Technologies will exploit massive networks in and across virtual, biological, and physical domains, including networks of sensors, organisations, individuals, and autonomous agents, linked via new encryption methods and distributed ledger technologies.

(a) *Trusted Communications*: The use of distributed ledger technologies (e.g. blockchain), quantum key distribution (QKD), post-quantum cryptography, and AI cyber-agents will ensure trusted interactions and information exchange.

(b) *Synergistic Systems*: The development of mixed (physical or virtual) complex systems-of-systems will create novel ecosystems (e.g. smart cities).

(c) *Biological-Physical Systems*: Technologies will exploit the human, machine, biological and physical domains via AI, human-machine interfaces, and genome manipulation.

3. **Decentralised**:



There will be distributed and ubiquitous large-scale sensing, storage, and computation.

(a) *Edge Computing*: Data storage, computation and analytics/AI will be embedded into agents and objects close to information sources.

(b) *Ubiquitous Sensing*: Low (or lower cost) sensors will create large sensor networks across the human-physical-information domains.

(c) *Decentralised Production*: Just-in-time local digital manufacturing and production will exploit AI-assisted design, novel materials, and (mixed material) 3D/4D printing technologies.

(d) *Democratised S&T*: The broad availability of S&T information and fostered innovation will result from increased and widely available high-performance computational capabilities, reduced design and production costs and the resulting generation of novel science.

4. **Digital**:

Novel disruptive effects (both positive and negative) will result from digitally blended biological, physical and information domains.

(a) *Digital Twin*: A digital simulacrum of physical, biological, or information entities digitally linked (often in near real-time) to the original will support predictive analytics, experimentation and assessment.

(b) *Synthetic Realities*: New perceived cognitive or physical realities would be created based on integrating psycho-socio-techno systems. Such realities may be augmented, virtual, social or cultural.

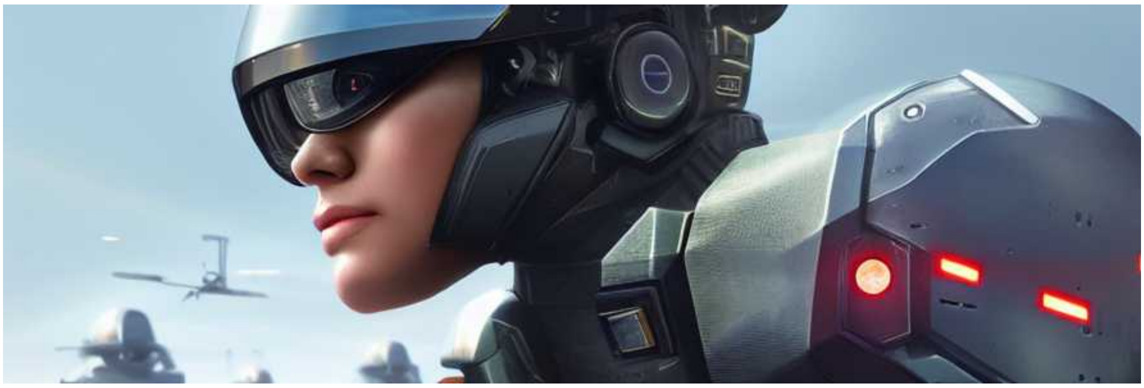
Each of the four S&T trends will create synergistic combinations of technologies that will drive specific military capability development trends. These are as follows:

1. **Intelligent Autonomous Action**: *Intelligent + Decentralised*

Intelligent and increasingly autonomous systems are already supplanting and exceeding the capabilities of human forces. However, autonomous systems have been quite limited, employing fixed rule sets and various levels of direct human control. The increased use of AI will enable autonomous systems capable of significantly more sophisticated decision-making, self-directed activity and, at the same time, increasingly complex human-machine teaming. Such increased use of intelligent agents will dramatically expand into our synthetic realities, including cyber, battle, and digital social networks. Autonomous agents will provide rapid analysis, advice and courses of action for strategic-operational-tactical planning. In turn, this development will allow for increased OODA

(Observe-Orient-Decide-Act) loop effectiveness, and bring an entirely different perspective on old problems unconstrained by old strategies. Such intelligent battle networks can potentially increase decision speeds to levels requiring new human-machine interaction and visualization methods. The resulting competition between battle networks will generate increased evolutionary pressures on algorithms, each seeking an edge or combination of effects that will lead to a decisive victory. Similarly, enabling autonomous vehicles will increase effectiveness across the conflict spectrum, creating large sensor and strike mesh networks. Recent events suggest that these developments may turn the future battlespace into one more akin to those found in the late nineteenth and early twentieth centuries.

2. **Cognitive Dominance**: *Interconnected + Digital*

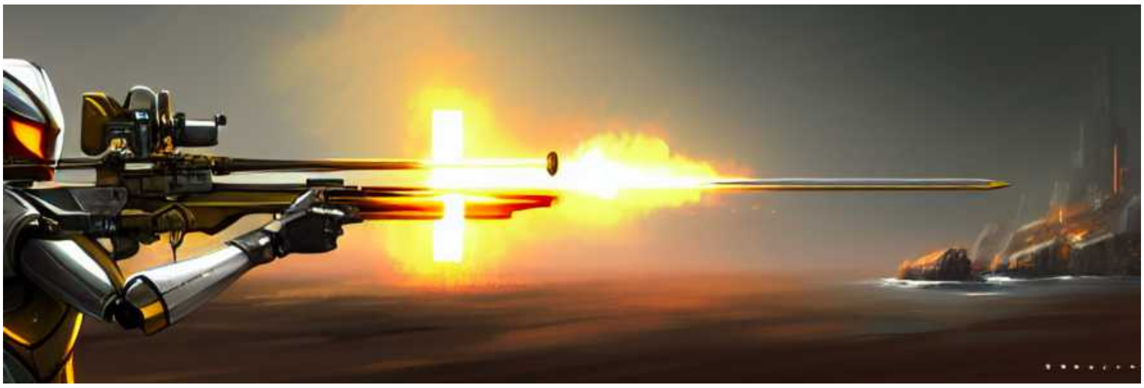


Evolving agile and adaptive mesh C4ISR battle networks will create deep military action-dependent operational dependencies. Such evolving battle networks will increasingly become targets in, of themselves, and subject to effects-based conflict. This increased reliance on seamless and ubiquitous connectivity will increase the operational importance of targeting such networks (military or civilian) through disinformation and cyber or physical attacks. Such attacks may be implemented long before the conflict is initiated and could indirectly strike at logistics, personnel, information, financial or other supporting elements of modern operational and strategic networks. Over a 15 - 20-year horizon, quantum technologies will increase C4ISR data collection, processing and exploitation capabilities through significantly increased sensor capabilities, secure communications, and computing. In concert with Big Data, Quantum computing and AI will contribute to the design of new materials with unique physical properties generated by increased S&T dominance. This will enable further developments in 2-D materials and novel designs. Space-based quantum sensors, facilitated by Quantum Key Distribution communication, will lead to a different class of sensors suitable for satellite deployment. Increasingly commercial, smaller, lower power, more sensitive and distributed space-based quantum-enabled sensor networks will be an essential aspect of the future military ISR architecture in 20 years. Finally, supporting technologies will enable decision dominance, allowing faster action-reaction cycles, especially in the cognitive and cyber domains.

3. **Expanded Domains**: *Interconnected + Decentralised*

As the operational environment expands to include space, cyber, and the broader information sphere, the need to think, plan, and operate in a widely dispersed, interconnected, and multi-domain manner will become even more critical to mission success. The growing numbers and wide distribution of multi-domain sensors, multi-domain missions, and the rising processing capabilities embedded at the networks' edges will present new demands for dominance, counter-domain capabilities, protection, counter-countermeasures, and other secondary functions. The increased exploitation of new domains will inevitably lead to the search for domain superiority, with attendant costs and capability demands. In concert with Big Data and Quantum, AI will expand our ability to exploit the biological domain, contributing to new designer drugs, purposeful genetic modifications, direct manipulation of biochemical reactions, and living sensors. These technologies will enable more effective human-enhancement technologies across the cognitive, social, and physiological domains. They will also increase chemical-biological countermeasures' effectiveness (speed and efficacy) while paradoxically enabling the development of even more virulent agents.

4. **Precision Warfare**: *Intelligent + Digital*



Increased digitisation across C4ISR capabilities, miniaturisation, edge processing and falling costs have been the underpinning technological developments enabling increasingly intelligent, interconnected, and distributed systems. This has dramatically increased the development of precision strikes and effects-orient capabilities. However, swarming and using lower-cost cheap precision weaponry has and will continue to put large, high-value capabilities at risk. At the same time, increased digitisation exposes new and hitherto unanticipated vulnerabilities. New sensors (e.g. quantum technology-enabled) and increased reliance on synthetic realities (virtual, social, mixed, twinned, etc.) will present risks and opportunities. Using more sophisticated analytical tools and leveraging the increased volumes of digital data will lead to new operational capabilities. For example, novel hypersonic weapon designs will be developed using increasingly higher-fidelity computational fluid dynamics models and embedded sensors. The development of exotic materials, novel designs, miniaturisation, energy storage, manufacturing methods, and propulsion will be necessary to exploit space and hypersonic operational environments by reducing costs, increasing reliability, improving performance, and facilitating the production of inexpensive task-tailored on-demand systems. Directed energy (precision) weapons will become more widespread and effective as power and energy storage issues are addressed.

AI, as a linking technology, will change the landscape of warfare. At the same time, the availability of digital data will allow decentralised and interconnected (autonomous) systems to analyse, adapt, and respond. In turn, these changes will potentially support better decision-making through predictive analytics [45]. All of this will occur in the context of synergistic and symbiotic systems, including sensors, societies, and organisations. In this way, EDTs will continue to change the ways and means of conflict for at least a generation but, at the same time, will need to integrate and operate alongside existing systems.

Emerging technology-enabled capabilities will increase the Alliance's operational and organisational effectiveness by enabling the NATO Warfighting Capstone Concept's five Warfare Development Imperatives (WDI): *Cognitive Superiority*; *Integrated Multi-Domain Defence*; *Cross-Domain Command*; *Layered*

*Resilience* and, wide-ranging *Influence and Power Projection* [46]. At the same time, such technologies will and indeed are presenting significant challenges to the Alliance, including operational, interoperability, ethical, legal, and moral concerns.

Figure 2.1 summarises the nature of this future NATO battlespace. The timelines associated with enabling this multi-domain future are difficult to define precisely, but the military and technological trends are increasingly evident. It took almost sixty years (US Civil War to WW1) to move through the *industrialisation* of warfare and a similar length of time for its *informatisation*. We are in the middle of a similarly dramatic shift with the *intelligentisation* of conflict domains, with potentially analogous consequences. These technologies will give military decision-makers options under ELM (ethical-legal-moral) norms and guidelines. That said, NATO and its Allies must be ready to counter the malicious use of such technologies that go against these norms.

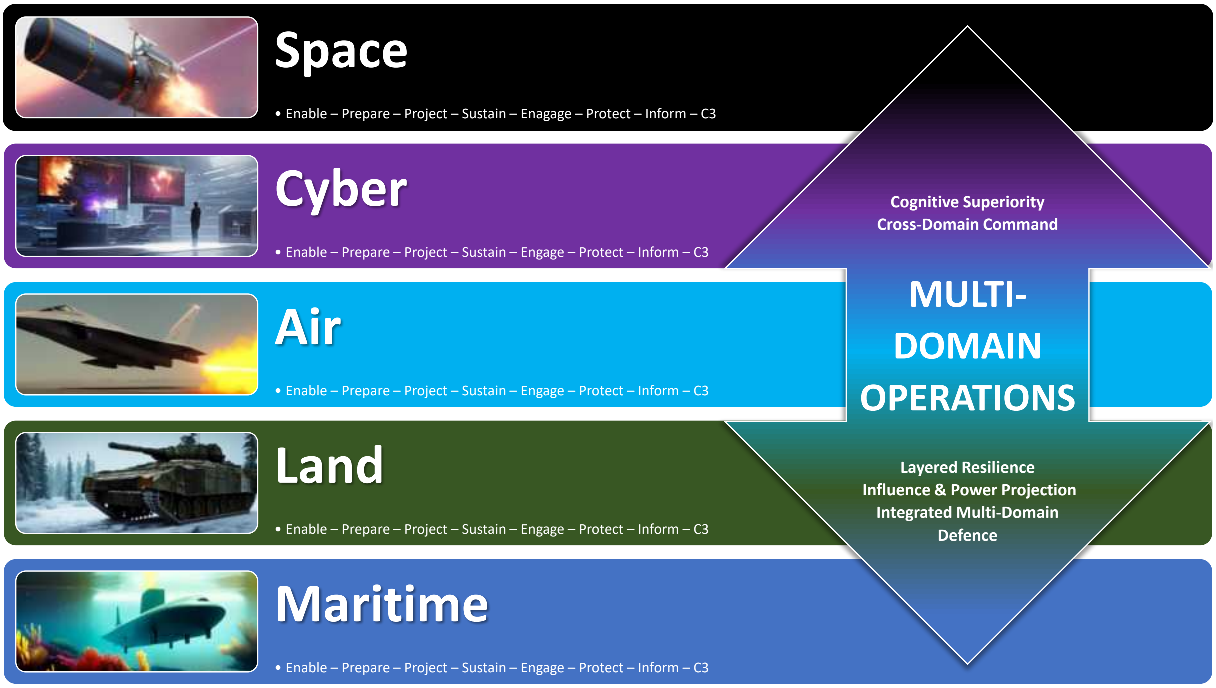



***Figure 2.1:*** *The future NATO Multi-Domain intelligent-interconnected-decentralised-digital strategic and operational battlespace.*

### 2.1.2 Synergy

To maintain a military-technological edge and to prevail in future operations, NATO forces must continually evolve, adapt, and innovate to be credible, networked, aware, agile, and resilient [47]. Such adaptation is most rapid and disruptive where EDTs work to enable one another or where the human, information, or physical domains overlap [48]. This highlights the importance of technology breadth (more opportunities for surprising combinations and unexpected synergies). Several such critical synergistic connections are identified later in this report.

In addition to interconnections between EDTs, it should be noted that many of the issues driving and limiting the effective development of new capabilities are non-technical. Murray [49, 50] notes that:

> *"What matters in the technological adaptation as well as technological innovation is how well new and improved technologies are incorporated into effective and intelligent concepts of fighting: it is not the technological sophistication that matters, rather, it is the larger framework."*

For active development of EDTs into Alliance capabilities, the implications of culture, concepts, risk-tolerance, organisational structure, policies, treaties, human capital, and ethics must be fully appreciated.

These factors will need to evolve as much as the technology if EDTs are fully developed into new operational capabilities.

## 2.2 Disruptive Technologies

This section provides a brief overview of critical developments and trends associated with this disruptive S&T. Volume 2 of this report provides a more comprehensive review of each EDT.

The scientometrics section at the end of each EDT discussion presents a table with the assessed potential impact, state, and rate of development for sub-areas associated with an EDT. These results are drawn from a survey of the STO's research network. This is followed by charts representing global EDT leadership and trends, as determined by assessing the last five years of **English** language scientific publication data. This data was integrated and processed in the S&T Ecosystem Analysis Model (STEAM), described in more detail in the methodology section of Volume 2.

### 2.2.1 Big Data, Information and Communication Technologies

**Big Data, Advanced Analytics and Information Communication Technologies (or *Data*)**

*Data* describes Big Data (raw digital data) that presents significant volume, velocity, variety, veracity and visualisation challenges. Increased digitalisation, a proliferation of new sensors, new communication modes, the internet-of-things and the virtualisation of socio-cognitive spaces (e.g. social media) have contributed significantly to the development of Big Data. *Advanced (Data) Analytics* describes advanced analytical methods for making sense of and visualising large volumes of such information. These techniques span various approaches drawn from research areas across the data and decision sciences, including artificial intelligence, optimisation, modelling & simulation (M&S), human factors engineering and operational research. Two additional aspects are essential in considering the big data challenge: *Information and Communication Technologies*, and sensors and sensing. This system-of-systems is necessary for an effective multi-domain C4ISR framework, reflecting the collection, processing, exploitation and dissemination of information supporting decision-making and C2.

Vast quantities of data and the algorithms to make sense of it underlie the development of the fourth industrial age. Our world of experience has become increasingly digital and virtual. To put this in proper context, the world created 94 Zettabytes (ZB) ($10^{21}$) of data, with 80 to 90% of that data unstructured, in

2022 alone. That number is expected to double every two years, rising to nearly 100,000 ZB annually by 2042 if this trend continues unchecked. 70% of global GDP is digital, and data (not in analogue form) created in 2021 and 2022 alone represent 90% of all data ever created. When the last technology trends report was written in 2020, the world's cloud data storage was 6800 Exabytes (1000 Exabytes (EB) makes a ZB). This is expected to grow to more than 200 ZB by 2025. All this data must be collected, transmitted, and stored, creating a growing demand for energy and analytical tools to help make sense of it. This demand also creates huge piles of waste products, including toxic e-waste. It is estimated that only 32% of the information available to businesses is leveraged in any form [51], and overall, only 0.5% of digital data is exploited. It is difficult to overstate just how important *Data* is in driving and enabling EDT development and ensuring that the digital backbone and analytical methods that NATO will use in the upcoming years will be up to the task. AI is a critical complementary technology whose growth, in some sense, is a reaction to this data volume challenge and information opportunity. In turn, this combination of *Data* and analytical technologies has created a global network with characteristics of neural systems, a point noted originally by the media theorist Marshall McLuhan [52, 53].

For the next 20 years, this growth in data will have a fundamentally disruptive effect on Alliance operations, capabilities, and technological development. Data sets of a magnitude and complexity that are difficult to handle logistically (a definition that it must be noted changes yearly) due to increasing *volume*, *velocity*, *variety*, *veracity* and *visualisation* issues will present significant technical, organisational and interoperability challenges. Distributed sensors, autonomous systems, new communication technologies (e.g. 6G), new antenna developments, improved spectrum usage, increased use of space assets, virtual socio-cognitive spaces, digital twins, ever more power-efficient electronics and the development of new and expanding analytical methods will increase our ability to *understand* the human, physical and information spaces around us. *Data*is the enabling technology for all EDTs and is central to their exploitation for enhanced military capabilities. Moreover, AI requires high-quality curated training data to develop new algorithms and applications, placing even greater demands for more and better data.

For NATO, *Data* will enable increased operational efficiency, reduced costs and improved logistics, real-time monitoring of assets and predictive assessments of campaign plans. At the same time, it will generate significantly greater situational awareness at strategic, operational, tactical and enterprise levels. These applications will lead to a deeper and broader application of predictive analytics to support enhanced decision-making at all levels, a point recognised by other near-peer competitors. It has the potential to create a knowledge and *decision advantage*, which will be a significant strategic disruptor across NATO's spectrum of capabilities. There is the potential to significantly impact NATO's kinetic and non-kinetic targeting effectiveness using cheap, widely distributed sensors (as part of the internet-of-things (IoT)), linked by new communication protocols (such as 6G), building on analyses and dissemination of critical information in real-time. Potential peer or near-peer adversaries will seek a similar technical edge, while asymmetric threat actors will exploit increasingly open and available data sources for targeted effect or disruption.

The commercial sector invests heavily in *Data* and ICT. Over the next 20 years, it is expected this will continue, and commercial interests will lead in the overall development and application. The effectiveness of this investment underlies the current knowledge economy. There are no indications that this will change. Nevertheless, the unique needs of NATO military forces will require developing methods and standards for interoperability, sharing, collection, modelling & simulation, analysis, classification, curation, communication, and data management. Finally, it is not a given that more data and advanced algorithms will ultimately produce better decisions. Understanding the complex socio-cognitive-technical context around decision-making and the proper role and integration of *Data* in this context will be essential to developing a NATO decision advantage. The human sciences will be particularly significant in guiding developments in this area.

To be understood properly, *Data* needs to be viewed as a series of technical challenges covering digital data collection, processing, exploitation and dissemination and analytical methods. Consequently, developments in *Data* are best considered along the lines of effort identified in the subsections below.

#### Advanced Computing and Methods

Developments in applied mathematics and the information sciences continue to yield new approaches to optimisation, modelling & simulation (M&S), management of uncertainty, and addressing complexity and chaos. Some methods explore foundational approaches to improving the modelling and simulation of complex and complicated systems. Other areas of note are developing new statistical and analytical methods to assess data integrity and graph and sparse data analytics. These methods are empowered by advanced computational methods such as multi-part computation (*"analytics to the edge"*), new probabilistic programming languages, and accelerating advances in quantum computing. Finally, emergent results are coming to light in modelling and simulation, especially around data-driven models where empirical models of natural, complex processes and phenomena use libraries of data modelling primitives and human-model interfaces. Such developments are expected to continue over the next 20 years. To support this analytical need, new approaches, especially new computational paradigms, such as quantum computing, mathematical methods and developments in traditional supercomputers, will be essential, [54, 55, 56]. Concerning conventional supercomputers, biomimetic approaches such as neuromorphic supercomputers provide a promising approach to significantly increasing supercomputer processing capabilities [57, 58, 59, 60, 61].

New approaches will also impact operational decision-making using new computing paradigms such as edge, fog, transparent, mobile, and dispersed computing.

#### Novel Applications and Decision Making

*Data* needs to be exploited if it is to support decision-making. Developments over the next years will focus on three core aspects: group decision-making; improved interfaces and visualisation; and the application of data analytics to enhance aspects of situational awareness such as comprehension, data fusion, control, discovery, design, and M&S. In particular, the increased use of digital twins (e.g. a virtual digital simulacrum of a natural system) supports the prediction of future failures or performance improvements through AI, analytics, or M&S methods. The use of digital twins is expected to expand dramatically as AI/ML and advances in predictive analytics will help extend its application [62, 63, 64].

Good advice is built upon good data and appropriate algorithms. Unfortunately, both are remarkably fragile, and research focuses on ensuring algorithms' fairness and intelligibility, associating embedded logic, and protecting data integrity. The need for new and innovative developments in this area cannot be overstated with the increase in data and an ever-greater reliance on analytics and AI/ML to make sense of the data. While it is difficult to predict the exact nature of such advances, the pressure for better and fast analytical methods based on new and evolving mathematics and programming paradigms will grow with the increase in available data.

#### Distributed Ledger Technologies

Distributed ledger technologies (DLT) hold promise for supporting logistics, personnel and financial transactions. Any digital transaction, which requires tracking and assurance, will benefit from DLT. That said, DLTs are only as strong as their encryption protocols, and the need to implement post-quantum encryption will become acute (e.g. the development of quantum-resistant ledgers (QRL)). The use of quantum properties is also being explored, specifically in the context of *quantum money*, which exploits quantum properties to work around issues of block-chain scalability [65, 66].

### Advanced Networks

*Data* must be moved to where it is needed to be useful. Therefore, developing new network technologies, such as the exploitation of 5G and the maturation of 6G technologies, will be essential. These will become even more critical aspects of military networks, with challenges of low-probability of intercept, hiding traffic in commercial signals, SWaP-C and rapid creation of mission networks critical challenges over the next decade.

Integrated sensor networks, communication links, and processing will continue to drive the need for C3 warfare or multi-domain battle networks. Exploiting these evolving networks for tactical, operational, or strategic purposes is an area of considerable R&D and their importance in the upcoming decades is only expected to grow. Much of this work involves understanding how to link new sensors and capabilities into a seamless and compelling whole. Given their importance on the modern battlefield, the role of offensive EW is also growing.

This, in turn, has led to the development of such concepts as *mosaic warfare*, which seeks to bring together current concepts of edge networks, data lakes, networks of low-cost sensors, multi-domain information networks, and autonomous and manned systems to create an asymmetric decision advantage through the leveraging of complexity [67, 68]. In addition, the use of AI to both rapidly exploits raw data and act as an information glue, e.g. linking incompatible systems into a cohesive whole. Developments are also expected to occur in the use of very low-power networks will allow surveillance networks to operate clandestinely for years without intervention.

The internet of things, cloud computing, power to the edge, etc., are all driven by the availability of advanced networks. There is considerable commercial activity in this area. Ultimately, this will increase the reliance on a mesh of nodes that facilitate greater situational awareness and exploitation of information.

### Sensors

Sensors collecting data are critical elements of any data strategy. Significant advances in quantum technologies (e.g. magnetic anomaly detection, gravimetric, etc.) are enabling novel sensors. Older technologies such as passive coherent location radars [69] are also growing in importance and will enable stealth surveillance. Another technology of note is the development of computational imaging systems, which are lens-free optical systems employing direct computational methods to create images [70]. Such approaches may also be extended to radar [71]. Finally, research on HF radars and 3D LiDAR show considerable promise and are expected to be refined further over the upcoming decades. Developments for wide-area surveillance and long-range communication [72] will be driven by concerns about the vulnerability of space-based sensors, innovative antenna designs and the challenges of operations in difficult environments [73, 74].

Bioinformatics and the sensors that support it are already important health and performance monitoring tools. Combined with smartphones, continuous monitoring of personnel and readiness is already possible, while new diagnostic and assessment technologies will greatly increase CBRN countermeasure options and detection.

### Storage

An often-overlooked aspect of big data is the need for storage. Technologies such as helium drives, shingled magnetic recording (SMR), DNA storage, large memory serves NVRAM, Rack scale design and 5D Optical storage [75, 76] hold promise but the energy and access speed challenges are not insignificant. DNA storage seems to be the most promising for large-scale storage of information [77], and developments in biotechnologies will enable developments in this area. As critical as technologies are, developing new data architectures will also improve the management and storage of immense volumes of data. Improvements to data warehousing, lakes and fabrics will be required over the next five to 10 years, as will data architectures that implement (biomimetic) *forgetting* strategies [78, 79] to reduce data storage and access issues.

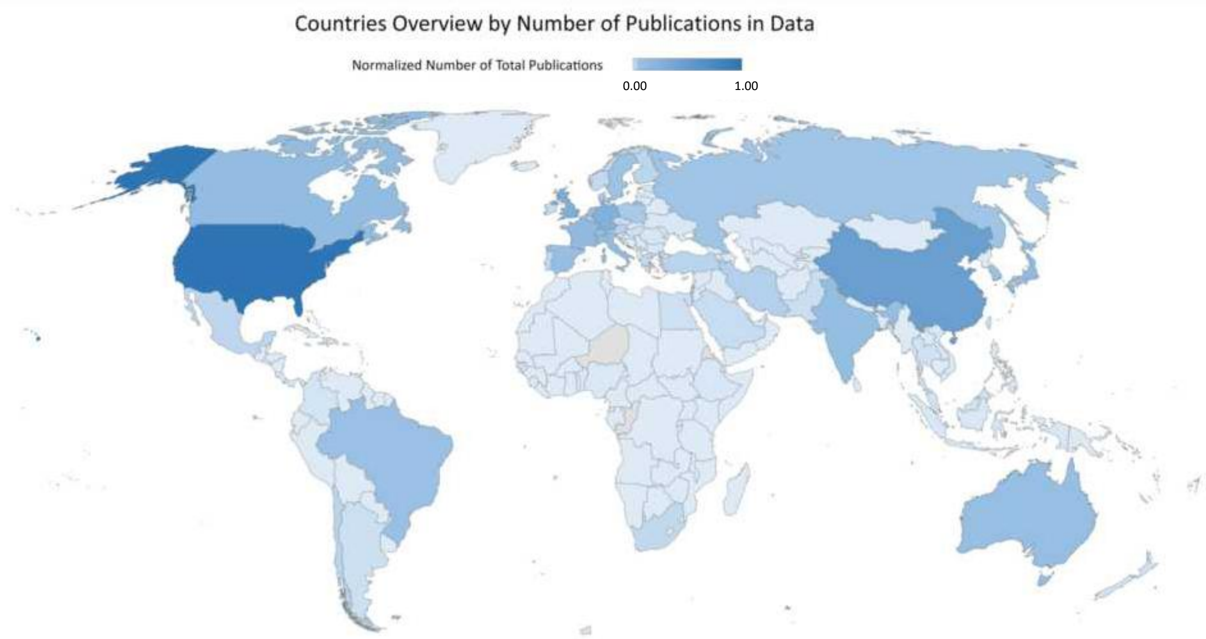
### Cyber

The increased reliance on data, networks, sensors, and analytics that may drive future success on the battlefield also presents significant cyber vulnerabilities. Cyberspace, as a domain that must be protected and manoeuvred within, is expected to grow in even greater importance and challenge. Solving the cyber defence dilemma will require bringing together *"hardware, humans and data"* [80, 81]. In particular, developments in zero trust security [82], and the role of trust in general will support more robust cyber-physical systems [83, 84, 85]. The use of cyber security meshes has also been identified as an area of interest and growth [86].

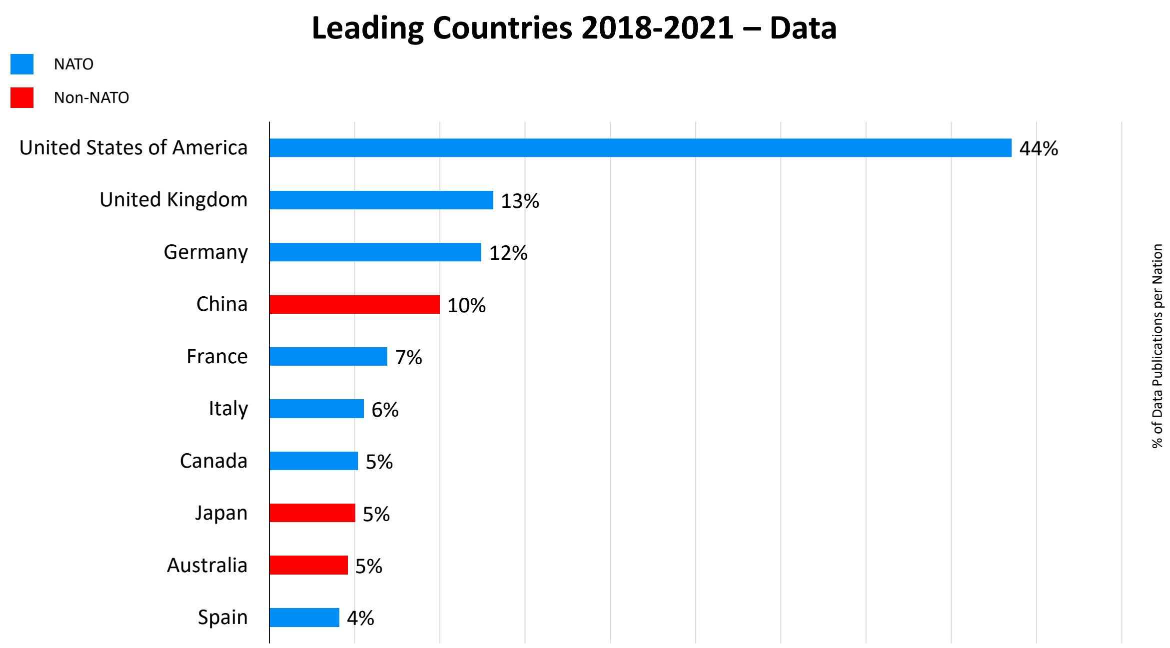
### Scientometrics

***Table 2.1:*** *Big Data, Advanced Analytics and Information Communication Technologies (Data) 2023 - 2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| Data | Advanced Computing & Methods | High | 7-8 | 2025-2030 |
| | Novel Applications & Decision Making | High | 5-6 | 2030-2035 |
| | Distributed Ledger Technologies | High | 5-6 | 2025-2030 |
| | Innovative Networks | High | 5-6 | 2030-2035 |
| | Networked Sensors & Sensing | High | 5-6 | 2025-2030 |
| | Data Storage | High | 7-8 | 2022-2025 |
| | Cyber | High | 5-6 | 2025-2030 |

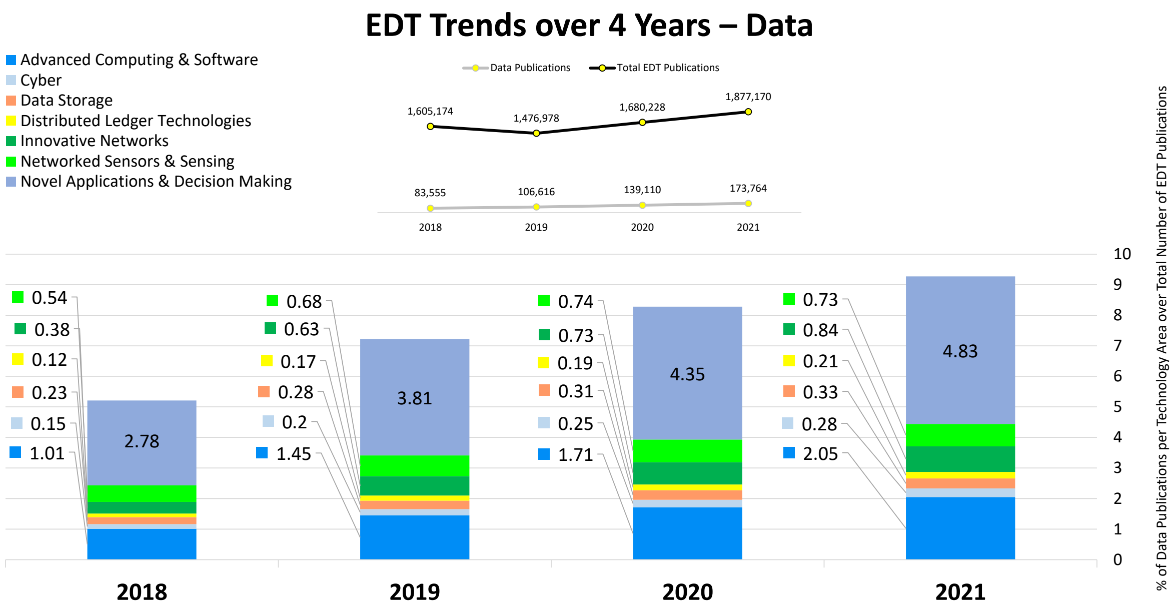



*(a) Data - Leading Countries (Map) (STEAM Analysis).*

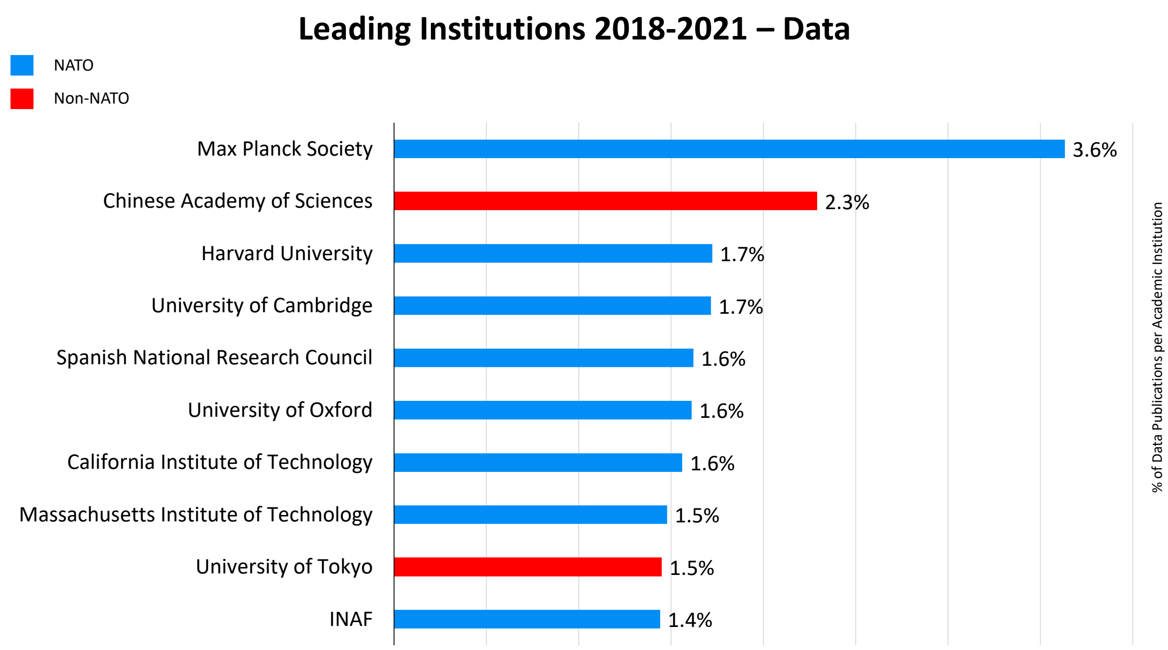



*(b) Data - Leading Countries (STEAM Analysis).*

***Figure 2.2:*** *Big Data, Advanced Analytics and Information Communication Technologies (Data) - STEAM Results - Countries*




*(a) Data - Topic Trends (STEAM Analysis).*




*(b) Data - Top Institutions (STEAM Analysis).*

***Figure 2.3:*** *Big Data, Advanced Analytics and Information Communication Technologies (Data) - STEAM Results - Trends and Top Institutions*

### 2.2.2 Artificial Intelligence

**Artificial Intelligence (AI)**

*AI* refers to the ability of machines to perform tasks that normally require human intelligence – for example, recognizing patterns, learning from experience, drawing conclusions, making predictions, or taking action – whether digitally or as the smart software behind autonomous physical systems [87].

#### Overview

Artificial Intelligence (AI) is the ability of machines to perform tasks that traditionally require human intelligence – for example, recognising patterns, learning from experience, drawing conclusions, making predictions, or acting – whether digitally or as the intelligent software behind autonomous physical systems [88]. There are several branches of AI, but the two of most interest to us are Machine Learning (ML), a branch of AI that exploits data and statistical methods, and deep learning based on neural networks, both algorithmic and biological [89].

AI has been called the most impactful technology ever invented and is expected to play a significant disruptive role in defence and security. While AI's practical and theoretical challenges have been explored since the mid-1950s, developments over the last decade have given new impetus to research and development. However, as AI techniques are widely used, their limitations become more apparent, leading to concerns about returning to an *"AI winter"* and highlighting the need to revisit the enabling science's mathematical, algorithmic, and technical foundations.

As a critical Alliance and national resource, *Data* may be the new *"oil"*, but AI is probably the most important modern tool for refining this data into actionable information. The need to automate the analysis, clustering, exploitation, and interpretation of increasingly large and complex datasets has been the primary driver for developments in AI. Each AI development cycle has expanded the methodologies and application of AI to real-world problems while driving the need for more curated and validated data. Today, AI/ML is deeply embedded in modern technology, and this dependency has exploded over the last 3 years with new astounding applications arising almost every day. New methods and the increasingly wide availability of sizeable (often) publicly available training sets are particularly important to this development. More critically, AI has become the essential driver of massive technological developments in other EDT areas, an often-overlooked aspect.

AI is a priority R&D area in the commercial world, with many nations making significant investments. Business is the primary driving force behind AI, although research is often based on widely available open-source tools and publicly available data [90, 91]. The brittle nature of most existing applications and the need for explainable AI are two serious technical challenges that remain to be overcome. Complex problems associated with human-AI teaming and psycho-socio-technical issues will also need to be considered but hold the promise of revolutionary applications. Notwithstanding these limitations, by 2030, it is estimated that the contribution of AI to the global economy will be $15.7 trillion (USD) [92].

The integration of AI into business has lagged in recent years, even as the pace of new applications grows ever more [93, 94]. Largely, this reflects the difficulties of fully exploiting any new technology within business, but also highlights the limitations of the AI talent pool. This has led some researchers to note that there appears to be a strong pull from the developers of new methods towards new applications. Over time, this separation between the state and rate of development of new methods and applications should be expected to lead to disillusionment with AI applications, given the brittleness and obtuse nature of many applications. This possible slowdown in research, the resulting exodus from the labs to business, concerns at the algorithmic level, abuse and legal issues on data and other AI challenges are all a recipe for another winter within 5 to 10 years, followed by the inevitable spring.

The holy grail of AI innovation is the development of Artificial General Intelligence (AGI, e.g. human-level generalized intelligent behaviour). Such an evolution would present a significant (and potentially impossible) technical challenge despite over 60 years of AI research. It is unlikely that AI systems will meet this level of cognitive ability within the next 20 years.

Undoubtedly, AI is and will have a revolutionary impact on NATO operations and capabilities. AI is the fulcrum around which big data will be leveraged into actionable knowledge and, ultimately, a NATO decision advantage. Integration of AI into combat models & simulation, enterprise systems, decision support systems, cyber defence systems and autonomous vehicles will allow for rapid and more effective human-machine decision-making. The use of AI on sensors to pre-process information and provide adaptive use of frequencies (e.g. cognitive radar) and bandwidth will paradoxically lead to decreased communication traffic. AI will also significantly affect the conduct of NATO S&T efforts as meta-analyses of existing research will expose discoveries, identify promising research areas, and provide improved S&T tools to support further research.

Policy, legal, and interoperability challenges will be serious challenges for NATO. In recognition of this enabling role and the associated challenges, NATO has developed an AI implementation strategy designed to guide NATO in the effective and ethical use of AI within operations and the enterprise [95]. Many nations are doing the same [96].

Much has been written on the growth of AI and its importance for the fourth industrial age, as AI is essentially an enabler for other technology areas. Developments in AI are clustered into four areas driven by a need to reduce data requirements, improve agility, increase resilience, support generalisation to other problem sets, and work more synergistically with “wetware” systems (e.g. humans). Such developments span various research areas and applications in the defence and security sphere. These are broken into the topics below.

### Advanced AI

Over the next 20 years, exploring new mathematical and statistical AI approaches is essential to long-term development and application. Such AI methods research is broad in scope. While the use of AI methods is expanding rapidly, there remain critical limitations to current approaches. Trust and transparency (or explainability) are two of the most pressing challenges. Still, some researchers have argued that current methods are deeply flawed, requiring a complete rethink of our approach to AI.

Two unique approaches underlie AI, symbolic and sub-symbolic [97], with each mostly explored separately. Research into identifying ways in which symbolic and sub-symbolic solutions may interact technically may improve the accuracy of systems and enhance military decision-making. Symbolic approaches to AI characterise the first wave of AI research. Work in this area would greatly increase the explainability and reproducibility of AI results, and is expected to be a growth area in the upcoming years.

Advances in neural networks have been one of the most critical enablers of effective AI over the last decade. They are a subset of ML and underlie modern deep-learning approaches. Neural networks are biomimetic algorithms suitable for pattern recognition and correlation problems with big data. They are exceptionally agile and adaptable, capable of continuous learning and broad applicability. Innovative developments focus on optimising their use for specific classes of prediction, classification, and processing problems. One area of interest is improving the effectiveness and efficiency of neural networks through such methods as long short-term memory, hierarchical recurrent, residual, convolutional, and quaternion-valued methods. Competitive strategies such as Siamese Networks and generative adversarial networks (GAN) have also demonstrated considerable promise. Another area of research focuses on learning architectures to make AI more agile and resilient while using less data. Methods such as deep Q learning, federated learning, and *"machine common sense"* hold promise. Significant embryonic developments are taking place in Convolutional Neural Networks [98] (optimised for 3D image recognition), Convolutional Autoencoders [99], and Dilated Convolutional Neural Networks [100, 101].

Additional areas of development are in:

- *Federated Learning*: ML methods are being developed to leverage local processing and federated data collected *at the edge* (e.g. mobile devices and the Internet of Things (IoT)). Such methods typically do not share collected data with centralized systems, exploiting the data locally, and are part of an *AI to the Edge* trend. Systems employing such an approach are more robust due to the increased volume of data used and are inherently more secure and private [102, 103].
- *Learning with Reduced Labelling*: Labelling data is a critical first step in training supervised machine learning (ML) algorithms. This approach is a time-consuming, resource-intensive, and costly step, leading to inflexible solutions. New methods require considerably less labelled data, and ML algorithms are far more adaptable to real-world conditions. These approaches provide systems able to use sparse data sets with methods that are easier to train, more versatile, able to generalize from related datasets and ultimately are more broadly applicable or valuable [104].
- *Machine Common Sense*: New AI algorithms seek to integrate *"common sense"* into AI reasoning. This means AI reasoning employs a baseline understanding of situations, perception, behaviour, motor functions, memory, and fundamental physics. As a result, such systems are expected to be more effective, robust, and agile, demonstrating greatly improved human-like reasoning [105, 106].

### Applications

Arguably, the most exciting developments in AI are those associated with their application. Perhaps the most exciting development in AI is the wide-ranging and high impact of its application. AI continues to integrate many systems, processes, and defence capabilities. Some of the more exciting and potentially disruptive applications are artificial social intelligence, automating disinformation and cognitive warfare strategies, producing and identifying "deep fakes," supplementing air or air-weapons control, aide in high-resolution image recognition, creating images from text descriptions, navigating human terrain, and providing universal (low usage) language translation.

One of the least appreciated and yet most significant area where AI disruption may occur is as an enabler of new scientific, mathematical, and engineering discoveries and as a forcing function for a new scientific paradigm [107, 108, 109, 110, 111]. The ability of AI to enable truly disruptive S&T is difficult to overstate as recent examples of solving protein folding (a fifty-year-old challenge) or the development of new materials highlight the yet fully untapped nature of AI for scientific discovery.

Another area of current and future disruption in the development of AI is to create systems that can generate images or video based on textual data. Significant breakthroughs have occurred within 2022, with the development of generative AI methods with the release of Stable Diffusion 2.1 (used to generate many of the images used in this report), DALL-E 2 and Midjourney [112]. Similarly, the artificial intelligence chatbot program ChatGPT can produce sophisticated text interaction with users and may even be used for diagnostic purposes [113]. The wide-spread use of these tools is expected over the next few years, with ever-growing sophistication and growing social challenges [114]. Indeed, the use of GPT-3 has raised a storm of concerns. GPT-3 is [115]:

> *GPT-3 (Generative Pretrained Transformer 3) is a state-of-the-art language processing AI model developed by OpenAI. It can generate human-like text and has a wide range of applications, including language translation, language modelling, and generating text for applications such as chatbots. It is one of the largest and most powerful language processing AI models, with 175 billion parameters."*

GPT-3 was used to build ChatGPT, which has surprised many with its ability to hold a conversation or write a paper. While the concerns are grossly overstated, it is clear that the development of increasingly sophisticated generative AI will be destabilizing over the next few years, and engender a burst of creativity at the same time.

#### Counter-AI

As Alliance and competitor forces increasingly use AI, it becomes increasingly critical to detect, deflect, and limit the impact of attacks on Alliance AI while undermining adversarial AI-enabled systems. AI-on-AI engagements are emerging (mainly in the context of disinformation), and the role of AI to enable criminal behaviour is underappreciated [116, 117]. Like any operational domain, there is a need to detect, deflect and limit the impact of attacks on Alliance AI. Countering adversary AI and associated decision processes through AI manipulation and deception is a difficult technical challenge. Similarly, detecting AI manipulation is not straightforward. Finally, AI-on-AI conflict is not just a possibility, but also an evolving reality in cognitive warfare and disinformation [118]. Therefore, these engagements will become increasingly common, and it is necessary to identify adversarial AI, model it, assess its weaknesses, and develop counter-AI strategies [68]. The importance of exploring AI countermeasures was noted in the D3TX exercise as a weak signal technology prime for increased R&D [119]. Similarly, the role of AI in enabling criminal behaviour is underappreciated [116, 117].

In addition, AI methods are often remarkably brittle, and estimating such brittleness is a difficult task [120, 121, 122]. Improving the robustness and tools for validation and assurance will be an area of focused development. Ensuring AI advice is robust, trusted, ethical and consistent with national rules-of-engagement (ROE) will require AI approaches with a strong emphasis on *robustness*, *agility*, *explainability*, *trust*, and human-AI *collaboration*. Further, it will be necessary, especially in Alliance operations, to define processes and standards for verification, validation and accreditation (VV&A) of such AI systems.

#### Human-Machine Symbiosis

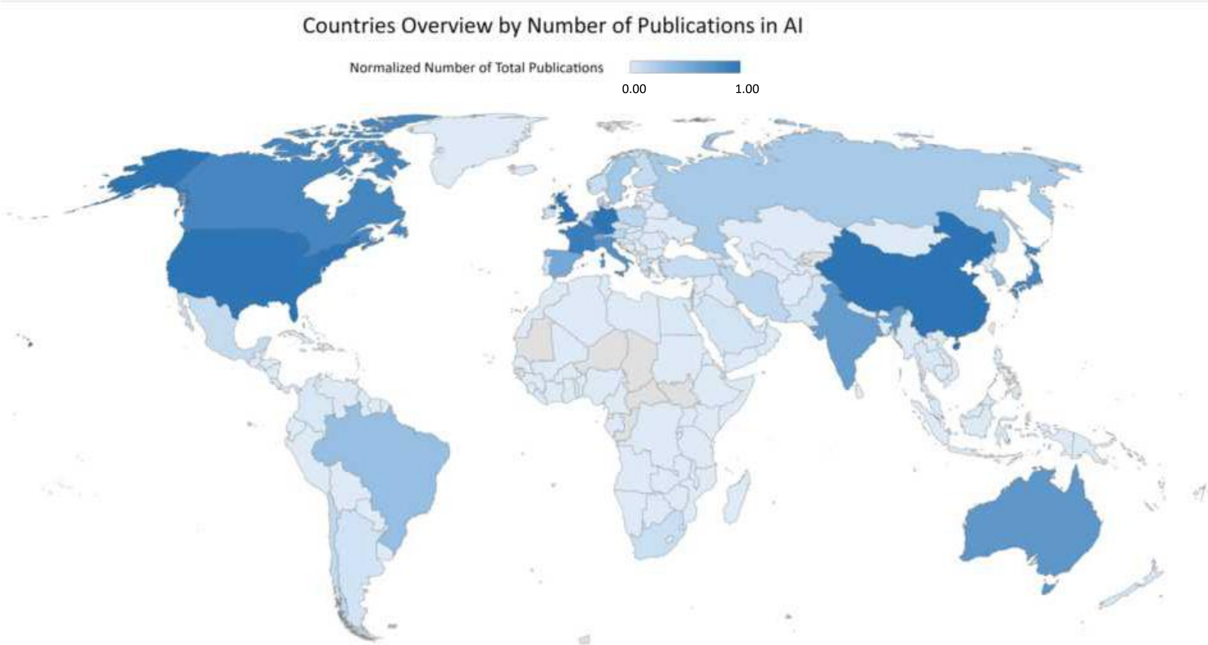
A core AI challenge is to marry AI with human-driven systems to create an effective psycho-social-technical collaborative system. Research is moving forward rapidly, focused on developing explainable AI, understanding trust-building and ensuring confidence (validation and assurance) in the operationalization of AI-enabled systems. Analysis of published data suggests that this is a growing concern as systems move away from focusing on the technical side of AI to considering the broader socio-technical aspects and optimal usage. Explainability, reproducibility, and trust are all critical research areas [123] and major leaps forward are expected over the next 5 to 10 years, as faith in AI methods will depend on such advancements. New AI/ML techniques will need to be developed to support their assessments and explicitly communicate associated constraints and limitations. These human-interpretable ML models are combined with visualisation and communication modes that are more conducive to human understanding and evaluation [105, 124].

Finally, rethinking human interaction with AI to bring about and impact acquired knowledge precisely when practical and applicable via user-friendly interfaces will be necessary to build trust in such systems. Trust is the Achilles heel of AI and human interaction. Understanding how to generate a trusted relationship between humans and AI and understanding what it means for AI to trust human judgment [105] a difficult technical challenge.

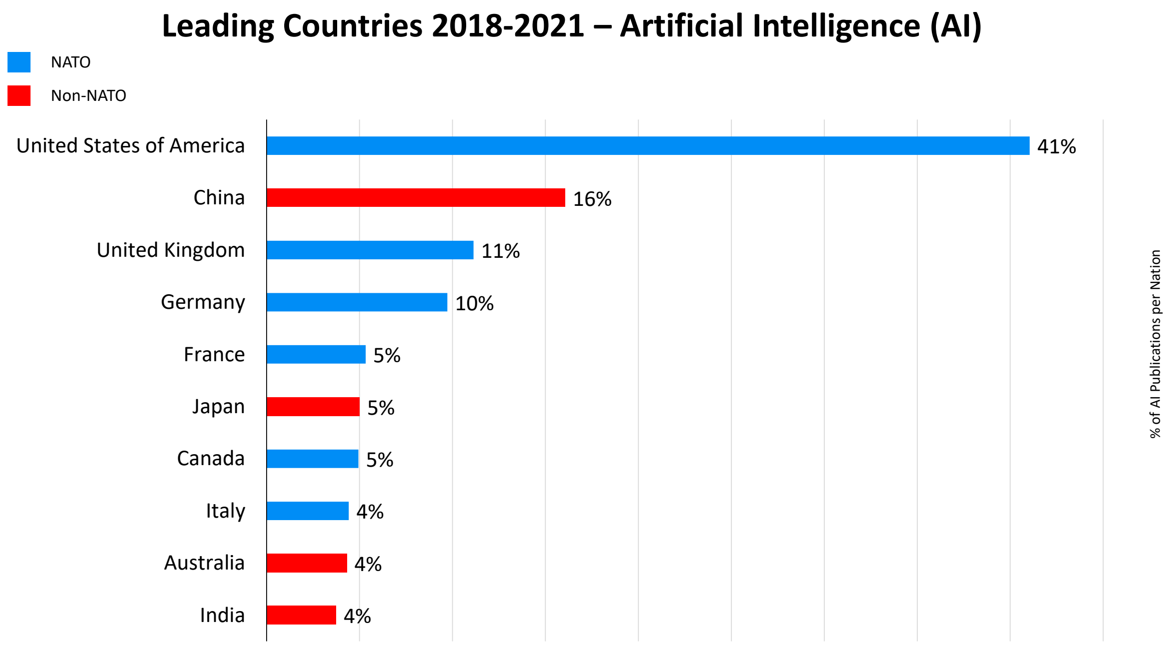
### Scientometrics

***Table 2.2:*** *Artificial Intelligence (AI) 2023-2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| AI | Advanced AI | Revolutionary | 3-4 | 2035 or (+) |
| | Applications | High | 5-6 | 2025-2030 |
| | Counter AI | Revolutionary | 3-4 | 2030-2035 |
| | Human-Machine Symbiosis | Revolutionary | 3-4 | 2035 or (+) |

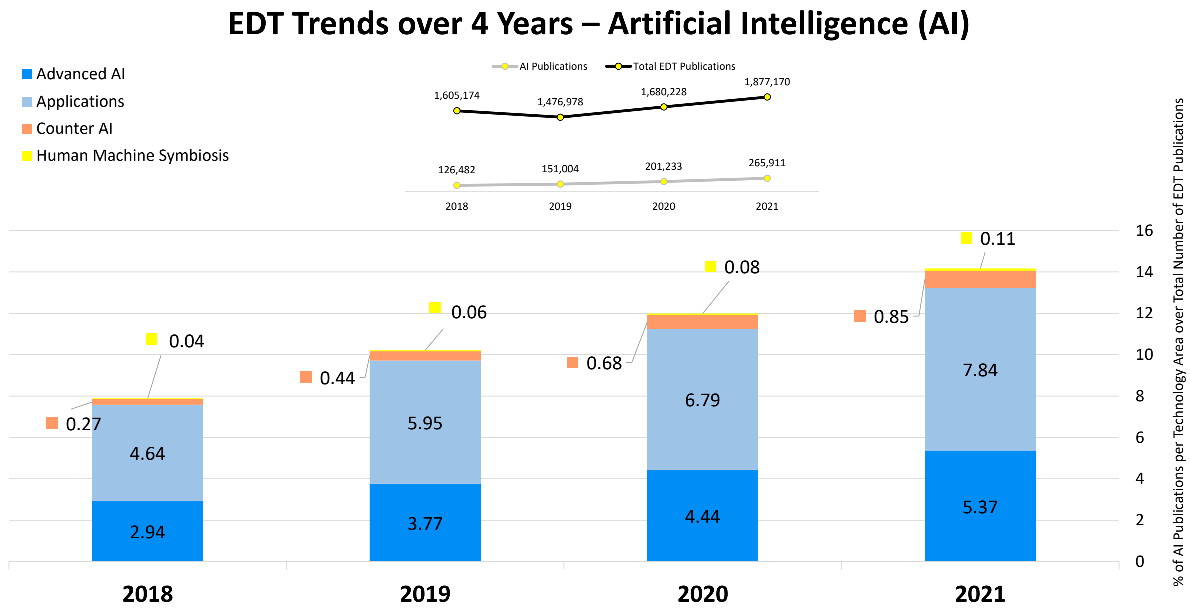



*(a) AI - Leading Countries (Map) (STEAM Analysis).*

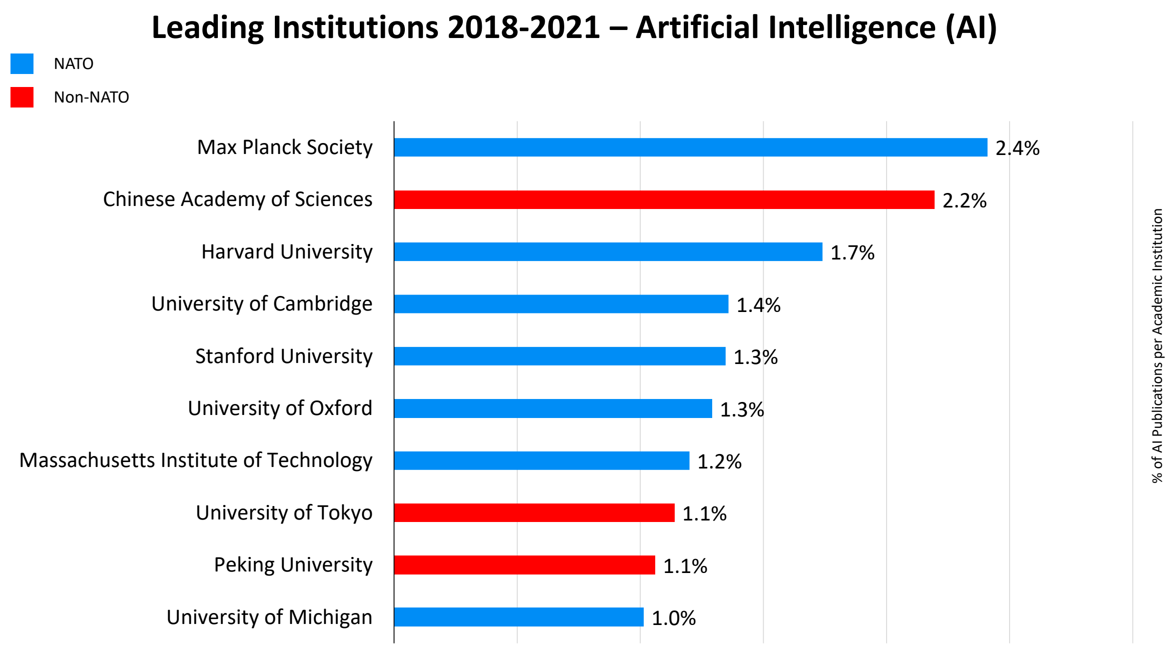



*(b) AI - Leading Countries (STEAM Analysis).*

***Figure 2.4:*** *Artificial Intelligence (AI) - STEAM Results - Countries*




*(a) AI - Topic Trends (STEAM Analysis).*




*(b) AI - Top Institutions (STEAM Analysis).*

***Figure 2.5:*** *Artificial Intelligence - STEAM Results - Trends and Top Institutions*

### 2.2.3 Robotics and Autonomous Systems

**Robotics and Autonomous Systems (RAS, or *Autonomy*)**
*Autonomy* is the ability of a system to respond to uncertain situations by independently composing and selecting among different courses of action to accomplish goals based on knowledge and a contextual understanding of the world, itself, and the situation. Autonomy is characterized by degrees of self-directed behaviour (levels of Autonomy) ranging from fully manual to fully autonomous [125, 126, 127]. *Robotics* is the study of designing and building autonomous systems spanning all levels of Autonomy (including full human control). *Unmanned Vehicles* may be remotely controlled by a person or act autonomously depending on the mission. Applications include access to *unreachable* areas, persistent surveillance, long endurance, robots in support of soldiers, cheaper capabilities, and automated logistics deliveries.

#### Overview

Robotics, autonomous systems, and uncrewed vehicles have become commonplace on the modern battlefield. Likewise, *Data* and AI have enabled operations in the information space. Robotic and Autonomous Systems (RAS) have extended these operations as effectors in both the physical and information domain. The history of autonomous systems in defence is a long one going back to at least 1898 with Nikola Tesla's demonstration of a wireless remotely operated crewless boat [128]. However, building upon advances in *Data* and AI, there has been a significant push over the last 20 years to use system autonomy across various physical and virtual environments. Collaborative autonomy, SWaP-C (size, weight, power, and costs) reductions and significant improvements in on-board AI have made RAS an effective force multiplier in operations across the spectrum. The success of these efforts is seen in the increased use of platform autonomy (e.g. unmanned vehicles (UxVs)), with ISTAR (intelligence, surveillance, targeting and reconnaissance) and precision strike platforms being increasingly common in operations. One need only look at recent operations in Ukraine [129, 130], Syria [131], and Nagorno-Karabakh [132] to see how profound the impact of RAS has been in altering the battlespace.

The ultimate objective of integrating RAS into operations has always been to unite the human and autonomous system (at whatever level of independence) into a formidable team, allowing the automated system to take on *dull*, *dirty*, *dangerous* and *dear* tasks (the four D's of robotisation) [133], while at the same time exploiting the unique talents of the human system. The underlying motivation is to decrease costs, reduce manning, improve operational effectiveness, and reduce casualties. The increasing importance of RAS in operations is driven by the creativity and availability engendered by SWaP-C reduction.

Approaches to autonomy may range from fully autonomous to semi-autonomous or even unmanned systems. Specific levels of independence depend on sensors, mission type, communication links, on-board processing, legal and policy constraints. The drive for more semi-autonomous and fully autonomous systems in operations will dramatically expand future NATO capabilities into an environment where every soldier acts as a company, every ship as a task group and every aircraft as a squadron. RAS development is primarily driven by operational needs such as high-altitude-long-endurance (HALE), increasing levels of integrated AI, decision speed and human-machine factors (e.g. how to make the overall human-machine team/system more effective while retaining necessary human oversight and decision-making). In addition, legal, policy and interoperability considerations will challenge the use of autonomous systems across the kill chain. Nevertheless, given the operational advantages to both NATO and potential adversaries, there is little doubt that autonomous systems will significantly and increasingly enhance, threaten, and enable current and future operational capabilities over the next 20 years [134].

Developmental areas in RAS may be grouped into four broad areas, like those for AI. We will consider each in the following sub-sections.

### Advanced RAS

Major advances in RAS, both current and foreseen, are predominately based on improvements to SWaP-C, manufacturing, AI, and swarming behaviours. SWaP-C reductions are and will be due to improved miniaturisation, manufacturing methods, novel low-power sensors, and advances in digital communication technologies. Improvements in this area are expected to be steady, resulting in costs continuing to decline while availability on the battlefield will increase. In addition, advances in printable electronics and other hardware will increase the use of 3D-printed task-tailored disposable systems (e.g. [135, 136, 137]) for boats, aerial swarms, autonomous submarines, missiles, loitering munitions, and logistics.

The most exciting area of advanced RAS is the integration of AI. Agile learning-based autonomy is an evolving technology, a critical certification challenge, and is expected to develop quickly with developments in AI. Technical challenges are being driven by advances in AI, especially deep neural nets for perception, reinforcement learning for control, and online model learning. Supporting such adaptability are significant developments in spatial tracking of multiple moving objects in real time. Some of this work is underpinned by sophisticated neural networks. However, other promising biomimetic approaches (e.g. modelled on insect neurons [138]) are being explored. Improving integrated AI systems' performance and power overhead will improve SWaP-C and system adaptability. Military development is dwarfed by commercial interests in this area, particularly in the development of self-driving vehicles [139, 140, 141]. However, despite the hype around such systems, significant technical challenges remain, and widespread military use on the battlefield is still a long way into the future. However, more limited use in support functions may come quicker [142].

### RAS Application

The use of RAS across the battlespace, operational domains, enterprise and industry (especially in manufacturing and logistics) is increasing as costs, adaptability and miniaturisation improve. There are three trends to note within this space: the increased use and development of collaborative systems, biomimetic micro- and mini-systems, and increased usage across the operational spectrum. Collaborative systems research of interest explores advanced mix-domain autonomous teams and improved human interfaces for control and collaboration. Other research explores the application of non-homogeneous RAS teaming and air-launched systems for independent or cooperative operations. In addition, exciting developments are arising in using RAS systems for specialised environments, such as urban ISR, long-duration underwater vehicles, crewless naval vessels, assisted communication, and supporting operations in subterranean environments. Finally, using RAS systems for 3D printing holds significant promise for deployed military operations in the future [143, 144].

#### C-RAS

With the increasingly widespread use of UxVs and swarms, research is ongoing to understand how to anticipate and defeat these threats through kinetic and non-kinetic means. Swarm-on-swarm engagement is an open area of study. It is clear from recent operations in Ukraine and elsewhere that improvement to C-RAS capabilities is an area that will need priority development over the next decade. Failure to counter ever cheaper and widely available UxVs can and will have undesired strategic consequences.

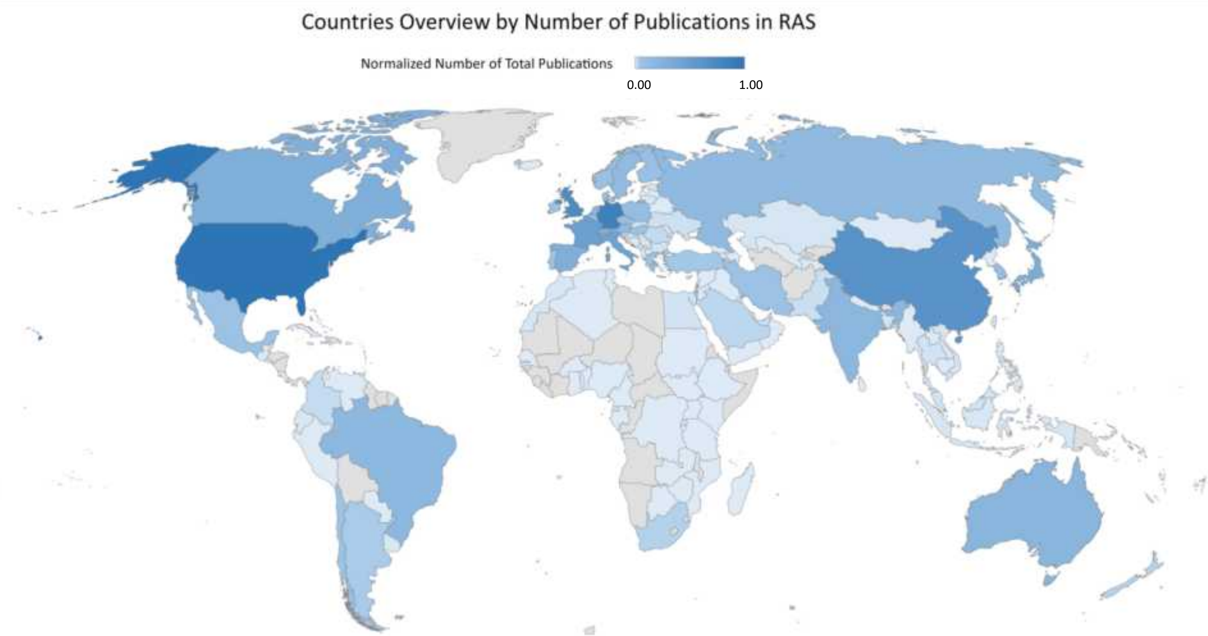
#### RAS Man-Machine Teaming

Research expands human-machine symbiosis, allowing humans and machines to work as colleagues, partners, and teammates. This research recognises that humans cannot fully assimilate, understand, and act on the volume of information presented nor control the autonomous collection of that data. Therefore, more effective and natural interaction of AI and RAS systems with humans will significantly enhance operations. Interesting aspects of this work consider determining and signalling the need for human control and how the embedded AI can assess whether the human operator's input can be trusted.

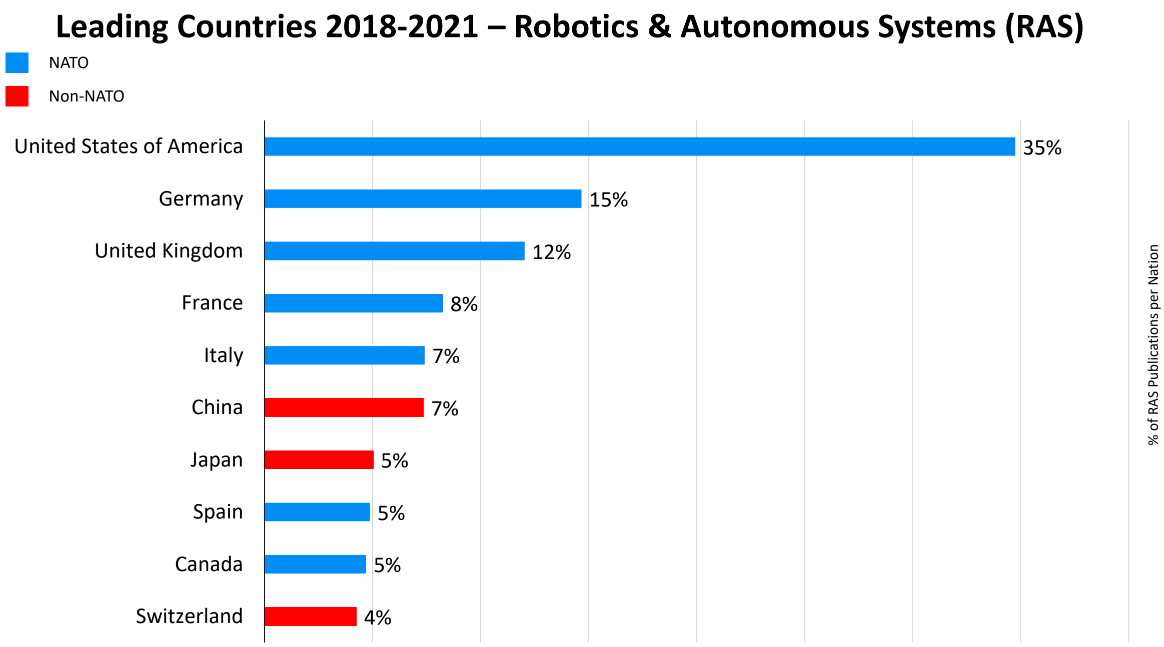
#### Scientometrics

***Table 2.3:*** *Robotics and Autonomous Systems (RAS): 2023-2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| RAS | Advanced RAS | High | 5-6 | 2025-2030 |
| | Application | High | 5-6 | 2025-2030 |
| | Counter RAS | High | 3-4 | 2030-2035 |
| | Human-Machine Teaming | High | 3-4 | 2030-2035 |

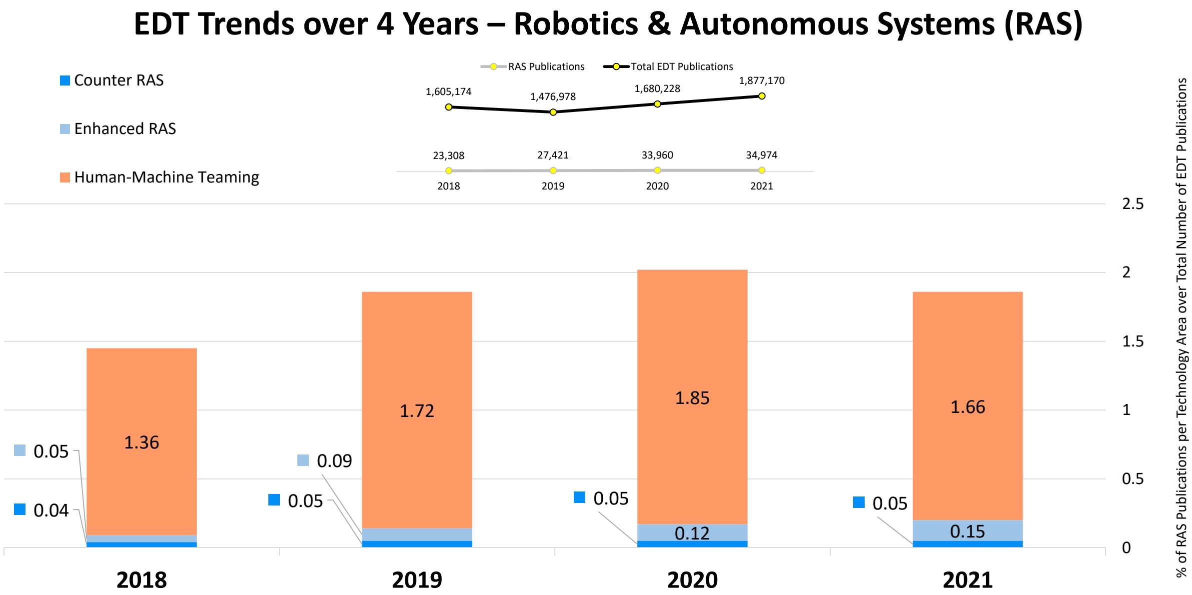



*(a) RAS - Leading Countries (Map) (STEAM Analysis).*

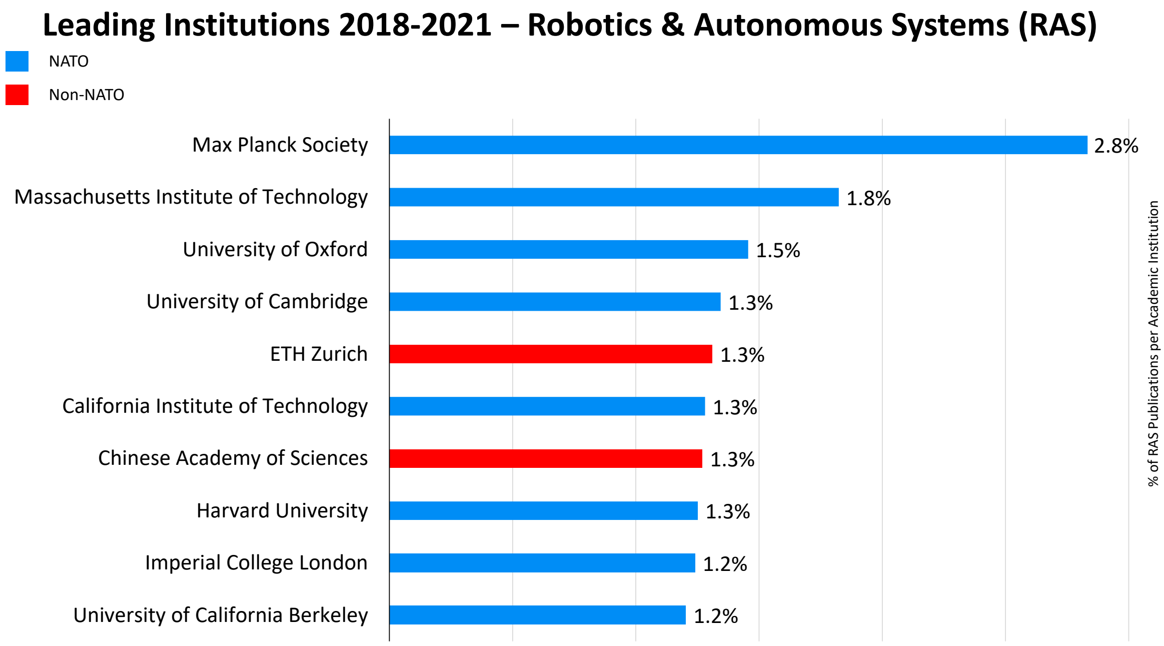



*(b) RAS - Leading Countries (STEAM Analysis).*

***Figure 2.6:*** *RAS - STEAM Results - Countries*




*(a) RAS - Topic Trends (STEAM Analysis).*




*(b) RAS - Top Institutions (STEAM Analysis).*

***Figure 2.7:*** *RAS - STEAM Results - Trends and Top Institutions*

### 2.2.4 Space

**Space Technologies (ST, or *Space*)**
*Space* is a unique physical domain challenging Allies' traditional perceptions of time, distance and geography. It is generally considered to begin 90 - 100 km (the Karman line [145]) above sea-level. *Space Technologies* exploit or must contend with the unique operational environment of space, which includes: freedom of action, global field of view, speed, freedom of access; a near-vacuum; micro-gravity; isolation; and extreme environments (temperature, vibration, sound and pressure).

**Overview**

Humankind has been making effective use of space for over 60 years. Still, over the last decade, there has been a renewed interest in exploring and exploiting space and the technologies that enable it. In this context, two interrelated and intersecting trends have led to an explosion in the exploitation of space and space-based assets.

First, commercial space has only grown stronger in the last few years, leading to the development of satellites, sensors, communication, and launch. Further, the assets that commercial companies have brought to the table have, in many cases, changed the economics of space exploration (e.g. Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS)). They have also contributed to a changing battlefield (e.g. the Ukraine-Russian war and the use of Starlink [146], and the availability of space-derived imagery has complicated military operations placing them under a global spotlight [147]). Finally, the global commercial space industry continues to lead on the path to dramatic decreases in launch costs, new options for deploying space-based assets, and the near real-time commercial availability of high-quality space-derived information (e.g. Electro-Optical (EO) and Infra-Red, Synthetic Aperture Radar (SAR) and Electronic Intelligence (ELINT) Satellites).

Second, new technologies and manufacturing methods have changed the nature, availability, and costs of using space (e.g. 3-D printing [148, 149, 150, 151]). Such technologies include new propulsion options such as advanced electric propulsion systems, spin launch, on-board AI, advanced robotics, on-orbit remote servicing of satellites, system miniaturization (enabling smaller and cheaper satellites), improved and novel sensors, 3D-printing, improved power storage and efficiency, and next-generation encryption technologies. As a result, space is becoming increasingly commercial, congested, contested and competitive [152, 153]. Of note has been the rise in implicit or explicit competition with the People's Republic of China (PRC) [154, 155], as well as their admirable achievements such as the operation of the Tiangong space station and plans for lunar basing. Consequently, space has become a strategic driver of technological development and geostrategic competition.

NATO recognized space as an operational domain in November of 2019, released an overarching Space Policy in January 2022 [156], and leaders noted at the Brussels summit in 2021 that harmful activities in space may lead to the invocation of Article 5 [157]. The use of space for Command, Control, Communication, Computers Intelligence, Surveillance and Reconnaissance (C4ISR), navigation and defence is central to many of NATO's existing capabilities, and it is the foundation upon which NATO has built a technological edge. This use of space and space-derived data will only increase over the next 20 years, enabling increasingly capable and ubiquitous C4ISR capabilities. Combined with *Data* and *AI*, this can significantly improve situational awareness at all levels, support near-real-time assessments of operational effectiveness and increase targeting success.

Most human space activity occurs relatively close to earth (Low, Medium and High Earth Orbit). However, in recent years there has been growing concern and global interest in cislunar operations, requiring a thousand-fold increase in operational volume. Over the next 20 years, NATO operational concerns will likely need to expand to consider the near-Earth environment and cislunar.

Many nations have significantly increased their presence in and access to space. Nevertheless, commercial developments and the increased use of space-derived data are expected to dominate events over the next 20 years. Increasingly powerful small-sats and large-scale constellations/swarming will facilitate increased use of space while posing significant policy and legal issues. These legal and policy challenges include conflicts between commercial, academic, and military use; governance of the global (space) commons; and the potential for the increased militarization of space.

Space technology developments can be roughly broken into four sub-areas. These are considered in the sections below.

#### Propulsion and Launch

Two areas dominate this research and developmental activities: high efficiency/thrust propulsion and rapid launch. In orbit, propulsion research is being driven by cislunar and deeper space operations.

Significant anticipated improvements to propulsion technologies beyond chemical (low efficiency but high thrust) and electric (high efficiency but low thrust) methods for generating thrust are expected. For example, currently under development, nuclear thermal propulsion (NTP) shows promise and, when developed, will enable significant improvements in operational space capabilities. However, on-orbit testing is planned for 2025 NTP using high-assay and low-enriched uranium, so it is unlikely this technology will have much impact before 2030.

Reusable and rapid launch are also areas of R&D, driven by the increased utility of small-sats (cube, nano, pico, etc.) coupled with the increasing risk of a contested space environment and terrestrial anti-satellite weapons. There is a need for scalable, low-cost, responsive and reusable launch systems designed to launch larger satellites into low-earth and sub-orbital trajectories. Turnaround times on the order of 24 hours are envisaged with sustained operations. Low-cost launch options such as SpaceX and RocketLab will continue to drive launch prices down, and creative solutions such as Spin Launch [158] will continue this push to reduce costs and increase availability. Mission-tailored systems are envisaged with development times in weeks rather than years. Most launch systems are incapable of such rapid turnaround or providing on-the-spot (e.g. on the order of hours) in-theatre launch. Commercial companies such as SpaceX and RocketLab aspire to meet such turnaround times consistently. Nevertheless, R&D will improve the performance and reliability of such rapid task-tailored systems and incentivise commercial development.

#### Platforms

Platform developments are expected to be dominated by increased use of small-sat constellations and a focus on size, weight, power and cost (SWaP-C) reductions. Increased processing, autonomy, and embedded AI will improve sensor performance, collection management, on-board processing and fusion, and inter-satellite coordination. Actively collaborating satellites (constellations) will increase operational effectiveness. Reduced costs using advanced manufacturing will also enable increased availability, agile reconfiguration of constellations and reliability. They will also significantly reduce the cost of entry and improve access to such systems by state, non-state or hyper-empowered groups.

Some space-based capabilities demand more extensive and expensive satellite systems, particularly in geosynchronous Earth orbit. The possibility of on-orbit repair offers the option of in-orbit assembly, refuelling, repair, repurposing and salvage. Demonstration projects have already been successful or are planned for the near term. Such capabilities will profoundly affect space access. In addition, these technologies, with only a change in intent, offer potential new anti-satellite capabilities.

#### Sensors and Communication

SWaP-C considerations will dominate research in this area, driven by the need for more capable small-sats. One area of enabling research interest has been the development of miniaturized and lightweight space-capable antennas and lens-free imaging. Quantum (magnetic, gravimetric) sensors will also be space deployable [159] in the foreseeable future. In addition, enabling AI and other autonomous functions will greatly improve the tasking and coordination of sensors.

These developments aside, the value of small-sats is driven by the reduction in SWaP-C of platforms and launches. However, developments of lightweight, low-power, wide-band sensors for communications and remote sensors will improve the operational effectiveness of such systems. In addition, the need for active sensors, such as space-based radar, has driven developments in miniaturisation and lightweight space-capable antennas. Such sensors allow, in low earth orbit (LEO), the rapid refresh of sensing technologies as low-cost constellations de-orbit, and are replaced by more up-to-date systems.

#### Counter-Space

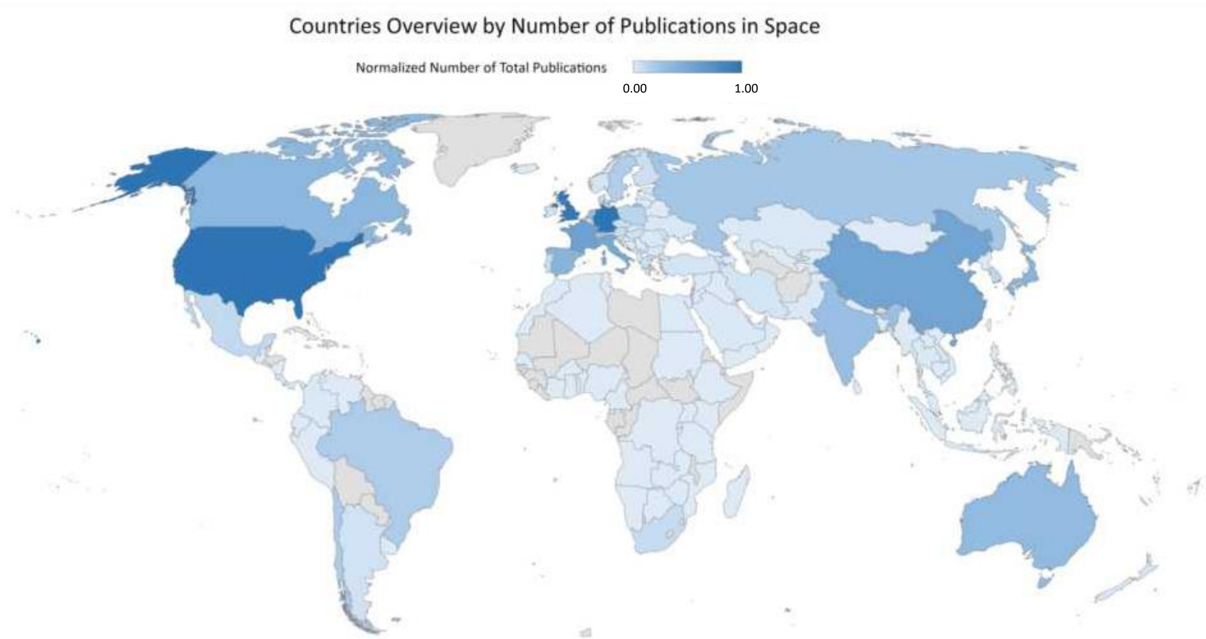
Cyber-physical-EM hardening has become an evolving issue as the reliance on space-based assets becomes a point of potential vulnerability. However, as more Alliance capabilities rely on these assets, the risks from ASAT (anti-satellite) or robotic parasitic systems will become more acute. In addition, increasingly congested orbits, increased use of large constellations of small-sats, and increasing levels of space debris will impact the effectiveness and reliability of space-based systems. Hardening of these systems will be an area of active research, and Counter-satellite cyber, electromagnetic, and physical countermeasures will evolve. This will require various measures, including cyber-EM-physical hardening, new operational concepts, and hybrid approaches to space-based platforms.

Developments such as Russian inspector satellites and Peresvet dazzlers [160, 161], Chinese directed energy weapons [162, 163, 164]. The growing hazards of space debris [165] raise an ever-increasing threat to space operations. At some point, so much debris will be created that space operations will no longer be feasible (e.g. Kessler syndrome).

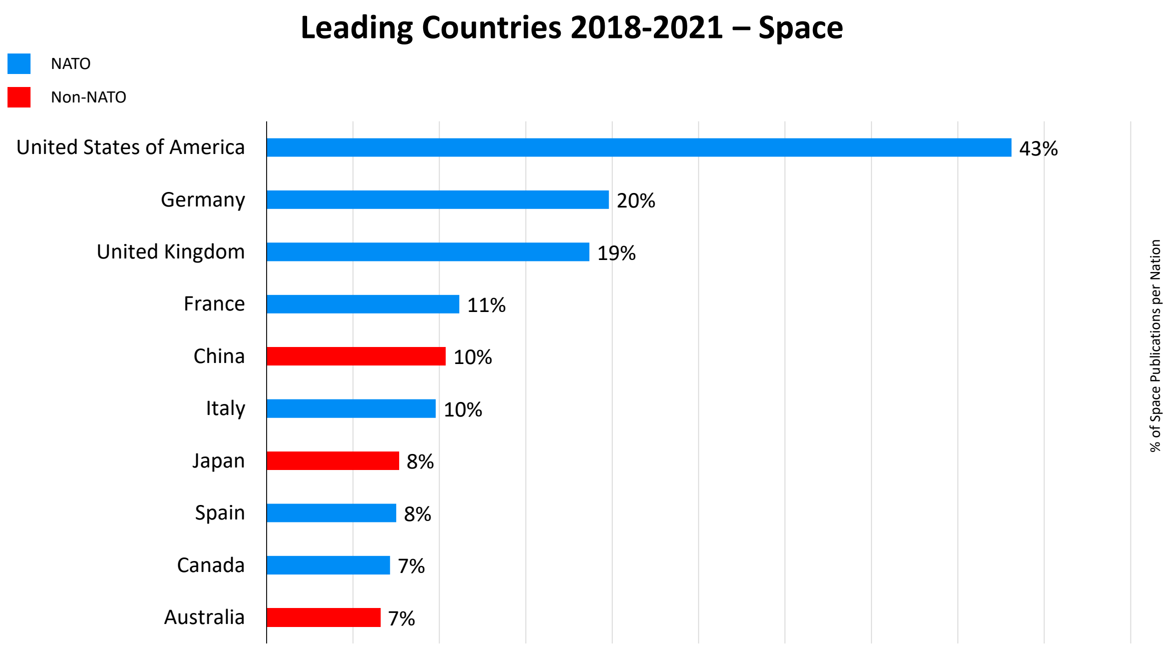
#### Scientometrics

***Table 2.4:*** *Space Technologies (ST) 2023-2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| Space | Communications | High | 9 | 2022-2025 |
| | Counter Space | High | 5-6 | 2030-2035 |
| | Platforms | High | 9 | 2022-2025 |
| | Propulsion & Launch | High | 9 | 2022-2025 |
| | Sensors | High | 7-8 | 2022-2025 |

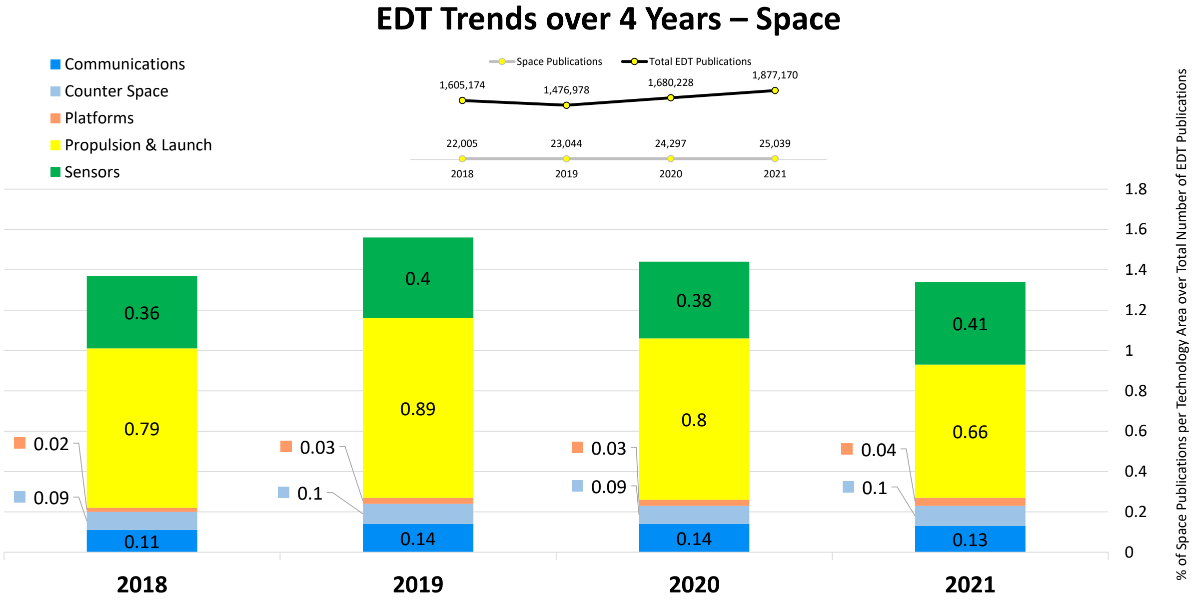



*(a) Space - Leading Countries (Map) (STEAM Analysis).*

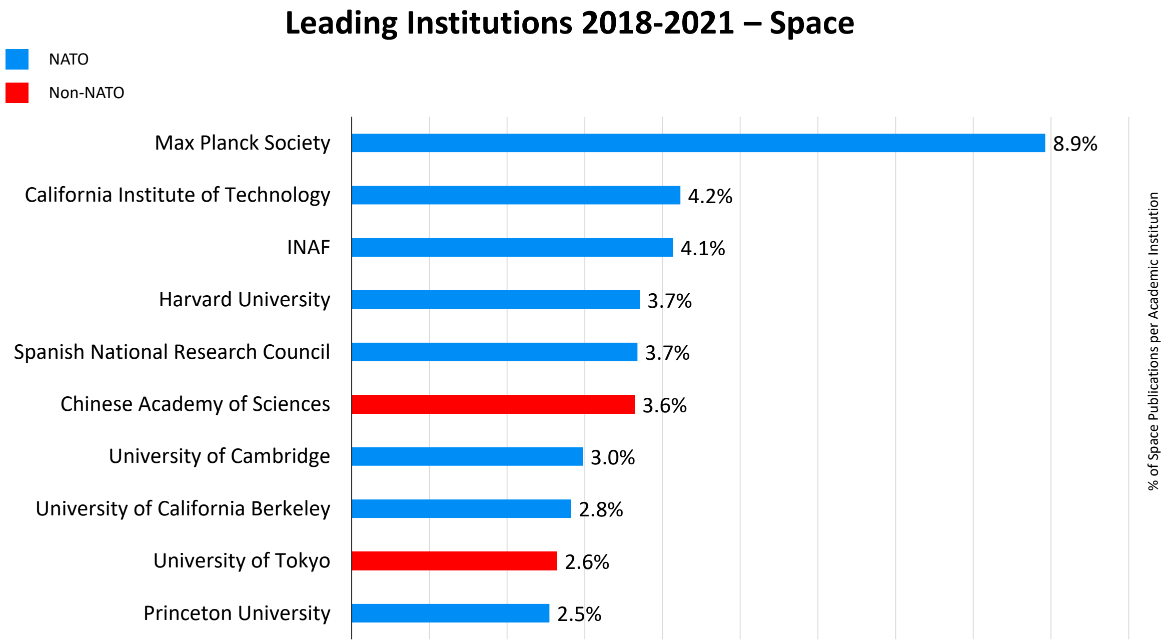



*(b) Space - Leading Countries (STEAM Analysis).*

***Figure 2.8:*** *Space Technologies (ST, or* Space*) - STEAM Results - Countries*




*(a) Space - Topic Trends (STEAM Analysis).*




*(b) Space - Top Institutions (STEAM Analysis).*

***Figure 2.9:*** *Space Technologies (ST, or* Space*) - STEAM Results - Trends and Top Institutions*

### 2.2.5 Hypersonics

**Hypersonic Technologies (or *Hypersonics*)**
*(Advanced) Hypersonic Weapons Systems (HWS)* (missiles, vehicles, etc.) operate at speeds greater than Mach 5 (6125 kph). In such a regime, the dissociation of air becomes significant, and rising heat loads pose an extreme threat to the vehicle. Hypersonic flight phases occur during re-entry from space into the atmosphere or during propelled/sustained atmospheric flight by rocket, scramjet or combined cycle propulsion. This class of weapon system includes air-launched strike missiles (HCM), manoeuvring re-entry glide vehicles (HGV), ground-sea *ship killers*, and post-stealth strike aircraft. Systems of this nature may rely primarily on kinetic effects alone or include supplemental warheads (nuclear or non-nuclear). Countermeasures against hypersonic systems' individual, salvoed, or swarms are particularly challenging due to the speed and manoeuvrability of hypersonic vehicles. [166].

**Overview**

The growing use of hypersonic systems by Russia and the People's Republic of China (PRC) has raised significant concerns about the strategic disadvantage of NATO and the Alliance. These systems are particularly strategically disruptive given the reduced reaction times available for ITWAA (Integrated Tactical Warning/Attack Assessment), manoeuvrability, reduced flight times, difficulty developing countermeasures, and the threat they pose to high-valued targets individually or en masse [166, 167].

Research on hypersonic systems goes back 70 years to the start of the space age. There are four types of hypersonic systems typically discussed: (manoeuvring) hypersonic glide vehicles (HGV); air-breathing hypersonic cruise missiles (HCM); hypersonic rail guns (HGV) [168]; and hypersonic crewed aircraft (HCM). The primary focus of this EDT will be on missile systems (HGV and HCM) and, to a lesser extent, tracking emerging research into hypersonic crewed aircraft.

New materials, improved modelling and simulation, and more efficient propulsion systems have enabled recent developments in hypersonic research and have greatly increased the likelihood of their wide operational use [169]. The PRC, Russia, the US, the UK, France, India, Japan and Australia all have openly acknowledged research, testing, and operational use of hypersonic systems [170, 167, 171, 172, 173]. In 2019 Russia announced the fielding of its first hypersonic manoeuvring air-launched ballistic missile (Kinzhal) and the operational deployment of the Avangard HGV. Russia is also working on a ship launched by HCM (Tsirkon) [171]. The PRC appears to have an active research programme and has had operational HGVs since 2020 [174, 175, 176]. U.S. systems are expected to be fielded no earlier than 2023 [177, 171] and more likely by 2025, with hypersonic drones following by 2035 [178, 179].

For NATO, hypersonic capabilities would increase effectiveness (lethality and response) against priority ground, and naval targets [180, 181]. Due to the high speeds involved, they may also dispense with warheads, relying entirely on mass and kinetic energy, thus simplifying weapon design. Such speeds will increase the odds of a successful strike and reduce the risks of interception.

Experts disagree on the potential strategic impact of a disparity in hypersonic systems and the ultimate effectiveness of such systems strategically or tactically [171, 182, 183, 184, 185]. Indeed, Russian systems have been seen to under-perform in Ukraine [186]. Whether or not such systems are more effective than conventional systems, defending against hypersonic weapons is a significant unmet challenge.

R&D of hypersonic systems of interest to NATO can be broken into several sub-areas. These are discussed in the subsections below.

#### Vehicles and Propulsion

The development of air-launch sustained cruise hypersonic boost-glide vehicles is moving forward, with research focused on affordability, manufacturing, aerodynamics, aero-thermal, and controllability. At the same time, encouraging research is occurring with dual-mode ramjet (DMRJ) systems with Turbine-Based Combined Cycle propulsion, potentially enabling transformational aircraft, and unmanned aerial vehicle (UAV) capabilities.

Over the last decade, air and sea-launched tactical range hypersonic boost-glide vehicles have been an active area of research. R&D continues in areas such as exploring flight characteristics (aerodynamic, aero-thermal, controllability and accuracy). Improving cost and affordability are essential aspects of this research. Technological developments focus on hydrocarbon scramjet-powered propulsion to enable sustained hypersonic cruise, thermal management approaches designed for a high-temperature cruise, and affordable system designs and manufacturing approaches.

Hybrid propulsion for aircraft is a potentially transformational technology for strike, intelligent, surveillance and reconnaissance (ISR), and two-state to-orbit launch [187, 189, 190, 191, 192, 193, 194, 195, 196, 188]. Nevertheless, there are significant R&D hurdles. Encouraging R&D is occurring with systems employing a dual-mode ramjet (DMRJ) with Turbine-Based Combined Cycle propulsion. Combined cycle engines promise cost-effective human-crewed hypersonic flight (turbojet for low-speed shifting to scramjet at high speeds). Research and development in this area continue and should be of interest given its apparent value for military operations [197, 198, 175, 199].

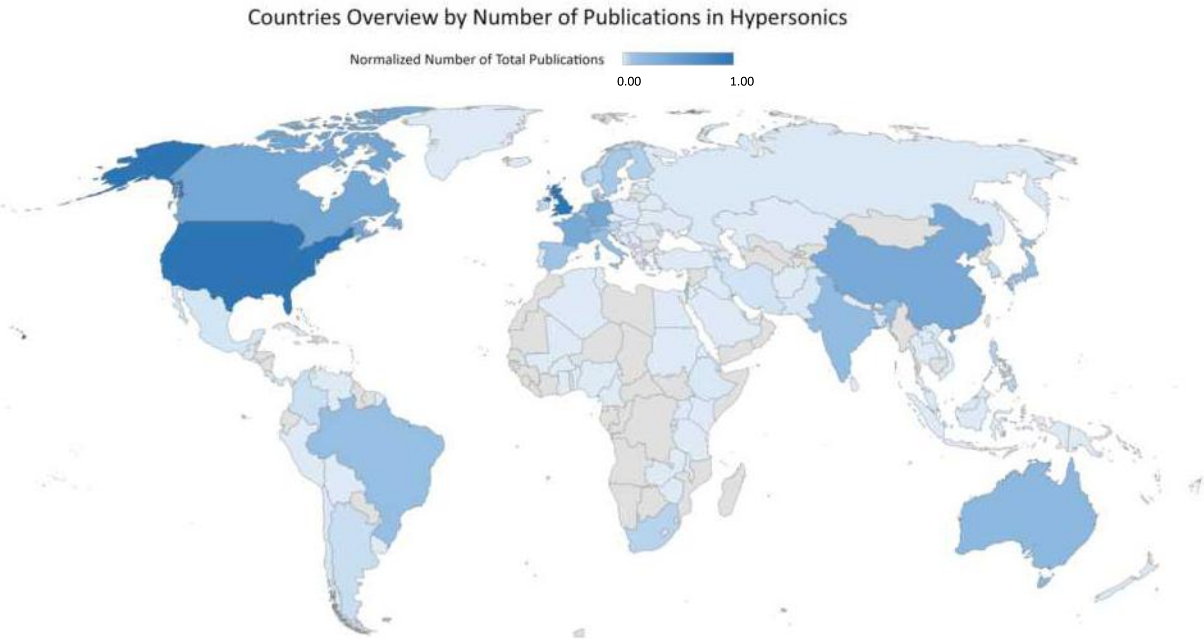
#### Counter-Hypersonic Systems

Hypersonic weapons present considerable challenges to strategies and technologies for defensive countermeasures. This challenge is particularly acute due to the speed and the possibility of large swarms. Countermeasures employing soft-kill approaches (e.g. jamming, deception, etc.) may be useful. Nevertheless, directed energy weapons (high energy lasers or particle beams) or space-based interceptors provide the best hope of a hard kill. These systems will need to be refined and operational within the appropriate policy and legal constraints if effective defensive countermeasures are to be deployed over the next ten years.

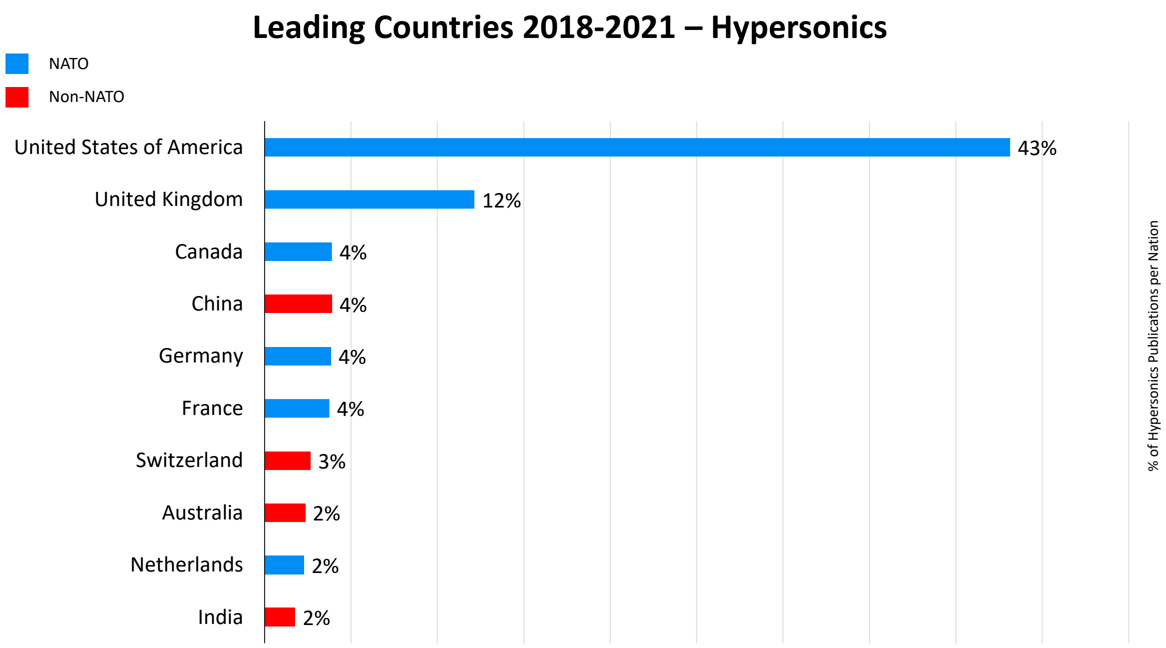
### Scientometrics

***Table 2.5:*** *Hypersonics 2023-2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| Hypersonics | Counter Hypersonics | High | 3-4 | 2030-2035 |
| | Vehicles & Propulsion | High | 5-6 | 2030-2035 |

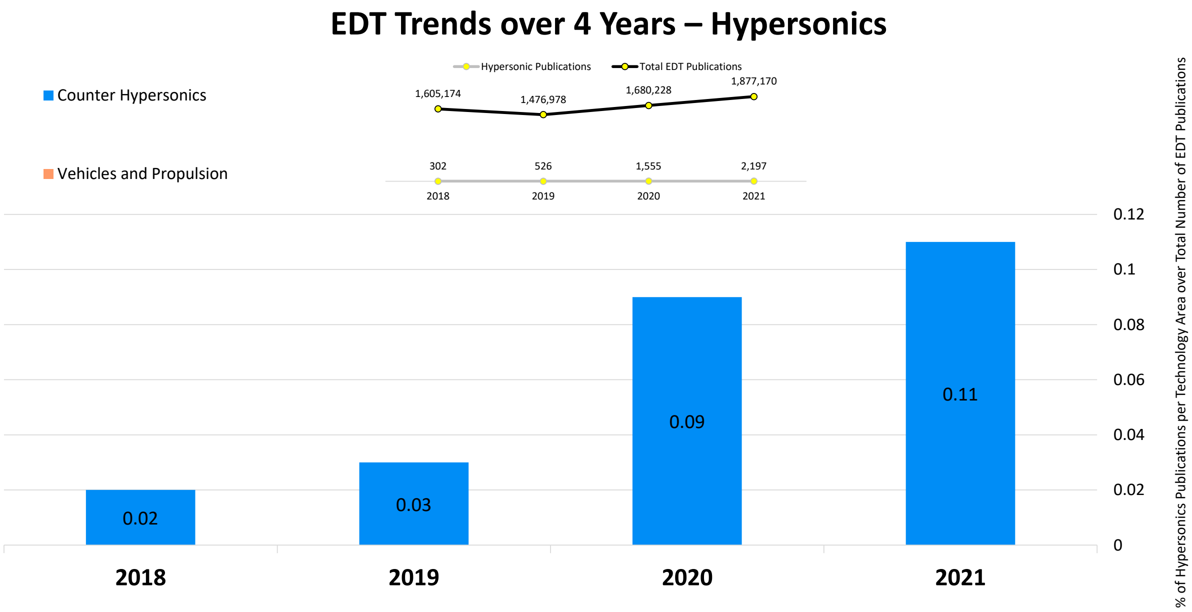



***(a)*** *Hypersonics - Leading Countries (Map) (STEAM Analysis).*

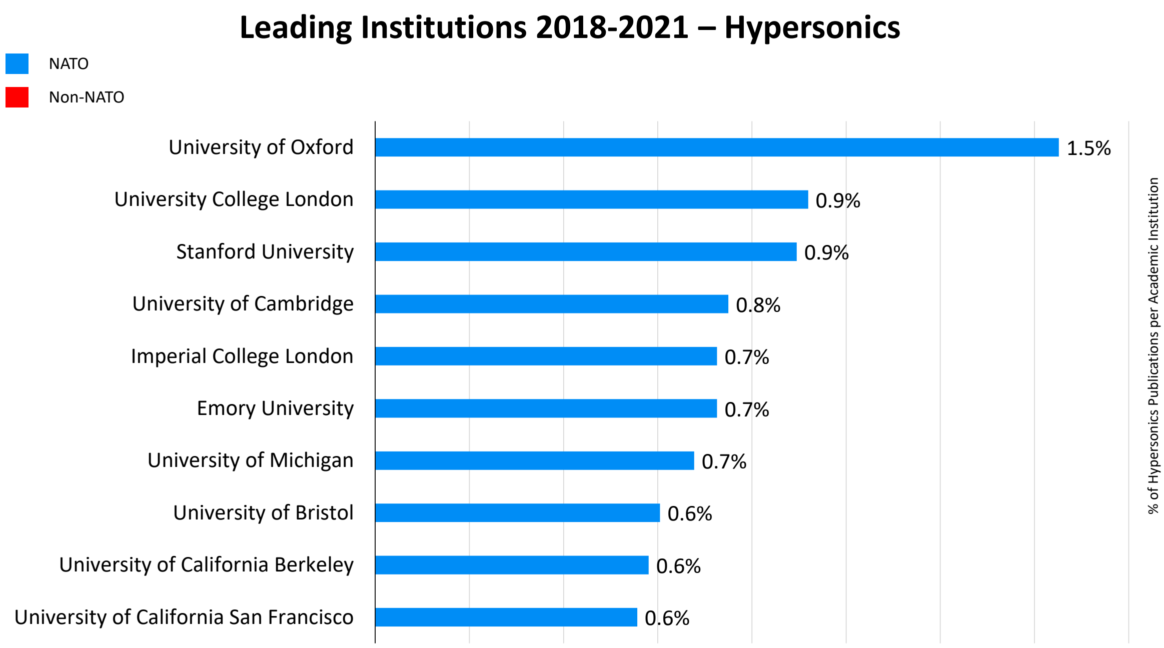



***(b)*** *Hypersonics - Leading Countries (STEAM Analysis).*

***Figure 2.10:*** *Hypersonics - STEAM Results - Countries*




*(a) Hypersonics - Topic Trends (STEAM Analysis).*

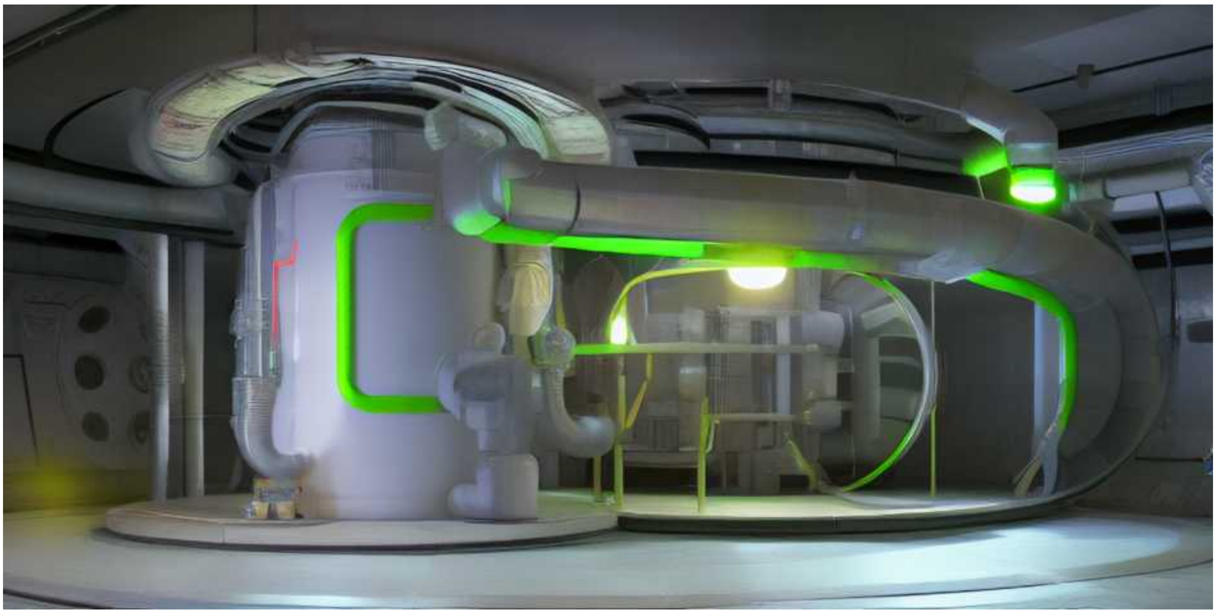



*(b) Hypersonics - Top Institutions (STEAM Analysis).*

***Figure 2.11:*** *Hypersonics - STEAM Results - Trends and Top Institutions*

### 2.2.6 Energy and Propulsion

**Energy and Propulsion Technologies (Energy)**
*Energy and Propulsion* considers the development of new generation, storage and propulsion technologies.



#### Overview

Mastering new means of propulsion and developing new energy sources have been central to humankind's development, which remains true even as humanity struggles with the consequences of anthropogenic climate change. EDTs will enable new means of energy production and help use energy more efficiently and effectively. But, at the same time, they contribute to the demand for more power and often come with negative secondary effects on the environment or energy requirements. For example, barring major advances in materials research, more than half of the world's energy production by 2037 will be consumed by electronic devices [200].

Commercial and societal interests drive most research and development around energy and propulsion issues. Nevertheless, NATO military capabilities will rely on these sources. As a consequence, energy and propulsion research of interest to NATO is generally concentrated in the following areas:

- Batteries and Energy Storage
- Power Generation
- Power Transmission
- Propulsion

#### Batteries and Energy Storage

Due to the increased interest in green technologies, batteries and energy storage research is of considerable commercial interest. However, research in this area of general interest in NATO is concentrated in two areas:

- **Batteries**: Research continues apace on optimising traditional lithium-ion battery technology. However, technological limitations and an ever-increasing demand for greater power densities are driving the exploration of new technologies. At the same time, economic, environmental and safety issues must be considered. Promising battery technologies are Al-air [201], dual-carbon [202, 203], Li-CO2 [204], lithium-metal [205], magnesium-sulphur [206], potassium-ion [207], sodium-metal [208] and zinc-ion [209]. Some of these technologies are focused on large-scale electricity storage, while others are more attractive for use in vehicles, including those used in military operations.

- **Capacitors**: Supercapacitors or ultracapacitors, which do not rely on electrochemical storage, provide another option for energy storage, with significant advantages in weight, safety, life, energy density, charging speed and toxicity [210]. Nevertheless, current technological limitations prohibit their general use [211]. A promising hybrid approach is supercapattery, which combines electrochemical energy storage with supercapacitors [212, 213].

### Power Generation

Clean energy generation is essential if NATO is to achieve its ambitious climate change objectives. Research in this area, especially in geothermal, solar, wind and hydroelectric, is not particularly focused on military applications. Nevertheless, the development of deployable and ruggedized equipment will benefit military operations. Given the commercial focus on this area, it is expected that NATO will have to focus on which of these power generation approaches is consistent with operational requirements. Some of these options are:

- **Renewables**: Solar efficiency and effectiveness improvements are being driven down yearly to the point where they are now competitive with fossil fuels [214]. Relevant research has focused on reducing production costs as well as increasing efficiency. Of interest are thin-film flexible solar cells [215], including non-fullerene organics [216], useful for wearables, clothing and windows. Power beaming is an exciting option to avoid the inevitable issues of clouds and daylight. Satellites in orbit would collect solar energy and beam the collected energy to earth. While it is unlikely such a system will be deployed before the 2030s, serious proposals are being made, and missions are planned to trial such a system [217, 218, 219, 220, 221, 222, 223, 224].

- **Renewables - Biofuels**: Arguably, biofuels provide an effective, rapid and low operational impact means of leveraging existing fossil fuel infrastructure and engineering with a sustainable and carbon-neutral fuel. Biofuels (including bioethanol, biodiesel and biobutanol) [16, 225, 226, 227, 228, 229] may be produced from a variety of sources, including cooking oils, algae, kelp, insects and alternative crops. One such promising approach is black soldier fly larvae biodiesels, which employ larvae to convert organic wastes to larval fats, which in turn may be used to create biodiesels [230, 231]. Research challenges, in general, are focused on addressing the many disadvantages of biofuels, such as costs, environmental damage, water use, land use, fuel quality and employment in existing systems.

- **Hydrogen**: Like biofuels, hydrogen is often touted as an alternative to fossil fuels. While there is substantial interest in hydrogen, most hydrogen is produced from fossil fuels, and it is unlikely to be a panacea in the search for green energy sources [232, 233].

- **Nuclear**: In recent years, nuclear power, particularly fission, has developed a strongly negative reputation. Nevertheless, relevant research continues to create safer and more deployable systems. For example, thorium-based molten salt reactors (MSR) [234, 235, 236, 237, 238] hold the promise of being safer and greener than traditional uranium-powered reactors, as well as presenting nuclear proliferation risks. Accident-tolerant nuclear fuels may also provide a safer path for future large-scale use of nuclear power. On a smaller scale, small nuclear reactors (SMR) [239, 240, 241, 242] are being developed to enable microreactors on military bases, support extra-terrestrial (e.g. moon, mars) habitation, as well as nuclear thermal propulsion (NTP) for space exploration. China is investing 440B (USD) in such technologies to move away from coal-fired electricity [243], and nuclearization of the energy grid is a central component of the PRC plan for greening China.

#### Transmission

Power, once generated, needs to be transported to where it will be used. Two areas to note. First, wireless power transfer (WPT) is expected to mature, driven by the demands of modern battery-powered electronics. Specific areas of wireless power transfer of interest to NATO are capacitive, dynamic, underwater and for charging communication devices. Second, microgrids will become increasingly important. Microgrids are localised power grids able to disconnect from the larger transmission grids, thereby increasing resilience and localizing power production. One of the major areas to be developed is overcoming the technical challenge of coordination and synchronisation with the main grid or other microgrids. Moreover, hybrid and military microgrids (e.g. shipborne) will be particularly useful and refined over the next ten years, with intense research interest due to their complex and complicated nature [244, 245, 246, 247, 248, 249].

#### Propulsion

Military vehicles' propulsion or powering is a significant technical challenge but has been under refinement and development for the last 300 years. However, from the perspective of weak technological signals, there are three crucial areas of development: electrification, novel aerospace engines and green operations.

The electrification of military vehicles is very much at the early stages of development and faces considerable challenges [250]. Nevertheless, it is only a matter before military vehicles move to electric propulsion with the electrification of the civilian private and industrial transportation networks [251]. By one estimate [251], the worldwide electrification market will grow from USD 4.8 billion (2020) to 17.6 billion (2030). The commercial movement towards electric vehicles is well placed to drive advances in batteries, motors and the AI/ML necessary to make this a reality. The utility of the Tesla cybertruck or semi for military operations is self-evident; however, the production and technical challenges associated with delivering these vehicles in quantity should not be underestimated [252].

Electrification of aircraft is another hot area of research, with several commercial vendors having demonstrated significant prototypes and announced near-production-ready aircraft [253, 254, 255, 256, 257, 258, 259, 260, 261]. Such electrification challenges are even more significant than those for land or naval vessels [260, 262]. In the short term, hybrid-electric or turbo-electric systems [263, 264, 265, 260, 266], along with fully electric turboprops and hydrogen planes [267] for short flights, hold the most promise [268].

Aircraft propulsion must be coupled with effective control surfaces and systems. Research is underway exploring the revolutionary improvements possible in in-flight performance using Active Flow Control (AFC). AFC technologies *"alter the aerodynamic flow field thru ejection or suction of fluid via an orifice on a lifting body"* [105].

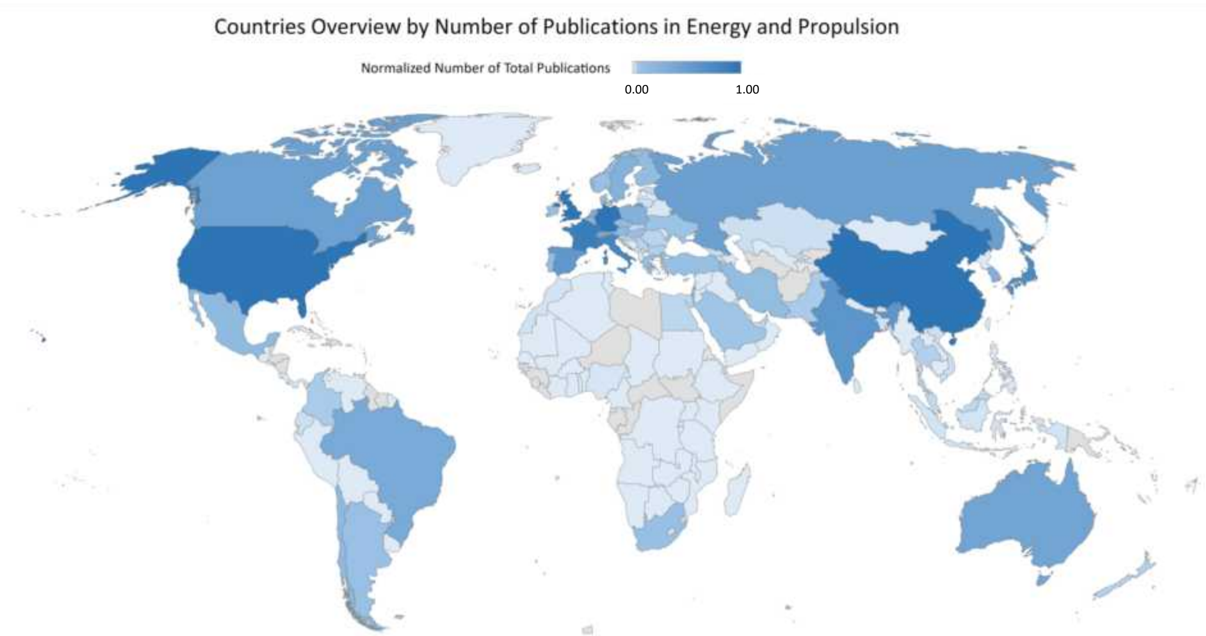
In-space propulsion technologies (nuclear, chemical, solar or electric) are evolving rapidly in a search for cost reductions, increased endurance, reliability and extended mission lengths. In particular, nuclear technologies are seen as a potential enabler of operations outside the earth-moon system [269, 270]. Propulsion options include [271] nuclear thermal or fission propulsion. NTP technologies [272] use a nuclear reactor to heat the propellant. Nuclear fusion propulsion is also very early in development [273]. Air scooping electric propulsion (AESP) offers promise for very low-Earth orbits.

Combined cycle engines promise cost-effective human-crewed hypersonic flight (turbojet for low-speed shifting to scramjet at high speeds). Research and development in this area continue and should be of interest given its apparent value for military operations [197, 198, 175, 199]

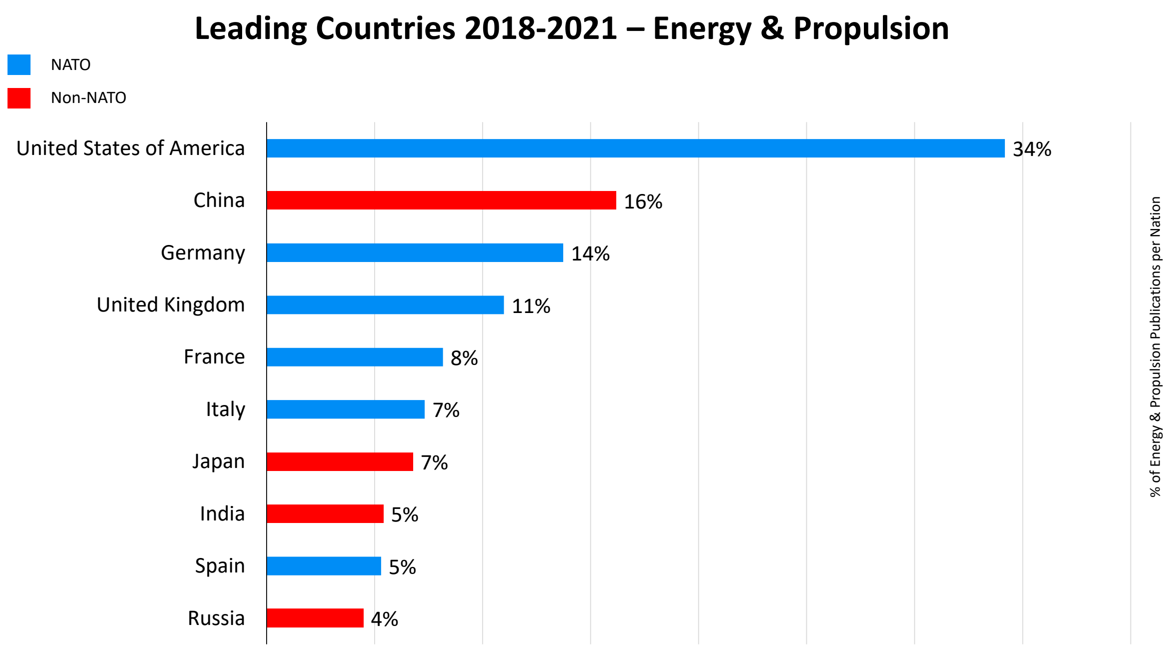
### Scientometrics

***Table 2.6:*** *Energy and Propulsion 2023-2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| Energy | Energy Generation | High | 5-6 | 2025-2030 |
| | Energy Storage | High | 5-6 | 2030-2035 |
| | Propulsion | High | 5-6 | 2025-2030 |
| | Transmission | High | 5-6 | 2025-2030 |

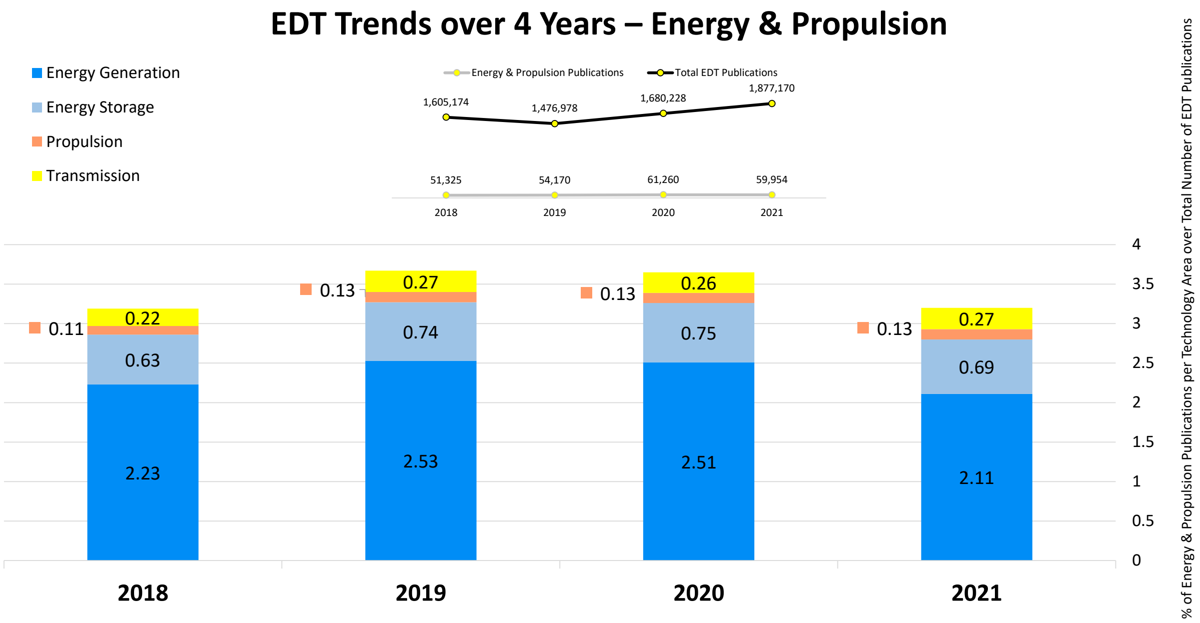



*(a) Energy and Propulsion - Leading Countries (Map) (STEAM Analysis).*

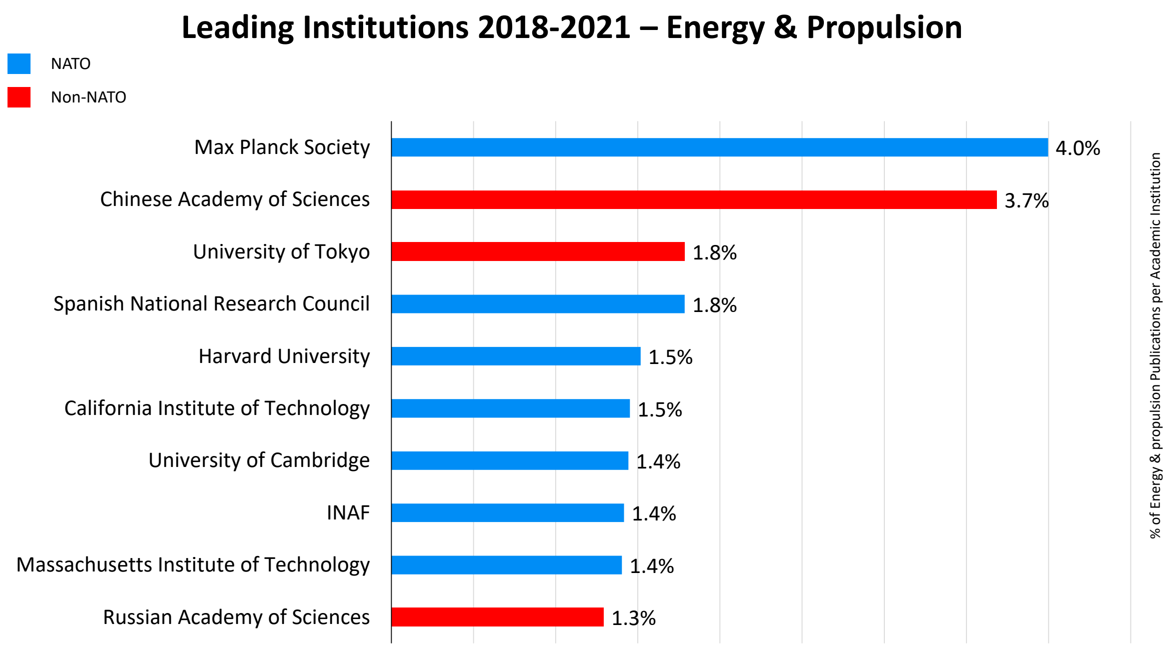



*(b) Energy and Propulsion - Leading Countries (STEAM Analysis).*

***Figure 2.12:*** *Energy and Propulsion - STEAM Results - Countries*




*(a) Energy and Propulsion - Topic Trends (STEAM Analysis).*




*(b) Energy and Propulsion - Top Institutions (STEAM Analysis).*

***Figure 2.13:*** *Energy and Propulsion - STEAM Results - Trends and Top Institutions*

### 2.2.7 Electronics and Electromagnetics

**Electronic and Electromagnetic (E&EM) Technologies**
*E&EM* considers electronic and electromagnetic technologies.

**Overview**

Technological progress is contingent upon developing new electronics and controlling the electromagnetic (EM) spectrum. The famous Moore's law encapsulates our ability to scale first-generation silicon-based electronics at a rate that doubles transistor counts roughly every two years. However, this scaling will encounter hard physical limits within the next ten years, necessitating new approaches to electronic systems [43] that exploit novel concepts, tools, materials, and designs. Therefore while continued refinement and optimisation of silicon-based electronics will be the preoccupation of the semiconductor industry over the next ten years, new developments exploiting novel materials, designs, architectures (combining memory and computation), physics (magnetic states, electron spin properties, topological insulators, phase-change materials, trapped-ion & photonic quantum circuits), photonics, AI-enabled design tools and neuromorphic chip designs are being explored to continue to scale computation beyond the limits of silicon [274]. At the same time, *"designed in"* electronics security must be undertaken to ensure a cyber-safe processing and computation environment.

The EM spectrum is becoming an increased area of competition and congestion. Therefore, developments are needed to maximise and optimise (e.g. cognitive radios and frequency management) the use of limited EM spectrum while simultaneously considering the challenges of electronic warfare.

Technological progress in many EDTs is contingent upon developing new electronics and controlling the EM spectrum. Among these technical challenges is moving beyond first-generation materials (e.g. silicon).

Developments over the next 20 years are expected to be in the following area:

- **Advanced Electronics and Electromagnetics**: New materials, designs and chip architectures are pushing the bounds of chip performance. Specialized chips, such as neuromorphic, show great promise for selected tasks.

- **Antennas**: 4D arrays and mechanically manipulated antenna designs are promising technologies to improve performance and enable long-range wireless communications, including underground and underwater.

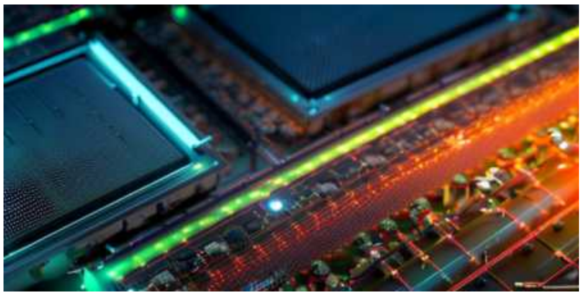
- **Photonics and Lasers**: Silicon photonics is a growing field, exploiting existing technologies to manipulate photons instead of electrons. This supports the development of photonic chips modelled on neural processes (neuromorphic photonics), ideal for AI/ML applications. In addition, developments in on-chip nanolasers enable a move towards photonic computing.

- **Spectrum**: Adaptive camouflage using novel materials and control processes shows promise.

The following subsections will explore these developmental areas further.

#### Advanced Electronics and Electromagnetics

The ability to develop new electronics is reaching the fundamental limits of silicon-based physics. This will impose hard limits on Moore's law, significantly limiting technological progress across a wide range of technologies. Nevertheless, it is also true that promising research is ongoing, looking at various means of moving beyond silicon [275]. Much of this research is clustered into three broad categories [274]: Materials, Architectures and Design.



- **Materials**: Materials research will develop new non-silicon-based materials supporting the next generation of logic and memory chips. Novel methods of computing are being explored based on non-traditional intrinsic material properties, mixed materials (compound semiconductors) and cryogenic computing (leading to a potential order of magnitude improvement in electrical usage or performance) [274], 2D materials, GaA (Gallium Arsenide), SiC (Silicon carbide) and GaN (Gallium nitride) hold out the promise of reduced power, noise, heat and size. Many countries, including China, invest in these technologies to embrace a potential technological leap-ahead opportunity.

- **Architectures**: Rethinking circuit architectures at chip and board levels offers improved performance and cost reduction using silicon-based transistors. Specialised circuits and AI/ML to assist and automate designs provides further opportunities to improve performance and reduce heat or energy usage. Biomimetic, neuromorphic and hyperdimensional computing are all promising developmental areas.

- **Design**: Improving chip design is another means of improving chip performance. Much of the work in this area exploits AI/ML to improve the design and optimisation of chip layout. While this dramatically opens up new architectural options and improves chip efficiency, it also has the potential to "democratise" chip design, making sophisticated chips more widely available and potentially open-source.

#### Antennas

As military and commercial communication or sensor systems are miniaturised, size, weight, power and cost (SWaP-C) considerations become more critical. However, reconsidering the design of such systems often comes up against the physical limits and vulnerabilities of the antenna. As a result, research into new antenna designs is of significant interest for defence applications. While developments in this area are extensive, less-known examples of research of potential interest are in the following areas:

- **ULF/VLF transmitters**: Ultra Low Frequency (ULF, 0.3 to 3 kHz) and Very Low Frequency (VLF, 3 to 30 kHz) are beneficial frequencies for underground and underwater communications [275]. Given the large wavelengths, classical antennas are often a kilometre or more in length [274]. A new approach to using mechanically manipulated magnetic/electrical fields can substantially reduce antenna size (c. 1m). This expands the use of long-range wireless communications, including underground and underwater.
- **Wideband**: The development of antennas for ultra-broadband emitters and receivers can provide a resilient and secured communication channel for military operations, with enhanced abilities to circumvent current electronic warfare jamming capabilities [274].
- **4D Arrays**: Manipulation of antenna arrays whereby individual elements are selectively turned off and on, creating unique and useful sidebands. These sidebands are suitable for multi-channel transmission and smart beamforming.

#### Photonics and Lasers

Photonics, or the study of manipulating light in a medium for transmitting information, is a well-established science. Still, one that continues to yield new and exciting applications, including breath-taking options for quantum computing. Applied physics research is still being conducted to understand basic photonic science and the interactions with integrated circuits and their application in communications, signal processing, spectroscopic sensing, and imaging [274].

The growing area of silicon photonics is noted [276, 277, 278, 279, 280], which uses silicon chips to manipulate light rather than electrons as in conventional electronics. As a result, power consumption, costs, speed, capacity, and scalability improvements are expected, although producing such chips is still a significant technical challenge. Areas of relevant research interest are improved optical signalling, neuromorphic photonics, opto-magnonics and topological photonics.

Developments in laser technologies will also provide technological shocks, especially as vital elements in photonics and communication. Significant developments in compact radiating photonics, nanolasers (lasers-on-chips) and SWaP-C developments in free-space optical lasers are a few areas to note.

#### Spectrum

The electromagnetic spectrum is increasingly contested, congested and commercial. The introduction of 5G and upcoming 6G technology is well documented. This will form a core digital backbone for NATO military and enterprise activities. The associated competition and conflicting standards may result in even more intense pressure for commercial use of the available EM spectrum. Nevertheless, military success in theatre often depends on a force's ability to control and exploit the EM spectrum while, at the same time, denying access to such spectrum by hostile actors.

The number of research activities in this area is overwhelming; however, a few emerging technological aspects in this research area are of potential interest.

- **Adaptive camouflage**: These developments seek to adapt the optical and near-optical signatures associated with a vehicle, person or facility so that the signature is like the existing background or surroundings. Such camouflage may span a variety of spectral bands. Adaptive camouflage seeks to change the signature simultaneously across multiple spectral bands dynamically.
- **High-Frequency High-Power Overmatch**: Developing high-power amplifiers tailored for high-frequency millimetre wave communications would open a portion of the EM spectrum that may be less crowded or contested. This would also support high-data-rate communications and increase sensitivity and higher resolution for various sensors.

- **Adaptive Spectrum Management**: Cognitive radios or sensors employ AI/ML algorithms to adapt to a changing EM environment, including jamming and increased commercial use. They support more effective and agile use of the available spectrum. Applications extend from radar, signals intelligence, electronic warfare, and communications.

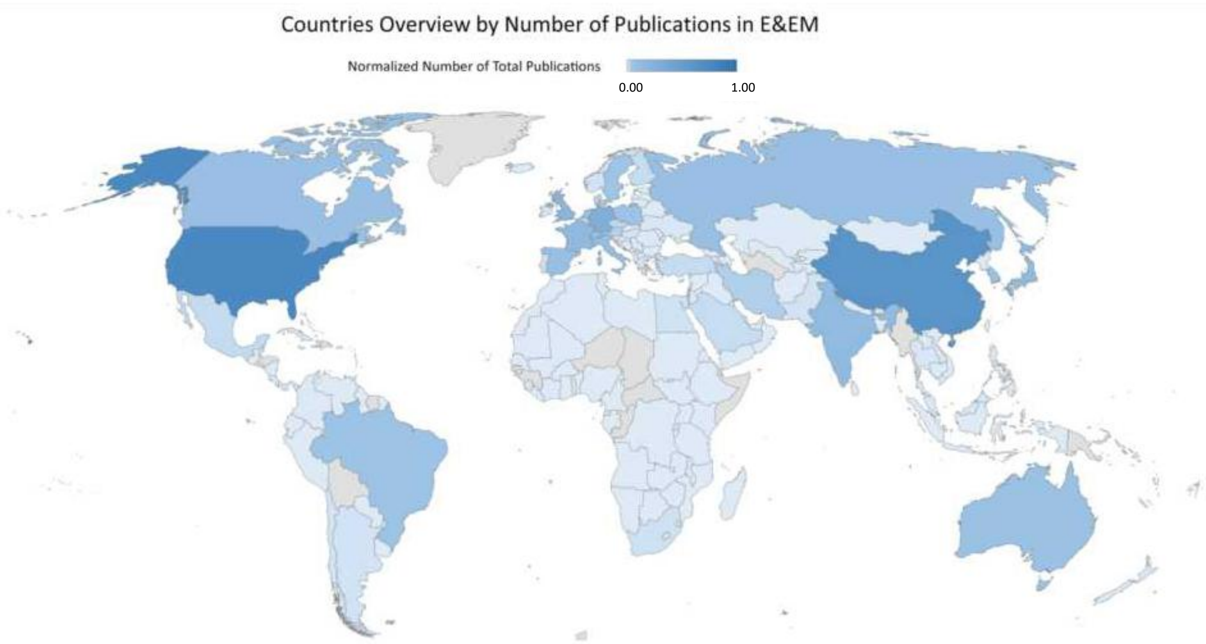
### Directed Energy Weapons

The recognition that non-kinetic conflict is essential to effects-based warfare is growing [281]. While hardly a new technology, directed energy weapons (DEW) have matured, and demand has surged globally. These lasers and high-power microwave weapons are already a disruptive force on the battlefield and are expected to be even more widely used over the next few years [282, 163, 287, 288, 289, 290, 281, 291, 292, 283, 284, 285, 286]. Estimates are that the current DEW global market is USD 14.3 Billion growing to USD 72.1 Billion by 2027 [293]. In no small measure, this growth is driven by improvements in energy storage, AI/ML and materials. Many DEW systems have become operationalised or are at very high TRL levels. The value of such systems and the continuing technical challenges were explicitly noted and played during recent STO technology watch games [119].

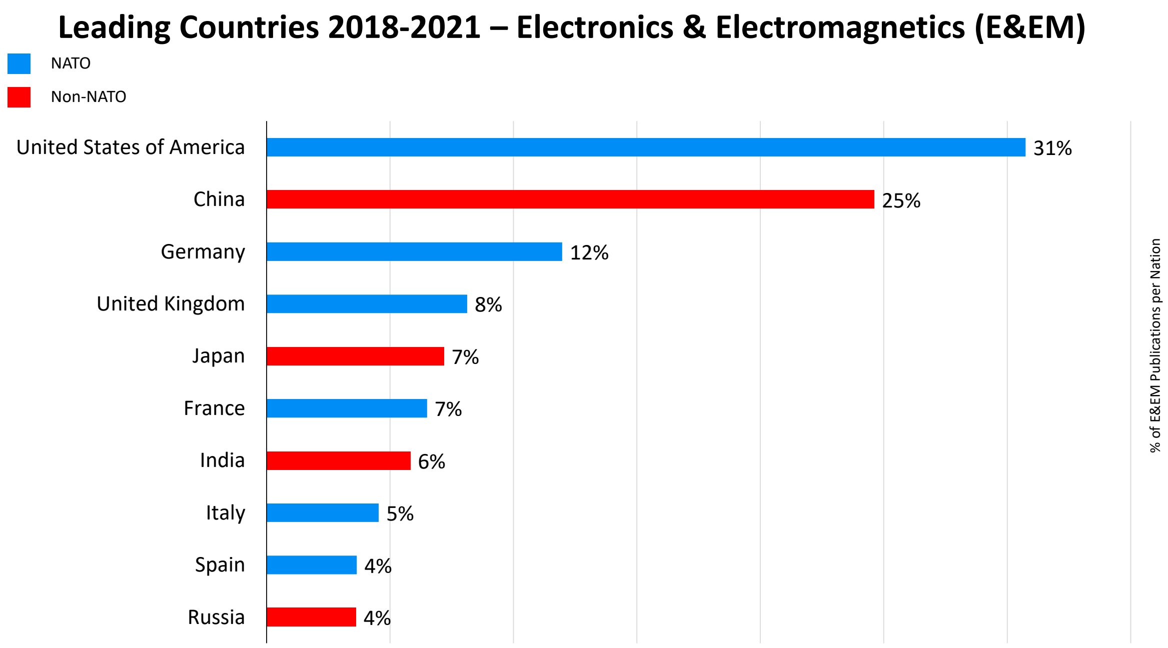
### Scientometrics

***Table 2.7:*** *Electronics & Electromagnetics (E&EM): 2023-2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| E&EM | Antennas | High | 9 | 2022-2025 |
| | Directed Energy Weapons | High | 5-6 | 2030-2035 |
| | Microelectronics | High | 9 | 2022-2025 |
| | Photonics & Lasers | High | 7-8 | 2025-2030 |
| | Spectrum & Signature Management | High | 5-6 | 2025-2030 |

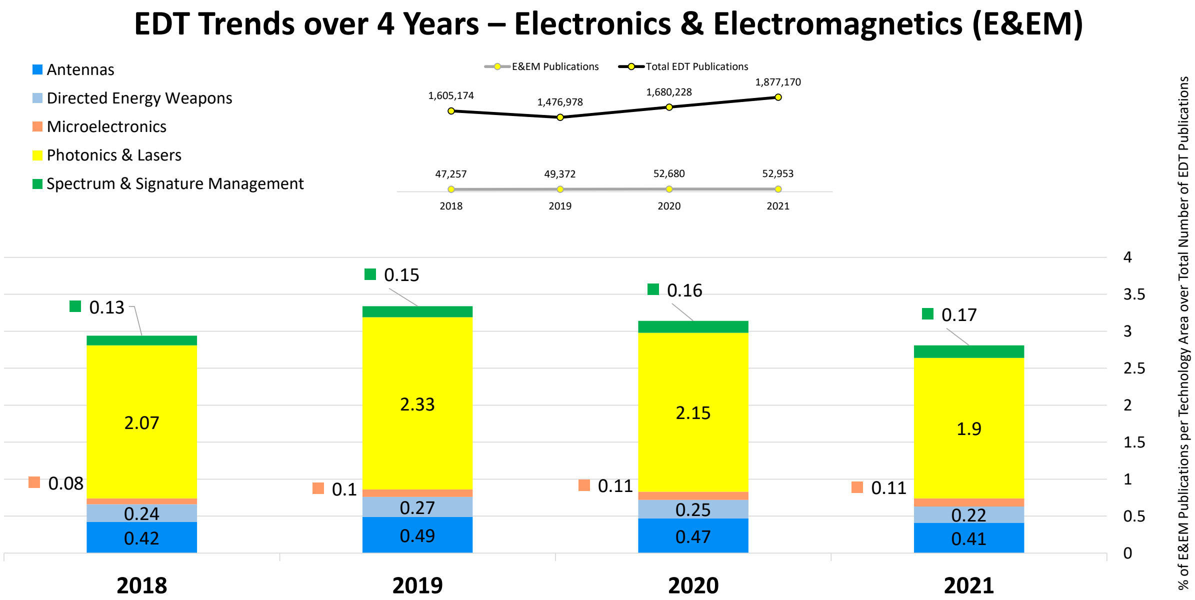



*(a) E&EM - Leading Countries (Map) (STEAM Analysis).*

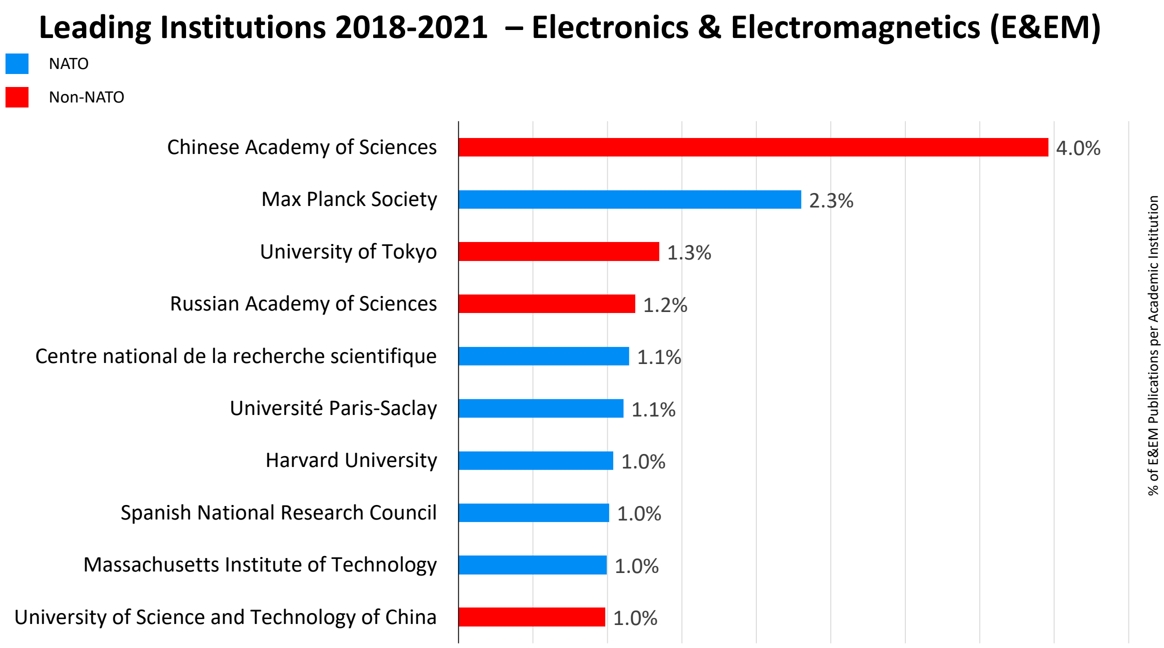



*(b) E&EM - Leading Countries (STEAM Analysis).*

***Figure 2.14:*** *Electronics and Electromagnetics (E&EM) - STEAM Results - Countries*




*(a) E&EM - Topic Trends (STEAM Analysis).*




*(b) E&EM - Top Institutions (STEAM Analysis).*

***Figure 2.15:*** *Electronics and Electromagnetics (E&EM) - STEAM Results - Trends and Top Institutions*

## 2.3 Emergent Technologies

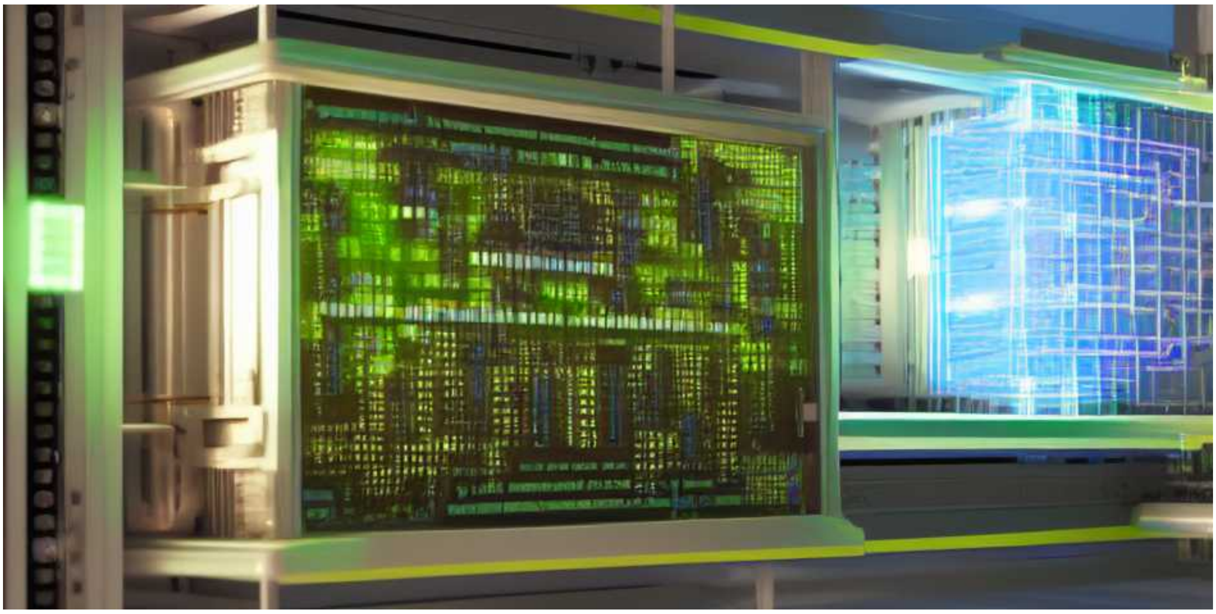
This section provides a brief overview of critical developments and trends associated with this disruptive S&T. Volume 2 of this report provides a more comprehensive review of each EDT.

Emerging technologies represent *creative destruction*, as originally described by the economist J. Schumpeter [294], and are characterised by the potential of shifting paradigms. The term *emerging* indicates novel scientific discoveries in the early stages of development, technologies that embody an uncertain and risky nature, and insecurity of their potential impact on military capability. This report uses the term to mean new or nascent technologies and scientific discoveries expected to reach maturity in 2023-2043. Such science is not widely integrated into technologies whose effects on Alliance defence, security and enterprise functions are unclear.

### 2.3.1 Quantum

**Quantum Technologies (QT)**

Next-generation *quantum technologies* exploit quantum physics and associated phenomena at the atomic and sub-atomic scale, particularly quantum entanglement and superposition. These effects support significant technological advancements primarily in cryptography, computation; precision navigation and timing; sensing and imaging; communications; and materials.



#### Overview

Quantum mechanics counts its origins from the beginning of the last century and is generally used to describe the behaviour of matter at the atomic scale (less than $10nm$). Quantum phenomena underlie modern technology, including the transistor, nuclear energy, electron microscopes, superconductivity, photoelectric detectors, medical imaging (functional magnetic resonance and positron emission imaging), lasers and solid-state devices. Such technologies exploit the rules of quantum behaviour.

Directly engineering, manipulating, and controlling individual quantum states has led to a second quantum revolution, beginning slowly in the 1980's [295]. Such second-generation quantum-enabled technologies rely on quantum phenomena such as superposition and entanglement, promising revolutionary military and security capabilities [296, 297, 298, 299, 300, 301, 302]. These quantum technologies are currently under intense research and development, with applications covering ultra-sensitive sensors, PNT (positioning, navigation, and timing), communications, and information science. This research has to *next-generation technology developments* such as ultra-sensitive sensors; incredibly accurate clocks;

*unbreakable* encryption and communications; and, hitherto impossible levels of computing power (for some classes of problems) [303, 304, 305, 306, 307, 308].

Quantum technologies are generally broken into three broad overlapping areas:

- **Quantum computing**: The use of superposition and entanglement to create qubits capable of being used for computation. The term quantum information science may also be used, although this includes not only quantum computers but the development of new specialised quantum-based algorithms, programming languages, interfaces, etc. Quantum computers are best seen as employing specialised processors suitable for a very limited (but important) class of problems in optimisation and simulation.
- **Quantum communication**: The use of secure or cryptographic methods for communication using quantum properties (e.g. entanglement) to provide intrusion detection or improved cryptographic techniques. Quantum key distribution (QKD) is a well-known example of this technology. Post-quantum cryptography is a separate area using enhanced encryption algorithms that are not amenable to solutions by quantum computers. The Quantum internet may also be considered part of this research area, defined as a (theoretical) network built through entangled quantum communication networks and computers.
- **Quantum sensing**: Using a quantum system, quantum properties, or phenomena to measure a physical quantity. The term quantum metrology is often used to distinguish sensors used for in situ measurements through quantum effects, especially in the context of measurement of fundamental physical constants. For example, measuring magnetic or gravitational fields for PNT is an example of militarily relevant quantum sensing. It is, therefore, often suggested as a separate technological area.

Two other areas of research may be identified, and both act as technological enablers for the three areas identified above:

- **Quantum materials**: These are materials whose properties are only explainable with reference to quantum phenomena. 2-D materials such as graphene or graphyne are often referred to as quantum materials, as are quantum topological materials whose electronic structures are different (and significantly more complex) than those shown by metals or insulators.
- **Quantum optics**: The application of quantum mechanics to understand and exploit the interaction of light with matter. This covers various applications such as interferometry, photonics, quantum computing, communication, sensing etc.

In considering this EDT, we will restrict consideration to the three generally accepted areas of militarily relevant quantum technologies. That is not to downplay development in the remaining areas but to recognise they are often considered fundamental aspects of other EDTs.

Large investments continue to be made around the globe in quantum technologies and are expected to reach nearly 30 billion USD in 2022. Unfortunately, the hype around such investments and developments continues to be equally large, often confusing near-term technologies such as quantum sensing with long-term and high-risk technologies such as quantum computing. While this level of hype has only grown over the last two years, there are indications that the reality of the long and difficult technical challenges involved is dampening enthusiasm in some areas. As a result, some authors and commentators have referred to the hype around quantum technologies as a *"classic bubble"* [309, 310, 311].

Quantum technologies will not come upon us together en masse, but sensors, communications and computers will arrive in a staggered fashion as their technology evolves. If successful, these technologies will have a profound effect on military operations [300, 301, 302].

Although new quantum technologies have the potential for a revolutionary impact on NATO operations, most (but not all) are in the early stages of development, and significant technical challenges lie ahead before operational systems are developed. The use of ultra-sensitive gravimetric, magnetic or acoustic sensors will significantly increase the effectiveness of underwater warfare capabilities, potentially rendering the oceans transparent [312]. Quantum radar [313, 314, 314] can make stealth technologies obsolete, provide more accurate target identification, and allow covert detection and surveillance. Accurate clocks will enable the development of (precision) PNT systems for use in GPS-denied or inaccessible areas (e.g. under ice). Unbreakable quantum key encryption will support more robust and secure communication. Quantum computing, potentially the most disruptive quantum technology of all, can render previously untenable classical computational tasks in areas such as optimization, BDAA, AI, and modelling & simulation viable. This computational edge can significantly increase the decision-making and operational effectiveness of NATO forces, as well as render current encryption techniques and encrypted data *crack-able* for the first time.

Interoperability considerations will be critical for the successful implementation of some quantum-enabled capabilities. Standardisation around quantum encryption and communications protocols will be a more immediate concern. PNT, sensors and computing will present fewer interoperability challenges as these will be tightly integrated into operational capabilities, which may also lead to significant disparities in operational performance between alliance members.

Of all the EDTs, Quantum technologies are the most nascent and variable in development, with substantial national and commercial investments being made. In particular, the operational viability of new sensors demonstrated at the laboratory level is a significant area of continued research [315]. This development is agreed to be at a much lower level of technical readiness [316, 317] than other quantum technologies. PNT and QKD are much closer to being fielded operationally.

We will consider these three areas separately in the sections below.

#### Computing

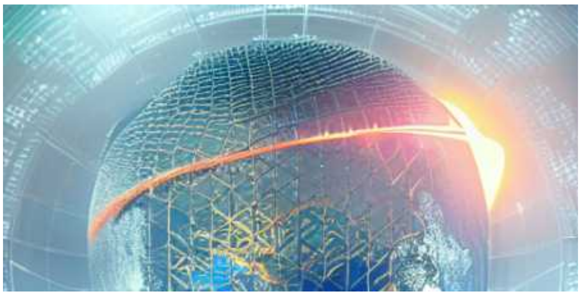
Quantum computing is part of a broader suite of challenges under the general banner of Quantum Information Science (QIS), which covers the R&D of quantum computers, algorithms, cryptography, programming languages, modelling, simulation, and knowledge applications. Research in quantum computers has focused on quantum error correction, noise reduction, logic gates, and exploring various qubit technologies. Photonics and semiconductor methods for room-temperature quantum computing have made great strides. A variety of companies are working towards developing thousand-qubit systems by 2023 and million-qubit systems by 2029. Related developments of interest are the research on quantum machine learning and the widely available (free but limited) access granted by several companies to quantum computing resources.

Quantum computing relies on well-developed, although non-intuitive, physics. That said, the engineering challenges of quantum computing are extreme. The People's Republic of China (PRC), Google, IBM and many alliance nations are investing heavily in a quantum race to develop specialised (e.g. optimisation through quantum annealing) and general-purpose quantum computer capable of demonstrating a real and significant advantage over classical supercomputers. Over the last two years, the number of qubits has grown from 54 to 433, with 1000+ qubit systems on track for delivery next year and million-qubit systems by 2030 are planned. This is an impressive technical feat, but future designs face significant scaling, noise, cross-talk, stability, and commercialisation challenges. It is a long journey to a million-qubit system needed to solve substantial problems. Investment and research challenges are significant. Given the current economic climate, hype, and the need for an eventual return on investment, it has been suggested that we are at risk of a "quantum" winter. Further, the hype around quantum is not necessarily good for research that seeks to expand our understanding of the quantum realm.

Nevertheless, new approaches such as nitrogen-vacancy or photonic systems, in contrast to ion traps or superconducting qubits approaches, are promising larger, more stable systems. Even if there is a quantum winter, quantum computers may eventually be developed for practical application, although it may take longer than the forecasted ten years. At this point, it is still being determined whether quantum computing will follow the path of energy production by nuclear fusion, e.g. always 20 years away. At the same time, disappointment may also set in as the limitations of such systems and the limited sub-set of problems/algorithms that can successfully employ quantum computing become apparent. Even the application of current methods to challenges of materials modelling (a role for which such systems were originally suggested) has so far been disappointing. As such, it must be noted that investment in quantum computers must not replace investment in classical supercomputing technologies. If quantum computing is to be successful, it will likely be as a specialised coprocessor as part of a supercomputing system.

#### Quantum Communications

In contrast to quantum computers, quantum communication is developing at an impressive rate. Real-world demonstrations of significant terrestrial and space-based systems have occurred, and the technical challenges appear surmountable. This promises the development of highly secure global communications. Some have suggested (e.g. US DoD) that the development of quantum communication technologies is unnecessary as there are reliable, well-understood methods for ensuring secure communications even in a post-quantum computing world. Next-generation post-quantum encryption techniques already exist and await verification (e.g. to ensure that classical and quantum methods cannot break them), standardisation and widespread implementation. Further, given their limitations and costs, quantum communication networks will augment, rather than replace, existing networks.



The development of a quantum internet holds great promise, although it has also been described as a solution to a problem no one has asked to be solved. The quantum internet is expected to leverage quantum computers and communication networks to create an ultra-fast and highly secure internet suitable for the big data challenges expected over the next 20 years [318, 319]. Since this relies heavily on quantum computing, developing a quantum internet is not a foregone conclusion.

Quantum communications and cryptography (often considered a sub-area of QIS) exploit many technologies for ultra-secure communications (e.g. intrusion detection and low probability of intercept). Examples of maturing technologies include QKD and quantum random number generators (QRNG). Using these and other related technologies will ultimately enable a secure quantum internet. Post-quantum encryption methods, such as Super-singular Isogeny Diffie–Hellman key exchange (SIDH), promise to establish a secret key between parties over an otherwise insecure communication channel. Quantum communications advances are considered essential in developing effective 6G technologies.

#### Sensors

Of all the quantum technologies, sensors are the most well-developed, enabling precision measurements of physical quantities such as atomic energy levels, photonic states, and spins. Moreover, quantum sensors may greatly exceed their classical counterparts with substantially increased precision, mapping magnetic, electric, and gravitational at exquisite resolutions. Nevertheless, SWaP-C (size, weight, power, and cost) challenges are considerable and will limit the fielding of such sensors. Examples of quantum sensors are:

- Atomic clocks: Positioning, navigation, timing, networking and metrology
- Atom interferometers: Gravimeters and accelerometers
- Optical magnetometers: Bioscience, geoscience, ASW and navigation
- Quantum optical: Local and remote sensing, networks, basic science
- Atomic electric field sensors: GHz-THz radiation detection

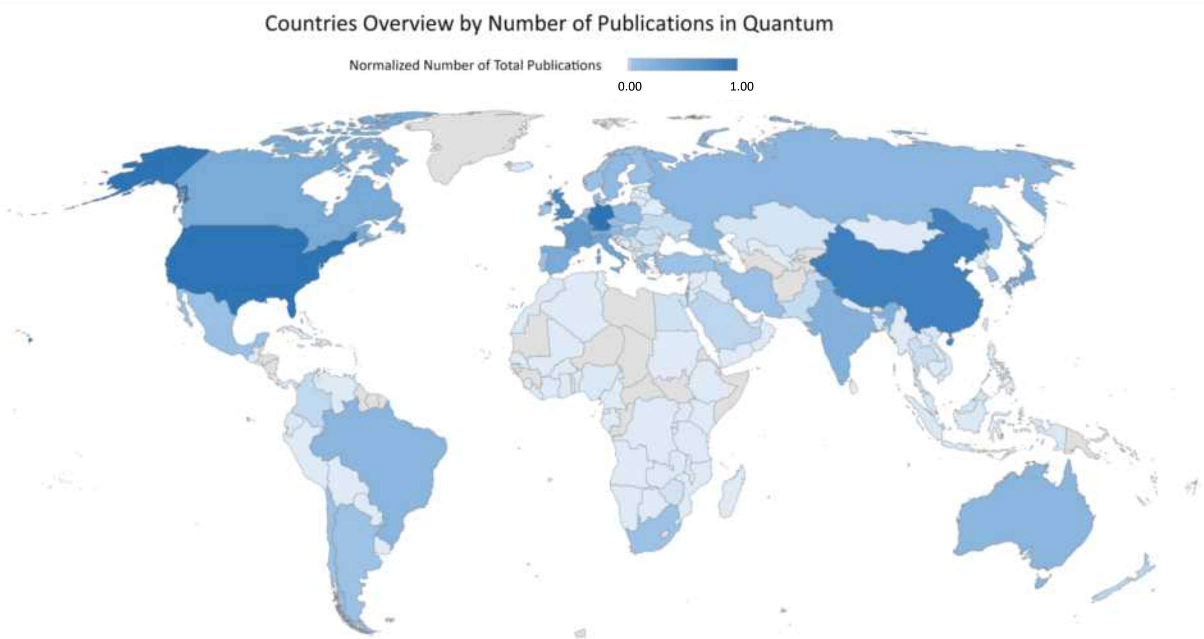
Sensor developments are ongoing in electromagnetics, gravimetric, imaging, radar, and magnetic sensing. These advances are especially important in the shorter term for naval mine detection and ASW (anti-submarine warfare). LiDAR (light detection and ranging) is an aspirational, longer-term goal for sensing capabilities, although the technology developed on-route will likely have short-term benefits for defence.

One particularly interesting application has been the development of PNT systems. The PNT market has been forecasted to reach 200 million USD by 2024. Developments are ongoing, but the critical SWaP-C challenges are the most vital, especially as they will enable unmanned vehicles (UxV) operations and navigation systems for large mobile military systems. Significant progress has been made in the development of deployable systems.

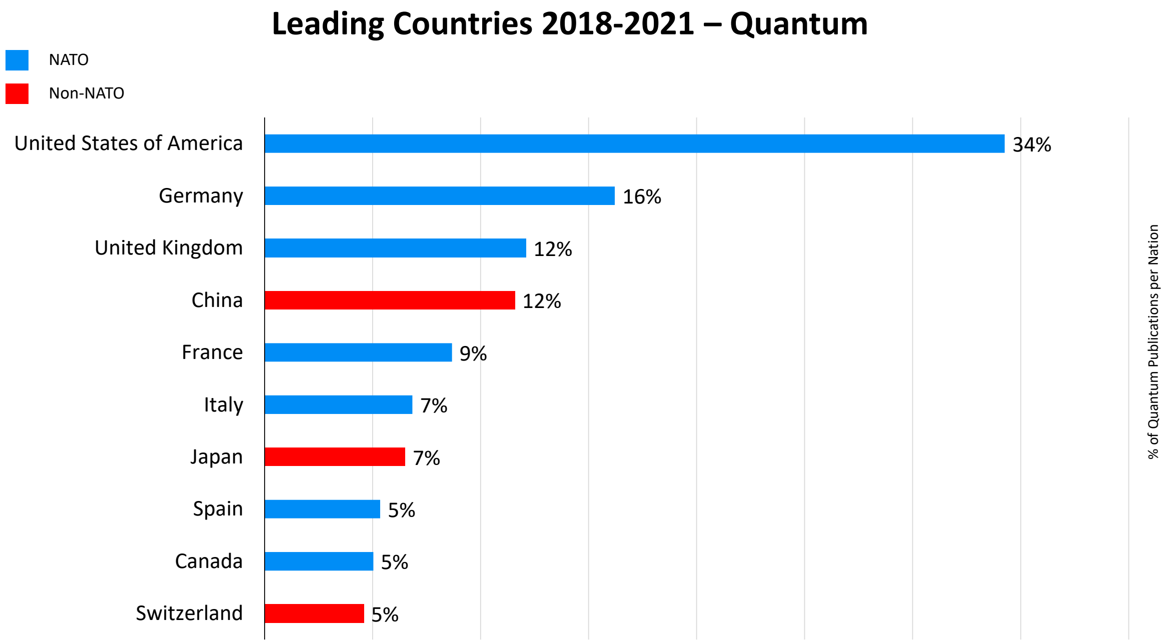
#### Scientometrics

***Table 2.8:*** *Quantum Technologies (QT) 2023-2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| Quantum | Communications | High | 3-4 | 2030-2035 |
| | Information Science & Computing | High | 3-4 | 2035 or (+) |
| | Sensors | High | 3-4 | 2035 or (+) |

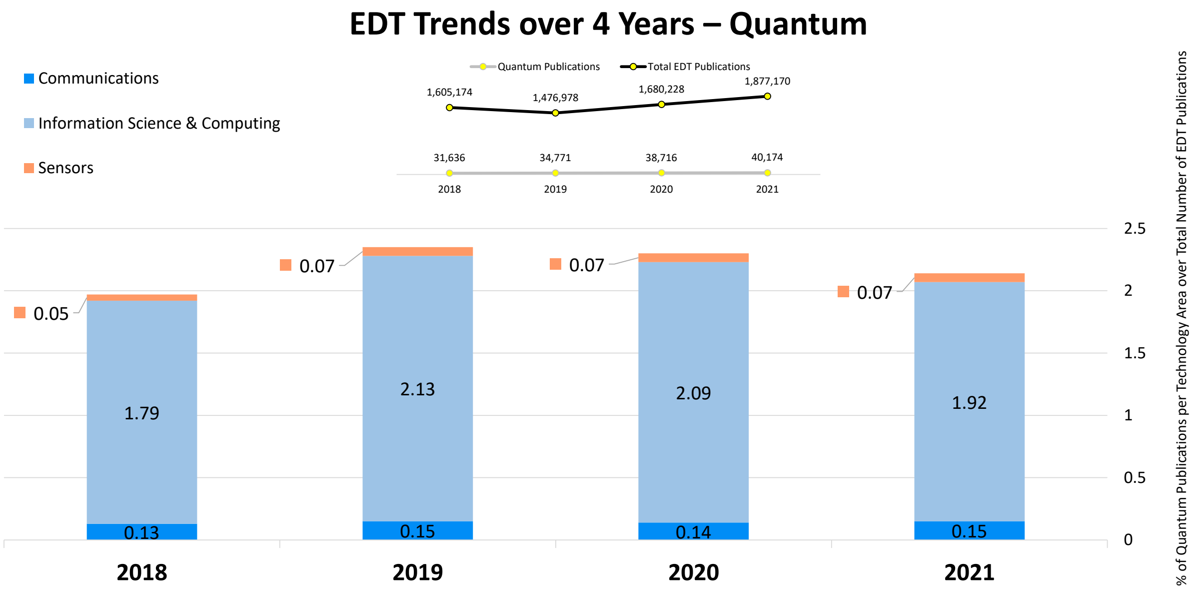



*(a) Quantum - Leading Countries (Map) (STEAM Analysis).*

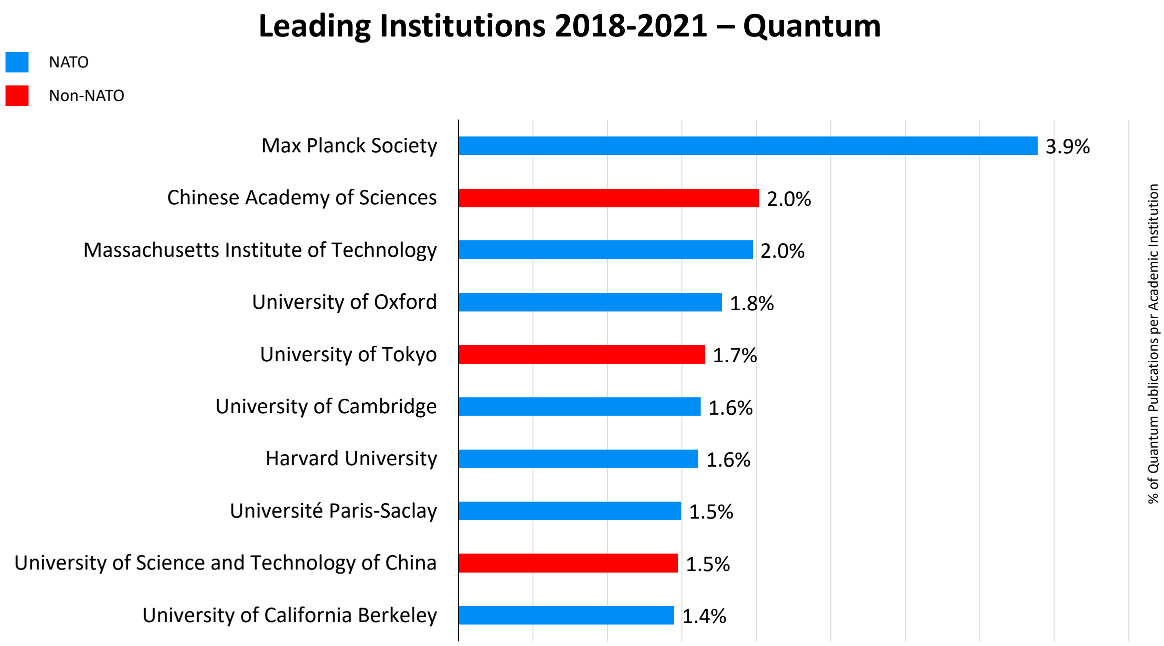



*(b) Quantum - Leading Countries (STEAM Analysis).*

***Figure 2.16:*** *Quantum - STEAM Results - Countries*




*(a) Quantum - Topic Trends (STEAM Analysis).*




*(b) Quantum - Top Institutions (STEAM Analysis).*

***Figure 2.17:*** *Quantum - STEAM Results - Trends and Top Institutions*

### 2.3.2 Bio and Human Enhancement Technologies

**Bio and Human Enhancement Technologies (BHET, or *Biotechnologies*)**
*Biotechnologies* use organisms, tissues, cells or molecular components derived from living things to act on living things; or act by intervening in the workings of cells or the molecular components of cells, including their genetic material [320]. *Human Enhancement Technologies* (**HET**) are biomedical interventions that improve human form or functioning more than what is necessary to restore or sustain health.

#### Overview

Biotechnology is *"a broad discipline in which biological processes, cells, or cellular components are exploited to develop products and new technologies for specific purposes"*. Biotechnology offers considerable potential for significant impact and opportunities for innovative R&D. A related research area is that of Human Enhancement technologies, *the process to augment physical form or cognitive, physiological, sensory, or social functions beyond baseline performance.*

Biotechnologies have historically been and will continue to be genuinely disruptive, mainly as they apply to human health issues. Nevertheless, this promise is often oversold as human and biological research is necessarily constrained by physical, biological, ethical, legal, and moral constraints. Thus, there is a tendency to overstate the maturity of biotechnology. Its general availability is often overestimated when conceptualising novel innovations such as personalised medicine, Human-Machine Integration (HMI), and direct neuro-interfaces between "wetware" and "hardware". Conversely, biotechnology's potential long-term risks and significant benefits are often misunderstood (e.g. COVID-19 vaccine developments).

Manipulation of our biological environment and human enhancement goes back to the earliest days of humankind when our ancestors employed skins, stones and agriculture to create an evolutionary advantage. However, BHETs are expected to be available over the next 20 years, changing our very definition of what it means to be a soldier, sailor or aviator. These technologies span the spectrum of biological sciences:

Genetic manipulation (e.g. clustered regularly interspaced short palindromic repeats (CRISPR)) to develop novel pathogens or medical countermeasures; Manufacturing methods exploiting biological processes; Human enhancement via integrated robotics (e.g. exoskeletons or replacement parts); Neural interfaces; Enhanced vision; Socio-technical symbiosis with AI and autonomous systems; Pharmacological approaches to cognitive and physical enhancement; Increased virtualization of the socio-cognitive environment supporting the development of new social, information and organizational structures; and, New bio-sensors and bio-informatics will increase our understanding of socio-cognitive, physiological, economic and neurological behaviours to improve operational performance and resilience and increase the effectiveness of non-kinetic targeting.

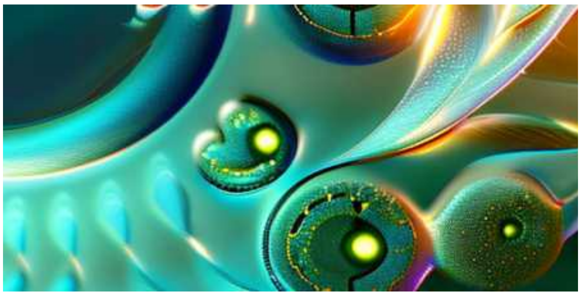
Biotechnology and next-generation human enhancement technologies are in their infancy. However, some commentators have stated that building on the information and (artificial) intelligence revolutions we have already experienced, the next revolutionary technology cycle will be (synthetic) biology-based. The need for NATO to adjust to this new environment (however it may develop) and the capabilities and threats it will engender are not trivial. Of all the strategies and implementation plans NATO expects to deliver over the next few years, biotechnology and human enhancement technologies will be the most challenging.

Disruptive BHET research areas of potential interest to NATO are presented in the following subsections:

#### Biowarfare and Heath

Specific areas of interest are new technologies and science for pathogen identification, stopping pathophysiologic processes of bioagents, new drug classes (e.g. performance and antibiotics), outpacing and preventing disease, biometrics, wound care and regeneration.

#### Genetics and Microbiology



Recent genetics research has focused on developing personalised medicines and curative/preventive treatments for diseases. Weak signals in this area suggest an increasing role for genomic information in the health care of military service members and its integration into the continuum of military medicine. The use of gene-editing technologies such as CRISPR-Cas9 – an enzyme capable of cutting DNA strands has brought increased investigation of other or similar gene-editing tools and means of mitigating accidental or deliberate misuse of gene editing.

Several significant advances are emerging and expected to mature over the next 20 years in the available technologies to obtain genomic knowledge that will help accelerate genome-based discovery for medical and biotechnological applications. These represent advances in the broader field of bioinformatics which is discussed as a separate area in more detail below. However, the trends described here are those that apply mainly to the areas of genetics and microbiology: Interesting research is already ongoing in protection against gene editing, alternative gene editing technologies, next-generation genomic sequencing, metagenomics, and de novo gene sequencing.

#### Bioengineering

Bioengineering describes applying engineering principles of design and analysis to biological systems and biomedical technologies. Emerging research is pursuing new approaches (often AI/ML-enabled) to engineer complex, multi-cellular methods (e.g. reproducing xenobots [321]) for enhanced capabilities and functional materials. Technical progress is also being made in the tools and techniques available for engineering biology. Bioengineering developments will deliver unique and creative applications of engineering principles to analyse biological systems, exploit them (e.g. biomanufacturing) and solve problems in the interaction of such systems.

Bioengineering is expected to become significantly easier and cheaper over the next twenty years, with new developments reducing the biotechnology transaction costs in gene reading, writing, and editing.

In addition, emerging research efforts are refining and extending the ability to engineer complex, multi-cellular systems for enhanced capabilities and functional materials with integrated biological functions. This includes 3D bioprinting, AI/ML-enabled bioengineering, hybrid materials, synthetic bio-mimetic materials, smart materials, and organoids ("brain balls").

#### Systems Biology and Bioinformatics

Systems biology is an approach to interrogating complex biological systems through large-scale quantitative analysis of the dynamic interactions among several components of a biological system. Areas of particular interest are novel CBRN (chemical, biological, radiological and nuclear) biological sensors and computational biology. Enabled by advances in *Data*, AI, RAS, and potentially Quantum, this systems approach and the associated bioinformatics advances in this area will enable other biotechnology and human enhancement technologies. Understanding the fundamental process of biological networks, leveraging big data analytics and AI, and developing new CBRN sensors are just some areas that are expected to mature over the next 20 years.

#### Cognitive Enhancement

Cognitive enhancement is one of the most sought-after and difficult human enhancement technologies. Improving cognitive capabilities relies on enhancing our understanding of the brain's structure and associated cognitive processes. Innovations in data, sensors and the development of brain-machine interfaces are underlying technologies critical in driving this rapidly evolving area. This is expected to continue over the next 20 years. In addition, new developments in brain science will be harnessed to improve cognitive performance and neurological and psychiatric care within military medicine and generate new techniques and technologies for treating brain injury, neurodegenerative diseases, and certain psychiatric conditions, including those likely to affect the armed forces, such as post-traumatic stress disorder.

A significant body of early research focuses on novel methods of cognitive enhancement. This entails cognitive augmentation and focuses on methods of recovery and replacement. Such novel neuroscientific techniques and technologies may, in the future, better enable the treatment and resilience of NATO personnel or optimise their performance, particularly for increasingly arduous and fast-paced operations.

Leveraging Systems Biology advances, predictive network models are emerging as an area of focus that will provide tools to quantify the structure and predict system function. In the future, this could enable the prediction of cognitive function, disease onset or progression, behavioural responses to health messaging, or optimal strategies for early intervention. As these new models of brain functioning emerge, new techniques have been developed to monitor and manipulate neural activity. As these technologies advance, there is hope for new direct interventions to treat neurological diseases and functions, improving post-combat medical care.

Innovations in data, sensors and the development of brain-machine interfaces are underlying vital technologies driving this rapidly evolving area. One specific area of research is cognitive recovery from trauma and augmentation. Innovation and applications are expected to be rapid but constrained by necessary testing protocols and ELM (ethical, legal and moral) considerations.

### Social Enhancement

Social networks and their importance in modern societies are effectively self-evident. Unfortunately, much of the research and development in this area is driven by commercial considerations. However, methods for understanding, modelling, and simulating the dynamics of such systems are becoming increasingly sophisticated and yielding a better understanding of human social behaviour. This sophistication is necessary to predict the emergent properties of such systems better and target social effects, such as disinformation, cognitive, and hybrid warfare campaigns. A second research trend is using "virtual reality" to augment and enhance social interaction. These areas are expected to grow in importance in civil and military applications. Developments in this area should be expected to be closely linked with human-machine teaming.

Research and development of interest will be focused on understanding, modelling, and simulating the dynamics of such systems to predict emergent network properties in the context of disinformation and cognitive warfare campaigns. Virtual reality social reality will continue to expand and deepen.

### Physical Performance

Augmenting physical performance, be this strength, endurance, pain tolerance or fatigue tolerance, has been the objective of militaries for a millennium. R&D will enable significant new approaches to man-machine augmentation and the potential of new pharmaceuticals. New computational methods will predict and optimise drug activity profiles to develop pharmacological interventions capable of modulating multiple targets within the body's biological systems.

### Human-Machine Symbiosis

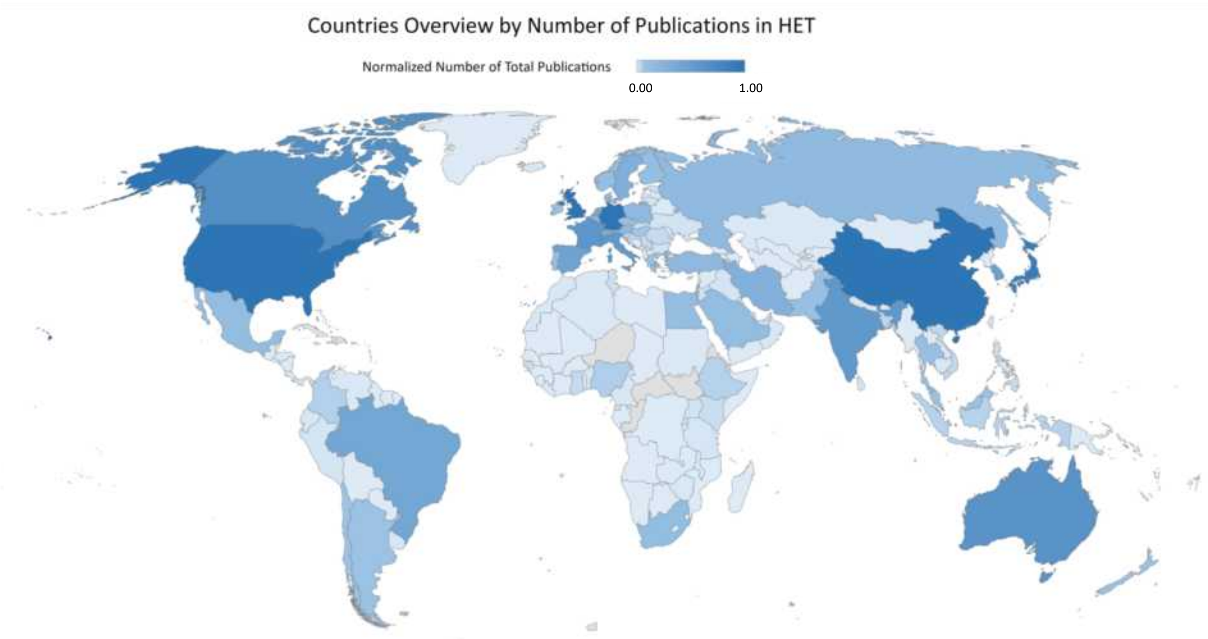
Means for augmenting human performance through mechanical or electronic means have been accelerated through increased use of AI/ML and human-machine interfaces. Areas of particular interest are substituting biological, cognitive functions, computer vision, and augmented reality.

Means for augmenting human performance through mechanical or electronic means have been accelerated through increased use of AI/ML and human-machine interfaces. Areas of particular interest are the substitution of biological, cognitive functions, computer vision, and augmented reality. The advances in this area are underpinned by AI and Machine Learning (AI/ML) methods combined with new recording and manipulation techniques that will allow researchers to study the integration of multiple sensor inputs and their transformation into behavioural output. SWaP-C (size, weight, power and cost) considerations will drive the use and ultimate capability development of sensory and motor augmentation, such as virtual reality contact lenses and exoskeletons.

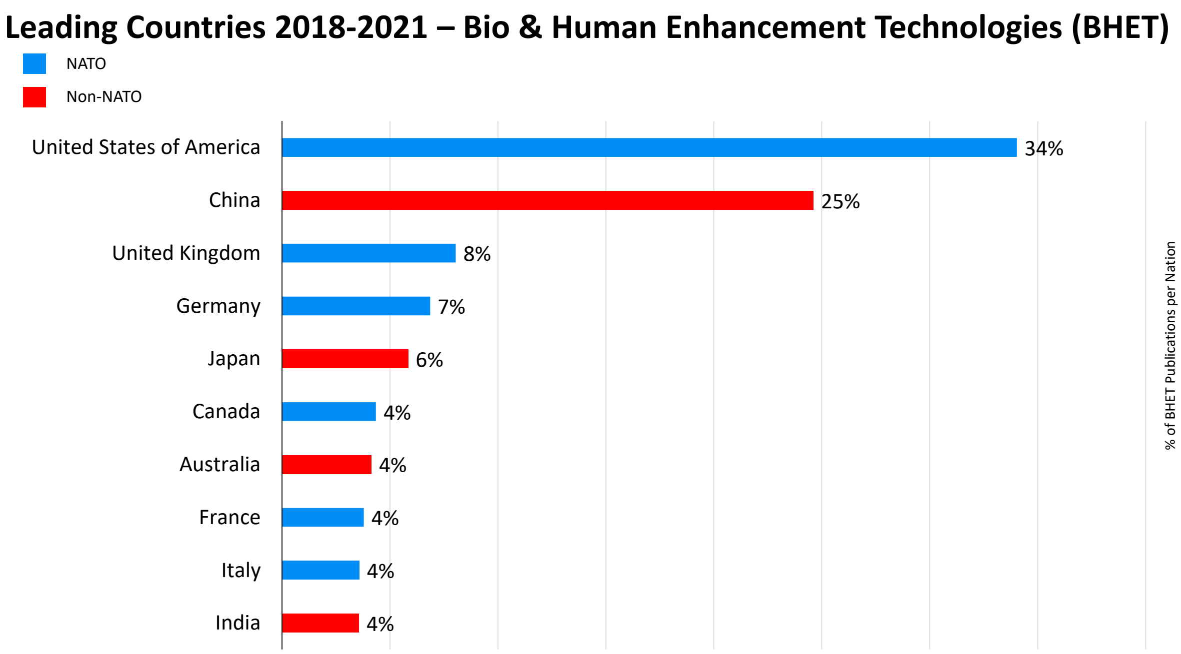
#### Scientometrics

***Table 2.9:*** *Bio and Human Enhancement Technologies (BHET) 2023-2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| BioTech | Bio-engineering & Genetics | High | 5-6 | 2030-2035 |
| | Bio-informatics | High | 7-8 | 2025-2030 |
| | Bio-manufacturing | High | 3-4 | 2030-2035 |
| | Bio-sensors & Bio-electronics | High | 3-4 | 2030-2035 |
| | Cognitive Enhancement | Revolutionary | 3-4 | 2035 or (+) |
| | Human-Machine Symbiosis | Revolutionary | 3-4 | 2035 or (+) |
| | Physical Enhancement | High | 5-6 | 2030-2035 |
| | Social Enhancement | High | 5-6 | 2030-2035 |

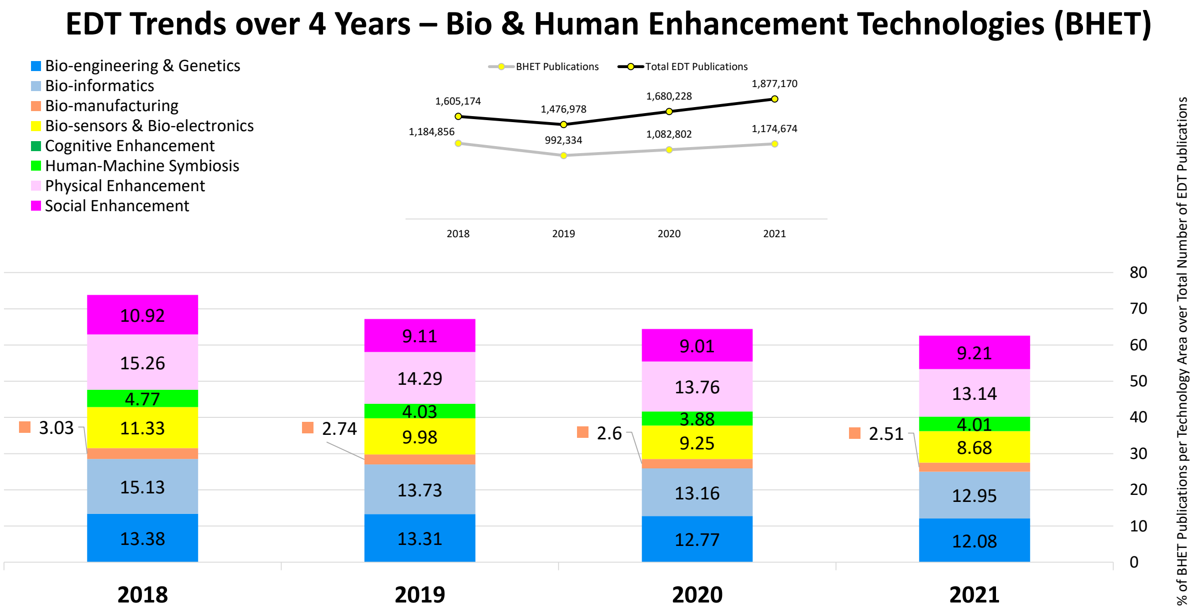



*(a) BHET - Leading Countries (Map) (STEAM Analysis).*

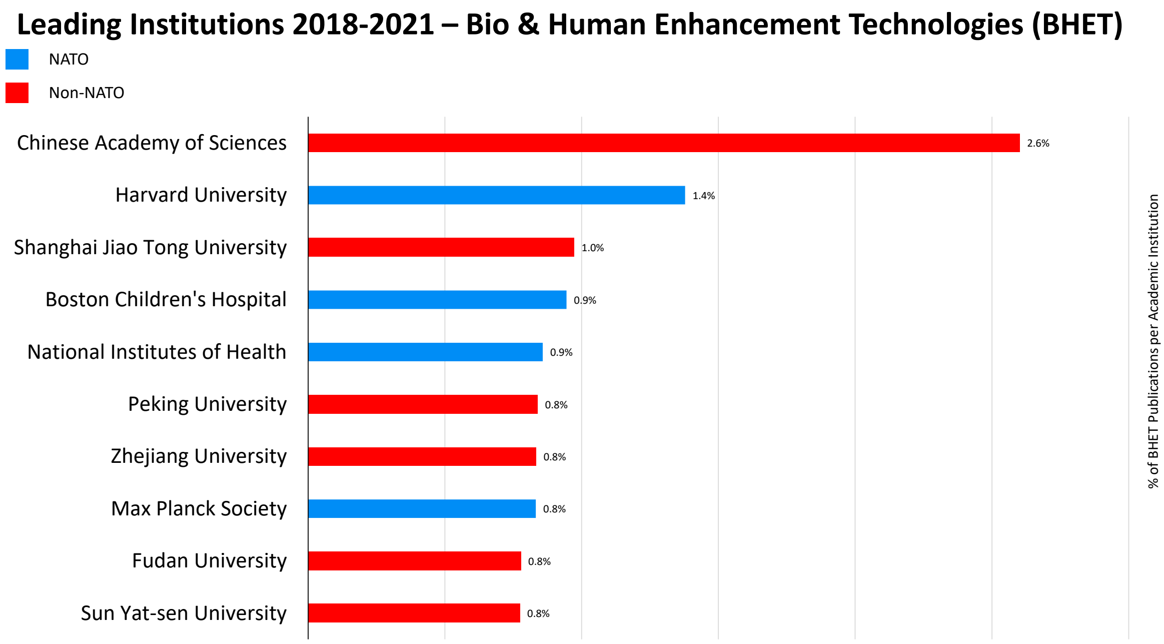



*(b) BHET - Leading Countries (STEAM Analysis).*

***Figure 2.18:*** *BHET - STEAM Results - Countries*




*(a) BHET - Topic Trends (STEAM Analysis).*

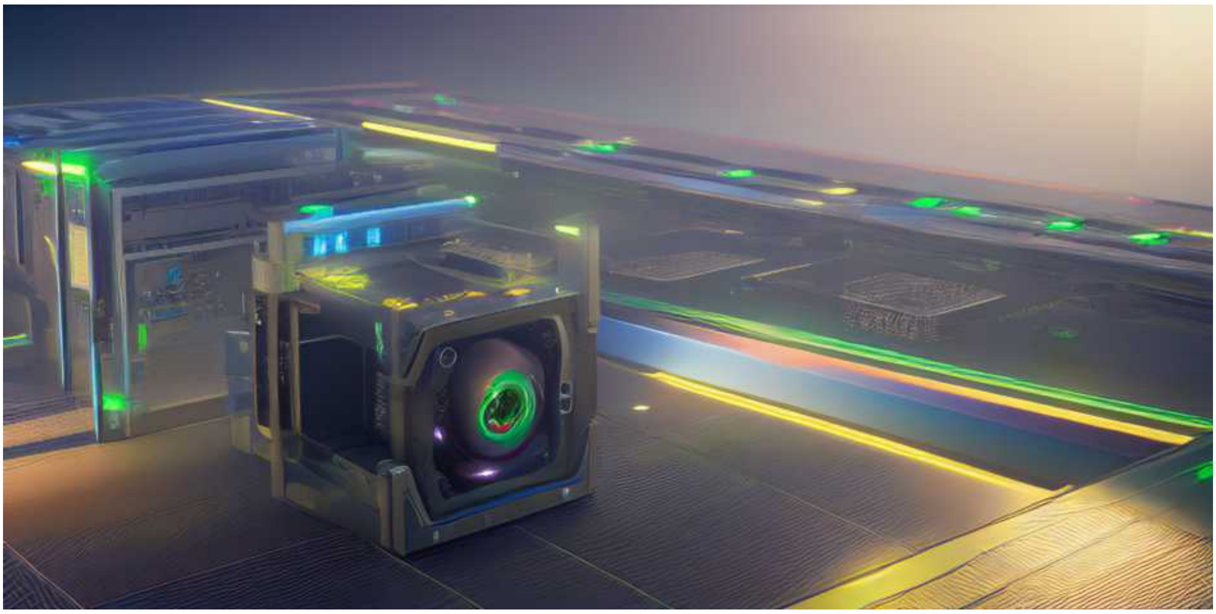



*(b) BHET - Top Institutions (STEAM Analysis).*

***Figure 2.19:*** *BHET - STEAM Results - Trends and Top Institutions*

### 2.3.3 (Novel) Materials and Advanced Manufacturing

**(Novel) Materials and Advanced Manufacturing (or *Materials*)**
*Advanced novel materials* are artificial materials with unique and novel properties. Advanced materials may be manufactured using techniques drawn from nanotechnology or synthetic biology. Development may include coatings with extreme heat resistance, high-strength body or platform armour, stealth coatings, energy harvesting & storage, superconductivity, advanced sensors & decontamination, and bulk food production fuel and building materials. Research into graphene, other novel 2-D materials, and topological materials is an area of high potential and growing interest. *Additive Manufacturing*, which is often used as a synonym for *3-D printing* [322], is the process of creating an almost arbitrary 3D solid object from a digital model through layered addition of materials. Additive Manufacturing can be used for: rapid prototyping; in situ production & repair of deployed military equipment; and production of precision, custom or unique parts.



**Overview**

From Neolithic stone tools to the mastery of iron, steel and aluminium, the advance of civilisation has relied on advances in material science [200, 323, 324]. Moreover, current research and development in the material sciences form the basis for disruptive advances in industry and manufacturing. Such research focuses on designing, developing, assembling, and optimising new and advanced materials and the manufacturing techniques necessary to produce new technologies and electronics. This area has been spurred by advances in Data, analytics, AI/ML, Space, Quantum, Hypersonics and Biotechnologies.

Research benefits in this area include rapid adaptation to changing requirements, on-demand printing, greater efficiency in manufacturing, design and development, platform survivability, new materials or designs unachievable through casting or reductive methods, and nano-to-micron-scale assembly. At the same time, such research is responding to SWaP-C (size, weight, power and cost) challenges generated by other EDTs. Central among these challenges is the need for greener technologies and industrial processes, as well as reduced energy usage.

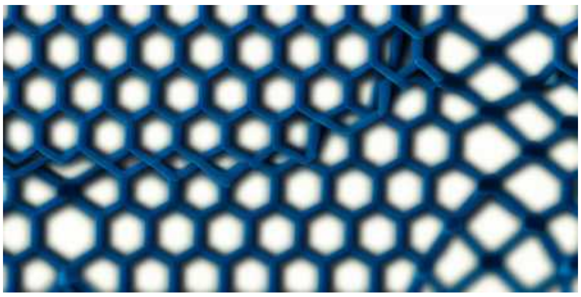
Developments in novel materials and manufacturing are expected to demonstrate disruptive and emergent aspects over the next 20 years [200, 325, 326, 327]. While elements of this EDT, such as agile manufacturing (e.g. 3D/4D printing), are assessed to be highly disruptive in areas of capability development, acquisition and logistics, the underlying technologies are already well in place and continue to be developed, expanded and used at a brisk pace by industry. However, at the cutting edge of research are the development and exploitation of new materials (e.g. graphene first discovered in 2004 and other 2-D materials such as graphyne); quantum nanomaterials [328, 329, 330, 331, 332] new material properties [333]; production of hitherto *impossible* designs; new manufacturing methods (e.g. biotechnology-based [334]); nano-scale manipulation of materials; mixed materials printing; and, the use of AI and *Data* (as in big data and advanced analytics) to find new materials with novel properties. These research areas are driven by a desire to discover or exploit new and unique physical properties (e.g. superconductivity), provide environmentally friendly options and address SWaP-C (size, weight, power and cost) challenges (e.g. energy).

Advances in this area of research can be categorised into two broad groups: **Novel Materials** and **Advanced Manufacturing**. Materials research areas of potential interest to NATO are presented in the following subsections:

### Novel Materials

Interesting areas include new 2D materials (beyond graphene) such as graphyne, novel polymers, nanomaterials, and meta-materials.

Materials research underlies much of the advancement of modern technology from electronics to clothes (e.g. nylon). Nevertheless, materials' properties and behaviours often constrain these technologies. As a result, breakthroughs in the material sciences have the opportunity to generate considerable impact across the technological landscape. A few of the most interesting and potentially disruptive will be considered.



First, 2-D materials host considerable promise for truly disruptive effects. Graphene, the quintessential 2-D material, was initially unequivocally isolated in 2004. Graphene is one of the thinnest, strongest, stiffest, and more stretchable crystal materials [335]. As a result, 2D materials are an area of intense research and development, focused on exploring the unique properties of graphene and similar 2-D materials, such as another form of carbon called graphyne [336, 337, 338]. Because of these properties, there is intense interest in identifying alternative 2-D materials. Recently eight new materials have been identified that have a structure similar to graphene [100]: antimonene [339, 340, 341], arsenene (a single-layer buckled honeycomb structure of arsenic) [342, 343], bismuthine [344], borophane [345, 346], borophene [347], phagraphene [348], phosphorene[349] and stanene [350, 351, 352]. Other similar 2-D materials such as Cr2ge2te6 [353], Rhenim Disulfide [354], Titanium Carbides [355] and Molybdenum ditelluride [356] have unique optical, ferromagnetic, physical or electrical properties. A search for unique electronic, optical and physical properties and applications in areas such as electronics and energy storage drives further exploration. These unique properties are especially useful for potential defence and security applications.

Polymers are integral and essential to modern economies and militaries, [357] and have been intensely studied for over a century. Nevertheless, there are several notable research areas [358]: the creation of complex topological structures, functional polymer materials, sustainable materials, biopolymers and self-healing polymers.

Nanomaterials, are materials with nano-scale (one-billionth of a meter) features may exhibit unique optical, electronic, biological or mechanical properties. Two critical research areas are [330, 331, 343, 359]: bionanomaterials and quantum dots.

Metamaterials are another area of intense R&D [360, 361, 362]: Originally developed in the early 2000s, metamaterials are functional engineered materials, employing distinctive physical structures or patterns to enable optical, acoustic and broad electromagnetic material properties not otherwise found naturally. This allows unparalleled control to direct and manipulate waves, be they electromagnetic or acoustic. Research areas of special interest are in acoustic, electromagnetic, and dynamic metamaterials.

As already noted, a considerable range of research is being conducted to develop new materials, not all of which fall neatly into the categories defined above. Some of the more exciting developments are occurring in the areas of superconductors, harsh weather, ultra-lightweight composites, nano-scale, and eco-friendly materials.

### Advanced Manufacturing

Advanced manufacturing methods cover many techniques more attuned to sustained advances in well-defined innovation processes. However, it would be misleading to see developments in this EDT as simply part of the normal refinement of industrial processes. Several technologies are being developed that are emerging as significant disruptors. Two are of particular note for their potentially disruptive effects on NATO: **3D/4D Printing** and **Biomanufacturing**.

3D Printing and the additive manufacturing process it supports entered the mainstream of manufacturing and public consciousness in early 2000. While the terms are often used interchangeably, 3D-print adds materials in an iterative process to build up objects from digital models. At the same time, additive manufacturing uses 3D printing at an industrial scale to manufacture products [363]. Over the last few years, significant research advances have been made [364] in printing methods, devices, materials development, printing process and post-process modifications [365]. Novel applications and new methods continue to develop rapidly and are areas of intense research. One promising application area is based on biomimetics, e.g. replicating biological structures through 3D printing [366].

The increased use of 3D printing can potentially be highly disruptive in a defence context. For example, production lines of equipment and vehicles are currently closed down after production ceases. This means all spare parts must be produced before the line is closed. Consequently, military equipment is often retired and made surplus once the ability to find spares ceases to be cost-effective. 3D printing theoretically would be able to recreate new parts as long as the digital models are available, thereby extending the life of major pieces of equipment. Similarly, production lines could be re-established quickly and effectively.

First developed in 2013, 3D printed materials that transform under changing environmental stimuli such as pressure, heat, pH, light, humidity, or temperature are called 4D printed materials [100, 367, 368]. Such materials hold promise for new designs or sensors, especially in biomedical applications such as biomedical robots, tissue engineering or bio-scaffolds. [369, 370, 371].

One of 3D-printing's biggest potential applications is biomedical, where living tissue (bone, skin, organs, etc.) is printed using 3D printers, and the printing of customized and designer drug tablets on demand, bespoke medial appliances or biological scaffolding [372]. Such technologies can revolutionise medical treatments, and combat casualty care, especially in forward medical units and for rehabilitation [100].

While additive manufacturing methods such as 3D/4D printing continue to develop, new ways of nano and micro-assembly are being explored, looking to synthesise, assemble and construct materials from the atomic to the macro product scale, seeing potential application in energetics, optics, and therapeutics, electronics [373, 374, 375] and other micro-nano printing applications. Printing and assembly of nano-micro scale materials, so-called nanofabrication [376], is being used for a variety of purposes, including the development of small-scale ultra-thin optics, miniaturised batteries and electronics, quantum dot synthesis, DNA origami-directed assembly, nano sub-assemblies of larger objects and nanoscale structures [377].

On a larger scale, 3D-printed extruded concrete provides a very high degree of design flexibility and structural options for large buildings, especially those with complex geometries [100, 378, 379]. This may significantly reduce construction costs, increase deployment options for buildings in operational areas, and potentially reduce the costs for garrison locales. This technology is particularly disruptive in emergency shelters or extra-terrestrial habitation using locally sourced materials, allowing reduced costs and viable habitats for human habitation on the moon or other such bodies [380, 381]. 3D printing of nano-ceramics [382] is also being explored and is a very challenging process.

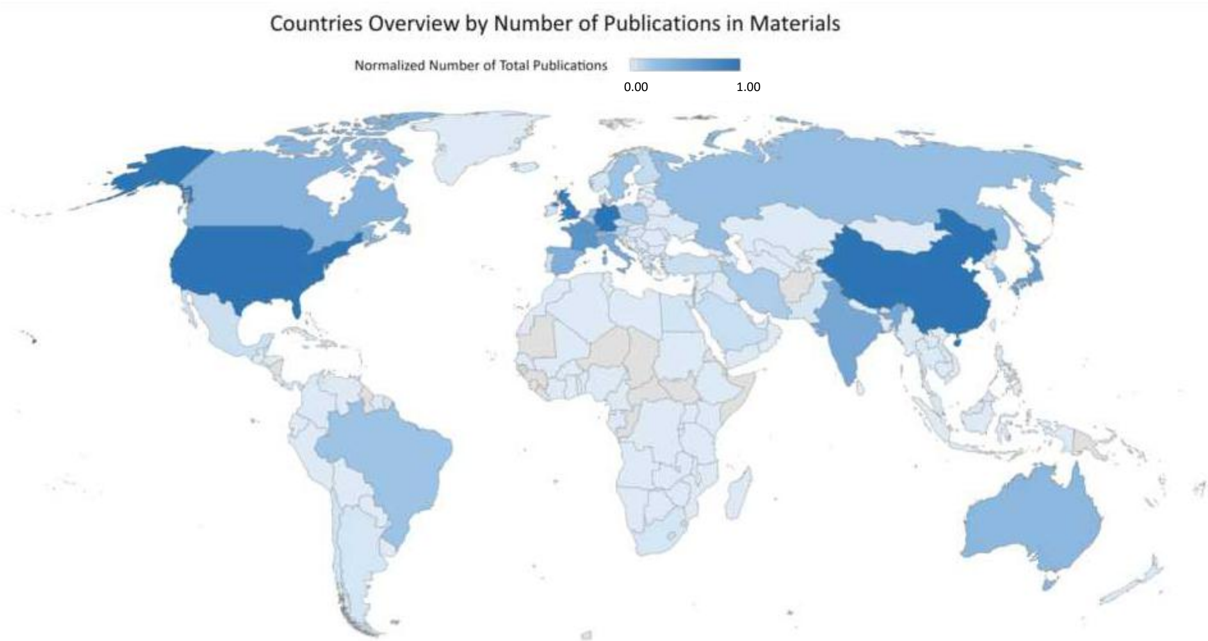
The means of 3D printing vary widely and are highly material-dependent. Depositional methods using polymers are well-established and widely used. However, two new approaches and applications are being explored: robocasting and wire arc additive printing. Robocasting employs a movable nozzle that extrudes a thin filament of paste material [100]. Applications are especially rich in wearables, soft robotics and medicine [383]. Wire arc additive printing uses wire source materials, which are then melted and deposited in layers in a manner already well-developed for plastics. The advantage of such a method is that it lowers the cost and time for fabricating complex homogenous or mixed metal parts, a valuable property to support repair and maintenance facilities in operational theatres.

A completely different approach to manufacturing leverages biological processes with wide application [384, 385, 386, 387, 388]. Such biomanufacturing or bio-fabrication leverages the growing success of new biotechnologies for industrial-level production and manufacturing. While such methods go back millennia to the invention of beer and wine, direct manipulation and engineering of biological systems have opened new approaches and opportunities. This area of research allows for unique fabrication and manufacturing capabilities for the large-scale production of materials, chemicals and pharmaceuticals. Simplistically, biological systems are engineered to produce a product [389] by creating new biological constructs (genes, cells or organisms) or modifying existing biological entities. Biomanufacturing methods hold great promise in energy reduction, increased innovation, reduced raw material needs and sustainability [390, 384], but may also present unknown health and safety risks. Areas of particular note are the use of biomanufacturing for construction (bio-cementation and bio-remediation), electronics (thin flexible substrates), consumer products (thereby reducing wastes), food manufacturing and pharmaceuticals. An application of particular interest is using microbial capabilities for bio-production in space [390], e.g. the B-SURE program in DARPA.

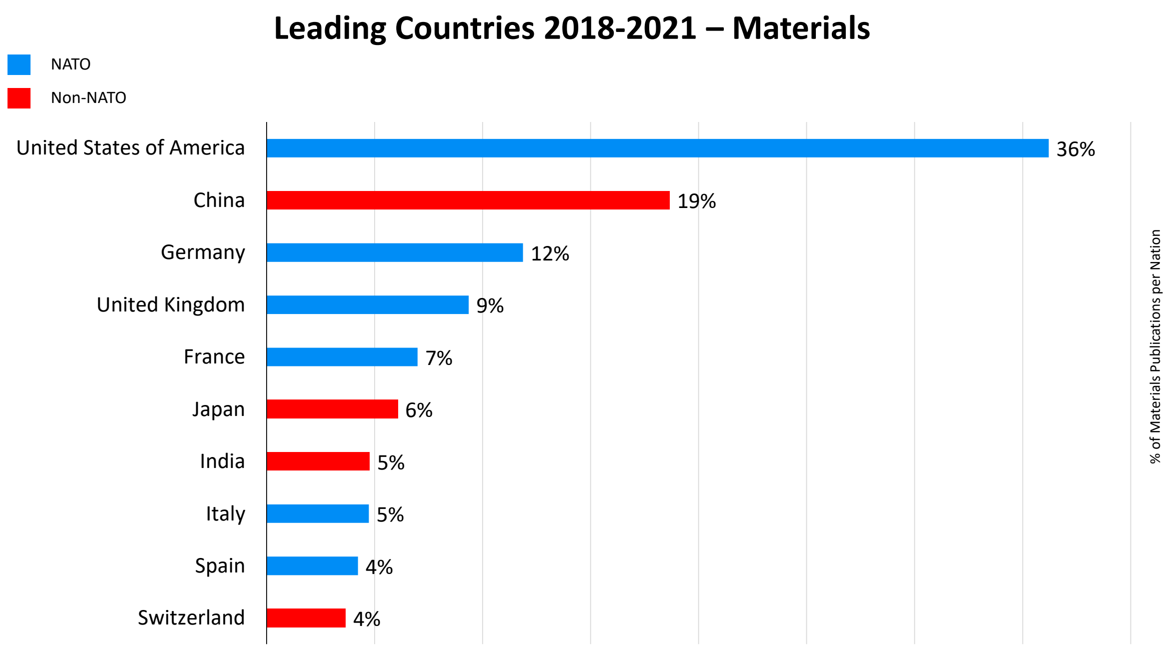
### Scientometrics

***Table 2.10:*** *Novel Materials and Advanced Manufacturing: 2023-2043.*

| EDT | Technology Focus Areas | Impact | TRL | Horizon |
|---|---|---|---|---|
| Materials | Nano-materials & Nano-manufacturing | High | 5-6 | 2025-2030 |
| | Novel Design & Additive Manufacturing | High | 5-6 | 2025-2030 |
| | Novel Materials | High | 3-4 | 2030-2035 |

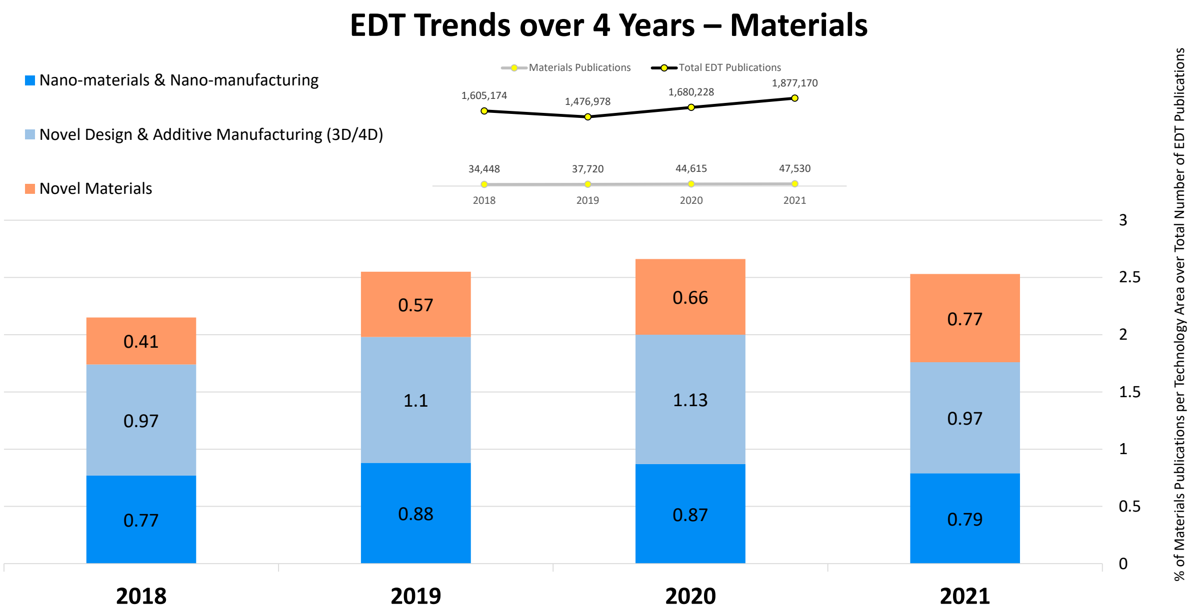



*(a) Materials - Leading Countries (Map) (STEAM Analysis).*

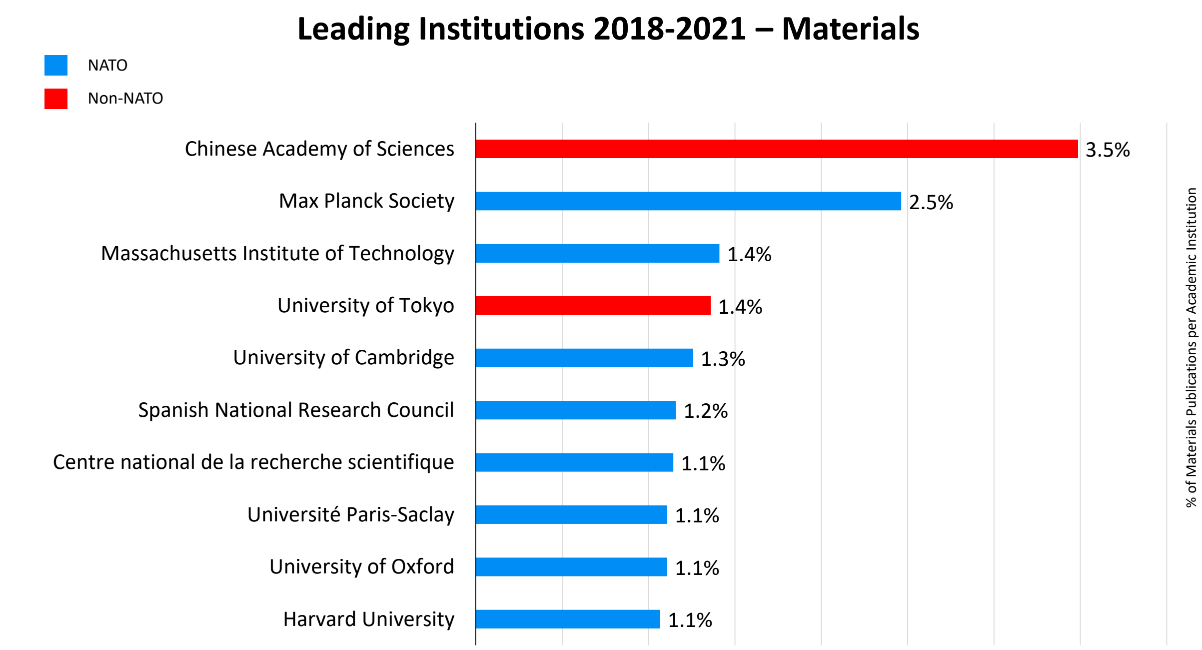



*(b) Materials - Leading Countries (STEAM Analysis).*

***Figure 2.20:*** *Novel Materials and Advanced Manufacturing (*Materials*) - STEAM Results - Countries*




*(a) Materials - Topic Trends (STEAM Analysis).*




*(b) Materials - Top Institutions (STEAM Analysis).*

***Figure 2.21:*** *Novel Materials and Advanced Manufacturing* (Materials) - *STEAM Results - Trends and Top Institutions*

## 2.4 Convergence, Inter-Dependencies and Synergies

EDTs rarely create an impact in isolation. Instead, they are most disruptive at the boundaries of the physical, information or human domains or where these EDTs overlap or converge. These synergies, serendipity, and explicit inter-dependencies between the following EDT groups are projected to be especially important in developing future capabilities. It is impossible to fully characterise all combinations of these EDTs, but six are potentially the most disruptive.

### 2.4.1 Data-AI-Autonomy

The synergistic combination of Autonomy, *Data* and AI is expected to have the largest disruptive effect on the Alliance and its military capabilities over the next ten years. Increased use of intelligent, widely distributed, ubiquitous, cheap, interconnected sensors and autonomous entities (physical or virtual) will lead to volumes of data that are virtually impossible to analyse by current methodologies and approaches. Interrelated technologies and methods will underlie solutions to these problems. Such technologies include 5G (and similar communication technologies), cognitive EM (electromagnetic) management, the internet-of-things (IoT), the AI-of-things (AIoT) [391], better battery technologies and even 3-D printing. Such changes, coupled with supporting space, bio- and quantum technological developments, can create a NATO strategic and operational decision advantage, leading to the need for new cyber and memetic warfare concepts and capabilities [38, 392].

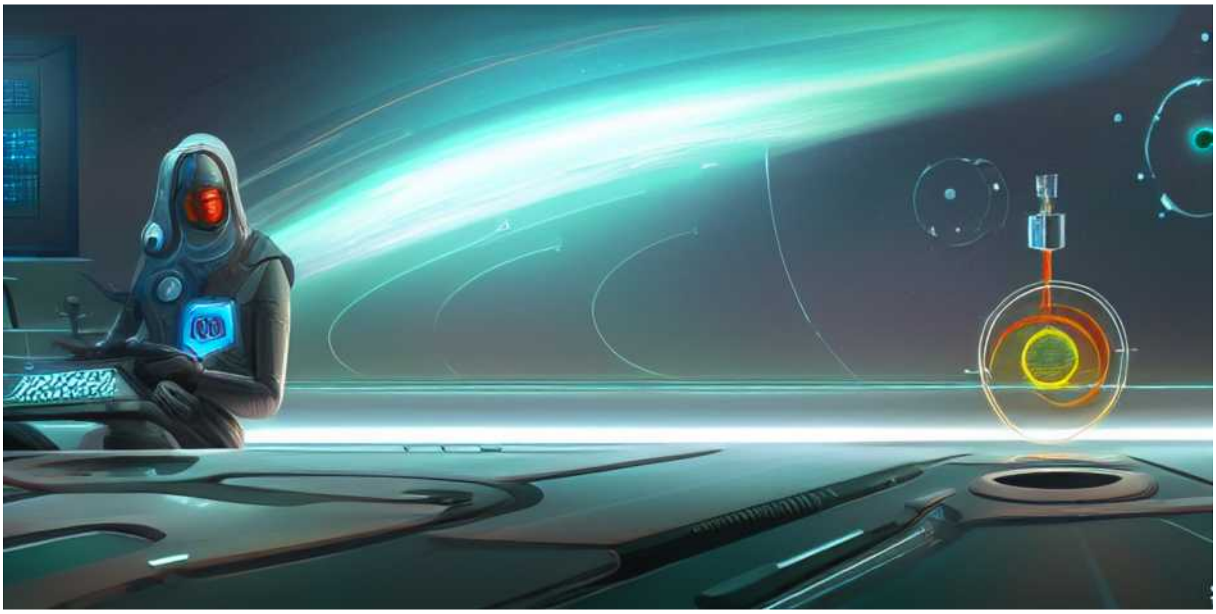
### 2.4.2 Data-Quantum

Over a 15 - 20 year horizon, quantum technologies will greatly increase C4ISR data collection, processing and exploitation capabilities through greatly increased sensor capabilities, secure communications, and computing. In particular, quantum computing may greatly improve modelling & simulation speed and fidelity for predictive analytics and enable a quantum approach to deep learning neural networks for greatly enhanced AI and data analytics. This increased computational and simulation capability will also significantly impact the conduct of Alliance S&T through a meta-analysis of existing science and the simulation of quantum-dominated systems. This capability will, in turn, lead to the discovery of new fundamental and applied science, novel designs, purpose-built genes or organisms, and identification of novel material, chemical and biological properties. All of these have the potential to generate disruptive effects beyond 2040.

### 2.4.3 Space-Hypersonics-Materials

Space and Hypersonics present challenging operational domains. The development of exotic materials, novel designs, miniaturisation, energy storage, manufacturing methods, and propulsion will be necessary if space and hypersonic systems fully exploit these domains' inherent advantages and opportunities. In addition, space and hypersonic systems share many of the same environmental challenges. The development of new cheap, strong and exceptionally heat-resistant materials will be essential to develop practical and affordable systems. The increased use of 3D/4D printing will also be critical as printing important parts (e.g. engines) will help reduce costs and increase reliability.

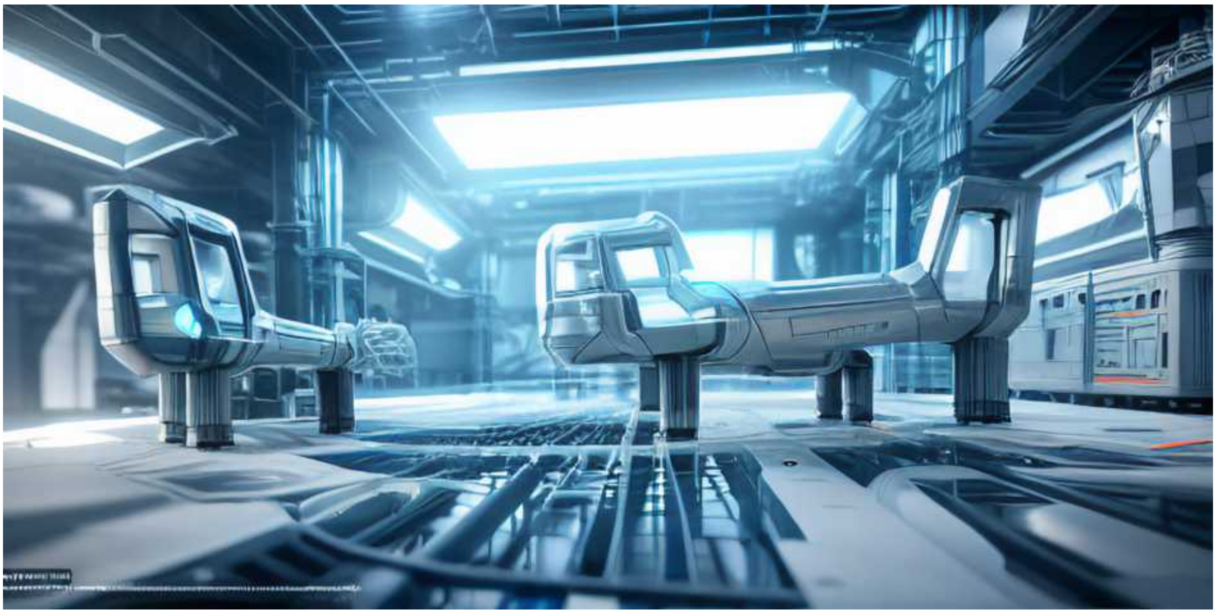
### 2.4.4 Space-Quantum



Space-based quantum sensors, facilitated by QKD communication, will lead to entirely different classes of sensors suitable for deployment on satellites. Currently, power limitations and sensor sensitivity significantly impact satellite design and operation. Smaller, lower power, more sensitive and distributed space-based sensor networks enabled by next-generation quantum technologies will be essential to NATO's future ISR architecture in 20 years.

The development of large-scale satellite relayed QKD quantum communication (QC) networks [393] will be essential if the Alliance maintains a fully secured global communication network. Satellite-to-Earth QC has already been demonstrated for ranges over 5000km. China is developing several extremely ambitious demonstration projects. Over the next 5 - 10 years, technological developments are expected to expand these early experiments and provide the technical framework for robust commercial capabilities.

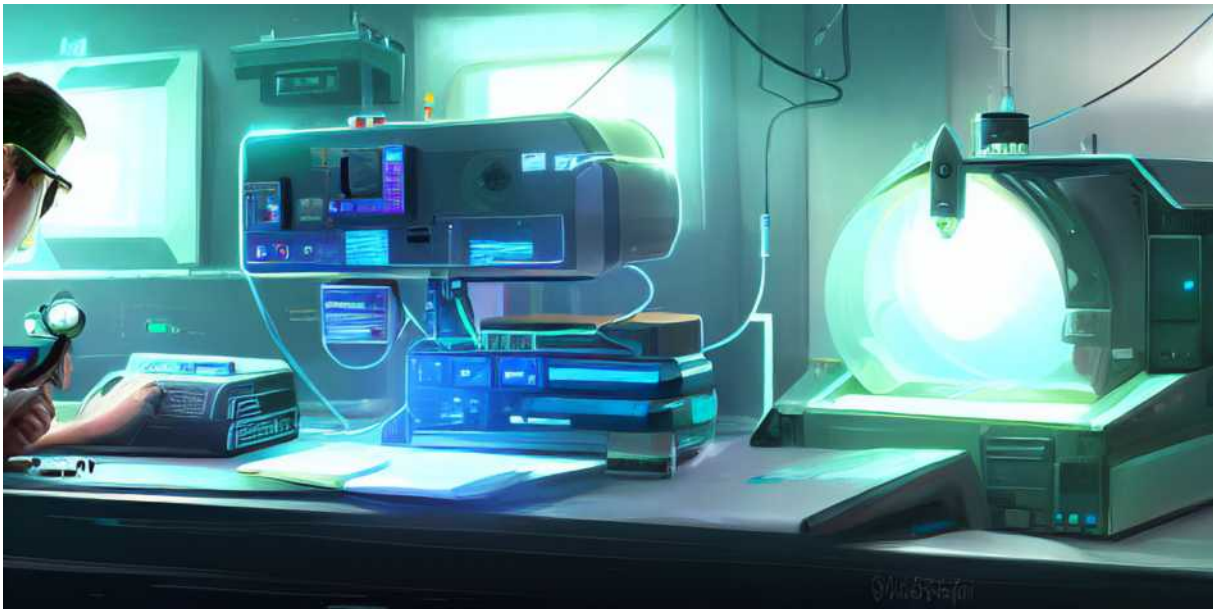
### 2.4.5 Data-AI-Biotechnologies



AI and biotechnology are developing exponentially, driven by greatly reduced costs, increased speeds, and rising commercial interest [92]. For example, the original human genome project took ten months and cost USD 3 billion (in 2001). Today, it takes less than one hour and costs about $1000 (USD) to decipher a human genome [92].

AI, in-concert with *Data* and biotechnology, will have an outsized impact on the world's economy and health. Such a combination of EDTs will greatly contribute to the design and discovery of new drugs, purposeful genetic modifications, direct manipulation of biochemical reactions, development of optimised biological agents, living sensors, new CBRN countermeasures and identification (through meta-analysis) of new research areas. The use of AI to optimise the design of new biological agents molecule-by-molecule or cell-by-cell will greatly expand our ability to tailor-make new pharmaceuticals (e.g. [394]) as well as create new means of manufacturing for sensing. Such disruption will not be confined to the bio-sciences but mirrored across all areas of S&T development.

### 2.4.6 Data-AI-Materials



AI, in-concert with *Data*, will contribute to the design of new materials, the identification and design of unique physical properties (e.g. [395, 396]), direct manipulation of chemical reactions, creation of novel structures and identification (through meta-analysis) of new research areas. This will support further development of 2-D materials. This disruption will be mirrored across all areas of S&T development.

AI and *Data*, combined with 3D/4D printing or bio-manufacturing, will push production towards the edge (e.g. the user) and facilitate the development of reliable, tailored, mixed material manufactured products.

### 2.4.7 Energy-Materials-AI

New developments in energy storage, driven by novel materials such as graphene and exotic battery chemistry, as well as stronger lightweight materials and novel designs (e.g. massive castings, super-capacitors or 3D printing), will continue to drive electrification or the use of green fuels (e.g. hydrogen and biofuels) in military operations. AI to support these designs and material developments and optimise energy use will contribute to the greening of NATO forces.

## 2.5 Countering EDT Threats

RED forces are themselves complex and adaptive. It is misleading to consider the RED force development of EDTs as a simple mirror of BLUE force development. Potential asymmetric and peer/near-peer competitors will take differing exploitation paths and may potentially target novel applications in the physical, human or information domains.

Nevertheless, for every military capability, there are eventually counter-measures and counter-counter-measures. Therefore, even with strict national, legal, and ethical limits to deploying such capabilities, Alliance nations must conduct appropriate S&T in these areas to develop such countermeasures. For example, this has been and will continue to be the case for CBRN threats, where (medical) countermeasures have been developed and, in some cases, have yielded significant benefits in the fight against virulent diseases such as Ebola [397, 398, 399].

The development of countermeasures for each advantage an EDT may provide must also be considered within the NATO capability development process. As technology is increasingly globalised and democratised, the life span of a technological advantage may become increasingly short. Therefore, operational success will come to those best able to integrate EDTs within the enterprise and operational functions effectively and those who continue to push the technological edge.

## 2.6 Summary

As an *"alliance of the willing"*, NATO was founded upon the principle that mutual security requires close and continuous contact between military and civilian elements of power, a focus on defence collaboration and burden sharing, and a recognition that alliance operational success is built upon a bedrock of common scientific and technological development. Leveraging the current perfect storm of intelligent, interconnected, decentralised, and digital technologies will be essential. For almost 70 years, the ability of the alliance to focus international collaboration on mission-oriented S&T of interest to the nations has been one of its central strengths.

The need to evolve and prioritise short-term and long-term national and alliance investments across current and future essential operational and S&T capabilities is an enduring challenge. A focus on more effective, efficient and coherent operational capabilities and relevant S&T investments are essential if mutual reliance and seamless interoperability are achieved. It is, therefore, vital for the Alliance and the nations to understand the potential impact, the current level of hype, readiness, operational applicability, and synergies associated with each EDT. As noted by Possony and Pournelle [7], there is little choice but to adapt to this environment:

> *"The primary fact about technology in the twentieth century is that it has a momentum of its own. Although the technological stream can be directed, it is impossible to dam it, the stream flows endlessly. This leaves only three choices. You may swim with the stream, exploiting every aspect of technology to its fullest; you may attempt to crawl out on the bank and watch the rest of the world go past, or you can attempt to swim against the stream and "put the genie back in the bottle"... The research does not create technology but is merely one of technology's major prerequisites, and technology alone cannot guarantee national survival."*

EDTs are poised to have a significant effect (positive and negative) on the Alliance over the next 20 years. However, productive employment of these new technologies will pose severe challenges and raise fundamental questions of ethics and legality. Expanded use of AI, *Data* and Autonomy will provide greater access to critical operationally relevant data and knowledge, but at the risk of the *fog of more*. Information itself will increasingly become a warfighting domain and a commodity. In parallel, using automated and potentially autonomous systems in operations where humans are not directly involved in the decision cycle will become more widespread and increase the pace of strategic competition.

Despite these potential leaps in innovation, the evolving battlespace will continue to feature a mix of old legacy and new weapon systems. This mix may challenge the Alliance's ability to fight together. Technological gaps will challenge connectivity, communications, doctrine, legal, and interoperability. Capability and capacity mismatches and shortfalls are expected as nations come to terms with the implications of these new technologies.

Technological advances coupled with demographic changes will place a premium on developing the right human capital capable of leading and operating across all domains, including strategic, operational and tactical levels, and across multiple terrains.

While it is likely that the Alliance will maintain a degree of technological advantage in some EDT areas, EDTs (in particular AI, Big Data, Biotechnology, and Hypersonicss) will likely become cheaper and more accessible to hostile actors. The Alliance's dependence on advanced technology could become a liability if care is not taken on how they are integrated and in developing countermeasures. Allies must be prepared to operate practically (credible, aware, networked, agile and resilient). EDTs will need to be aligned with NATO military functions (prepare, project, protect, engage, sustain, C3 and inform) and development must be focused on achieving desired military effects (assure, contain, deter, defeat, defend, deny, stabilise and transform). We must understand the nature of these new technologies, analyse their implications for defence and security, explore the opportunities they offer, push the boundaries of what is possible, and ensure that we are ready to mitigate their risks. By its international and collaborative nature, NATO is well-placed to consider these issues.

The development of an EDT is rarely, if ever, constant in speed or unerring in its path towards practical application, either in the military or civilian spheres. How the underlying science and resulting technologies will develop, what complex interactions they will have with one another, and ultimately what military capabilities they will enable or engender is fundamentally uncertain either in result or timeline. Nevertheless, much as the former US President and NATO's first Supreme Allied Commander Europe (SACEUR) Dwight D. Eisenhower said *"Plans are worthless, but planning is everything"* [400], the *process* of forecasting S&T trends prepares NATO for the associated opportunities and risks presented by these technologies.

# 3. Contextual Trends

**Science in Context**
"Science has become an integral and most important part of our civilisation, and scientific work means contributing to its development. Science in our technical age has social, economic, and political functions, and however remote one's own work is from technical application, it is a link in the chain of actions and decisions which determine the fate of the human race." — *Max Born* [401]

## 3.1 Introduction

S&T developments do not take place in a vacuum, as they are driven by strategic, technological, individual, economic, societal and organisational needs and trends. In turn, these S&T developments create events that fundamentally change societies/individuals and force the evolution of organisations and governments. Therefore, understanding the forces that generate these developments is an essential first step in assessing future technological and scientific disruption.

This chapter presents a brief contextual overview of key global and strategic forces driving technological progress. It draws on several future studies and NATO documents, including [402, 410, 411, 412, 413, 414, 415, 416, 417, 403, 404, 405, 406, 407, 408, 409]. More specifically, this chapter seeks to address the following questions:

- What do we mean by an agile and innovative Alliance?
- How can NATO explore, develop and exploit the best cutting-edge technology to deliver disruptive military effects for the Alliance?
- What geostrategic issues do we need to consider as well that may impact or be impacted by the development of these technologies?

## 3.2 Geostrategic

The world has changed significantly over the last decade. Interstate competition, an unstable international economy, multi-domain operations, existential shocks (e.g. pandemics and climate change) and techno-authoritarianism have changed the strategic landscape. However, the defining characteristic of the last three years has been increased strategic competition between the NATO Alliance and Russia / China [410]. In response, NATO has adopted a new Strategic Concept [418] based on extensive international collaboration and coordination. Second, only to the North Atlantic Treaty, the new Strategic Concept reasserts NATO's commitment to its values, purpose and mission and provides an agreed understanding of the broad security environment. Third, as a foundational document, it defines and drives NATO's strategic adaption and institutional agility, responding to Russian aggression in Ukraine, a nationalist agenda from the People's Republic of China (PRC), continued terrorist activities, technological challenges and technological challenges and the threat posed by global warming. Further, it underscores the key purpose and greatest institutional responsibility of NATO: to ensure the collective defence of Allies against all threats and from all directions.

The Concept defines three core tasks: 1) *Deterrence and Defence*; 2) *Crisis Prevention and Management*; and, 3) *Cooperative Security*.


***Figure 3.1:*** *NATO 2022 Strategic Concept [CREDIT: NATO]*

NATO and the nations have expressed their fundamental interest in a strong, independent Ukraine. Unfortunately, the current conflict has reintroduced the world to the horrors of armed interstate strife in Europe. Russian actions have shattered the peace and security, which have been the hallmark of an evolving Europe over the last 20 years. NATO no longer considers Russia a partner but a threat to be addressed through increased vigilance, deterrence and institutional resilience. NATO's response to the destabilisation of its eastern flank has been dictated solely by Russia's action. Thus NATO has agreed to deploy fully combat-ready forces, up to brigade-size, on its eastern flank. At the same time, it will introduce a new NATO force model and ensure enhanced rapid response through collective defence exercises. Despite these actions, as a defensive alliance, NATO remains open to communication, collaboration and partnership with Russia. NATO is a threat to no nation. Alliance nations desire only the stability and safety of their members and are united in respect for international laws and mutual benefit.

In contrast to Russia, the People's Republic of China (PRC) is seen by NATO as a rising strategic power. The PRC is not a direct threat to NATO, but its stated policies, techno-authoritarianism, nationalism, industrial espionage, expansionist behaviour, coercion, and aggressive militarism challenge the international order. China's values and security interests present a clear long-term challenge to Euro-Atlantic security, albeit with its own significant long-term internal challenges and contradictions.

Terrorism, while diminished, remains a threat to NATO nations. This threat arises from all angles of the political and religious spectrum, external and internal to Alliance Nations. The withdrawal from Afghanistan, the rebirth of the Taliban, unrest in Iraq, Mali and Syria, as well as the destabilising influence of Iran are of particular concern. This threat is asymmetric and evolutionary in its tactics, capabilities and reach. Moreover, it is driven in no small measure by human insecurity and humanitarian challenges.

To counter these threats, the Strategic Concept reinforces the critical nature of national, institutional and Alliance-wide resilience and efforts to safeguard our societies, as it underpins all three core tasks. It also means mitigating strategic vulnerabilities and dependencies such as critically important reliable energy supply and sources, countering disinformation and malign influence, and ensuring open standards and availability of strategic materials. To ensure this is the case, NATO strives to adapt to new operational domains, including cyber, space and hybrid, contested and under the malign influence of authoritarian actors. The Strategic Concept underlines the potential of malicious cyber or space-directed activities or operations and hybrid operations to reach the level of an armed attack, leading to the invocation of Article 5 of the North Atlantic Treaty.

NATO's new Strategic Concept emphasises its increased efforts to anticipate and prevent crises and conflicts, building on expertise and capabilities acquired in the last three decades. Human security will be central to this approach, as well as deterrence and disarmament. Unfortunately, the Alliance recognises the negative impact of the erosion of the arms control, disarmament and non-proliferation architecture on strategic stability. Consequently, NATO's strategic nuclear forces remain the supreme guarantee of security for the Alliance, with the fundamental purpose of preserving peace, preventing coercion and deterring aggression.

NATO has noted that Cooperative security makes it stronger and contributes to stability beyond its borders. Accordingly, NATO is strengthening its ties with partners with common values and interests, especially in upholding the rules-based international order – both around the globe and in our neighbourhood. NATO is committed to an Open Door Policy, reaffirmed by the Madrid invitation to Finland and Sweden to join the Alliance and its ambition to enhance the NATO-EU strategic partnership.

Finally, climate change is an existential threat to Alliance security, both as a generator of instability and threat multiplier and as an operational challenge. NATO has clearly stated that integrating the implications of climate change, human security and the Women, Peace and Security agenda will be critical across NATO's three core tasks. In particular, this will require NATO to adapt to changing operational environment, new security challenges (e.g. famine, environmental disasters and human migration), and the opportunity to transition to new energy solutions.

The defence and security environment is changing [47] driven by the evolving nature of conflict and geopolitical factors. *Chaos*, *complexity* and *competition* [419] are said to be the defining characteristics of this future. Through its new Strategic Concepts and its follow-on strategies, NATO is adapting.

Two decades after the fall of the Berlin Wall, the potential for great power competition [420, 421, 422] is greater than ever and is arguably here already, given recent tensions in the Asia Pacific and the war in Ukraine. As stated in the 2022 NATO Madrid Summit Declaration:


***Figure 3.2:*** *The NATO Secretary-General Jens Stoltenberg at the NATO Summit - Madrid 2022 (CREDIT: NATO).*

> *"We continue to face distinct threats from all strategic directions. The Russian Federation is the most significant and direct threat to the Allies' security and peace and stability in the Euro-Atlantic area. Terrorism, in all its forms and manifestations, continues to pose a direct threat to the security of our populations and international stability and prosperity. We categorically reject and condemn terrorism in the strongest possible terms. With determination, resolve, and solidarity, Allies will continue to counter Russian threats and respond to its hostile actions and fight terrorism in a manner consistent with international law ... We are confronted by cyber, space, and hybrid*

*and other asymmetric threats, and by the malicious use of emerging and disruptive technologies. We face systemic competition from those, including the People's Republic of China, who challenge our interests, security, and values and seek to undermine the rules-based international order. Instability beyond our borders also contributes to irregular migration and human trafficking."*

The NATO Secretary-General Jens Stoltenberg has also stated [423]:

*"We have just concluded a transformative Summit with NATO's Heads of State and Government. With far-reaching decisions to adapt our Alliance for the future ... We agreed [on] NATO's new Strategic Concept. We agreed to step up in the fight against climate change. And to establish a new one billion Innovation Fund ... And we agreed to deepen our relationships with some of the Alliance's closest partners, not least in the Indo-Pacific ... We also addressed how Russia and China continue to seek political, economic, and military gain across our southern neighbourhood. Moscow and Beijing are using economic leverage, coercion, and hybrid approaches to advance their interests in the region ... We face the most serious security situation in decades. But we are rising to the challenge with unity and resolve. The decisions we have taken in Madrid will ensure that our Alliance continues to preserve peace, prevent conflict, and protect our people and our values."*

Such geopolitical challenges have increased dramatically over the last few years and are expected to grow even further over the next 20 years. These developments will present significant operational challenges to the Alliance, compounded by the increased democratisation of technology and new technological threats from peer & near-peer competitors, terrorists, criminals and irregular forces.

## 3.3 Innovation and Investment

Scientific discoveries are, in and of themselves, only a potential first step towards developing new technologies or effectively applying technologies. Technologies which focus on the application of emergent technologies are sometimes referred to as *"deep tech"* [424] although the term is often used to describe a characteristic of start-up companies that focus on highly innovative engineering or scientific discoveries. Deep tech usually requires long-term, high-risk investments to translate scientific discoveries into effective technologies or apply such technologies to critical problems. It is *"... all about tackling these gnarly complex challenges that have huge potential for impact"* [425]. This complexity distinguishes it from so-called *"shallow tech"*, which focuses more on straightforward technological development. Many of the most important aspect of the NATO EDT set can be considered deep tech problems.

Technological innovations have always been decisive factors in international rivalries. And once again, today, innovation is at the heart of global competition, revolutionising international security conditions. In particular, emerging disruptive technologies often characterised as dual-natured involving both civil and military sectors will profoundly change the character of war conflicts. Thus, those who secure a technological advantage will dominate the future.

Interestingly, the dual nature of these technologies and their consequent application in both the civil and military spheres implicitly introduces the notion of an increasingly close triangular relationship between governments, academic institutions and industry (triple-helix innovation model). As [32] points out, knowledge generation and the S&T landscape is an endless frontier, with a quintuple helix [426] of actors from industry, academia, government, venture capital and the crowd. Thus highlighting the need for changing the geometry of the innovation ecosystem focused on strategically significant ABC (atoms, bits, cells) technologies. [32]

Over time, the branching out and thickening of the network of relations and synergies have required the definition of innovation infrastructures as highways for the circulation, dissemination and democratisation of knowledge and investment from granular to national and then international level. But on the other hand, (national) innovation systems, although they enable the creation of knowledge and facilitate the

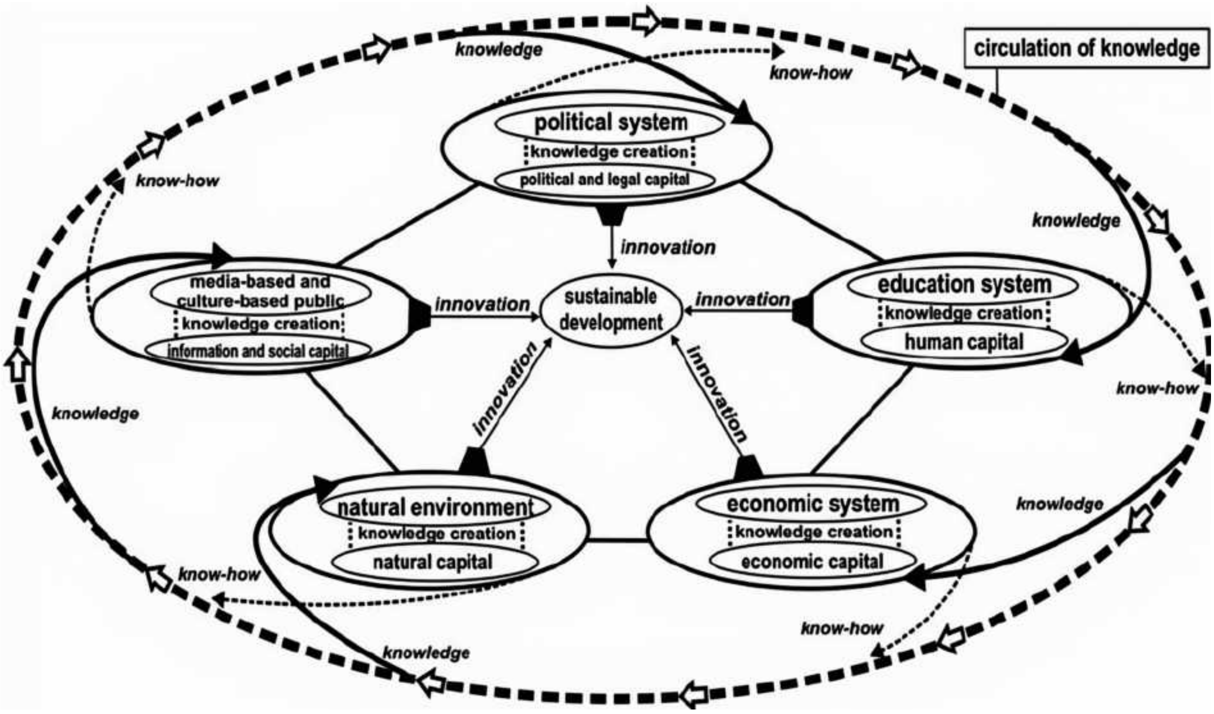



*Figure 3.3: The Quintuple Helix model and its function (functions).*

generation of innovation, still need to develop concrete competencies. Expertise and innovation produced by S&T must then be transformed for capacity building.

For NATO, the path from S&T idea to military capability is tied to continuous assessment, concept development and experimentation. This process is an essential framework for evaluating the potential military value of EDTs and ensuring appropriate operational concepts exist for uptake into operational capabilities. Alliance collaboration facilitates these activities through coordinated investment and assessment. New NATO 2030 initiatives such as the Defence Innovation Accelerator for the North Atlantic and the Defence Innovation Fund [427, 428, 429], which will provide over a billion euros for dual-use early-stage technologies.

Differing national S&T funding levels, acquisition programs, operational priorities and time horizons are challenges to this collaboration. Nonetheless, bringing to bear the intellectual and financial resources available across the Alliance provides a robust framework for assessing and developing new EDT-based capabilities. Despite existing monopolies, new technologies that offer a cost-effective alternative to current approaches tend to be adopted widely and quickly. With this investment comes the increased availability of technology for military capabilities.

High levels of investment generally drive rapid technological development and reflect their success (real or potential) in the marketplace or battlefield. Innovative countries leverage this investment through intense R&D efforts, developing high-value and value-added industries, and nurturing a highly-skilled, productive and educated workforce. Figure 3.4 presents a ranking of the top 132 innovative countries for 2022 [430]. Alliance countries consistently rank highly for innovation, but others, notably China, are rapidly evolving serious innovation systems.

Investment in S&T remains substantial (see Figure 3.5 and Table 3.1) as it is often seen as a key mechanism for shaping the national innovation agenda [431]. However, over the last 20 years, the drivers for S&T development have resided more and more outside the Defence and Security community, with commercial and societal needs providing the impetus for new capabilities (e.g. [432]). Technology uptake within a society impacts the development of EDTs, creating potential vulnerabilities in both military and civilian spheres.

Underlying science (TRL 1-3) for such commercial successes still overwhelmingly comes from government funding and research activities, which are better placed to absorb the risks associated with

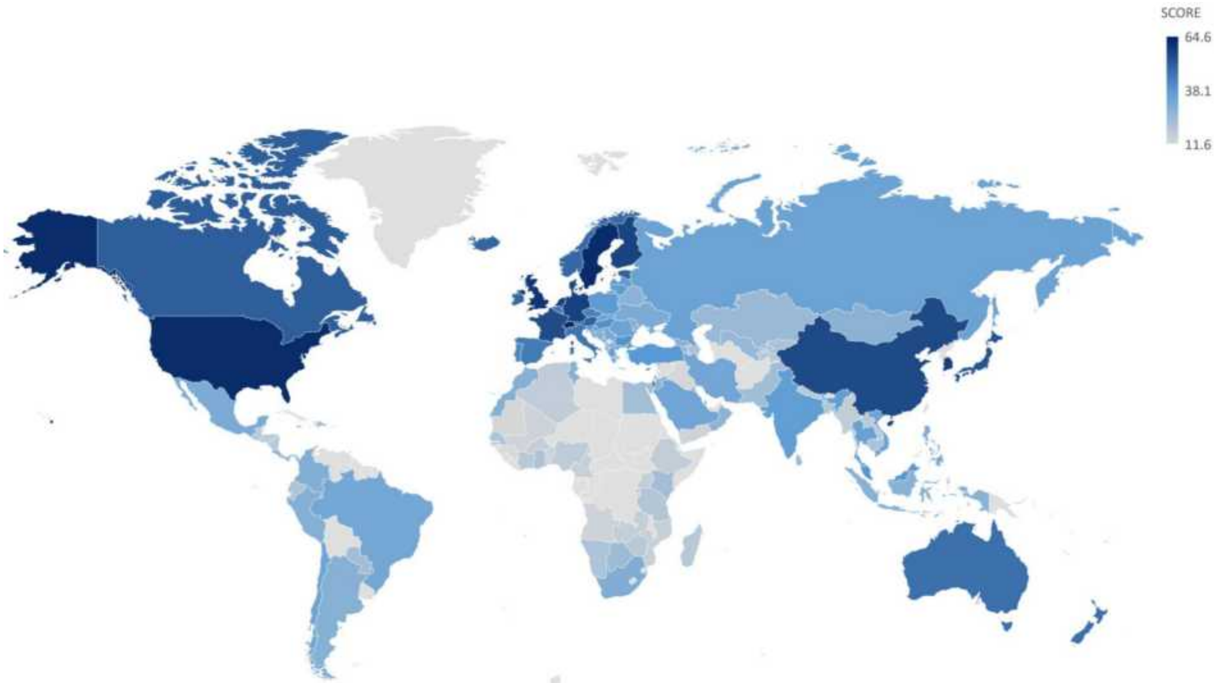
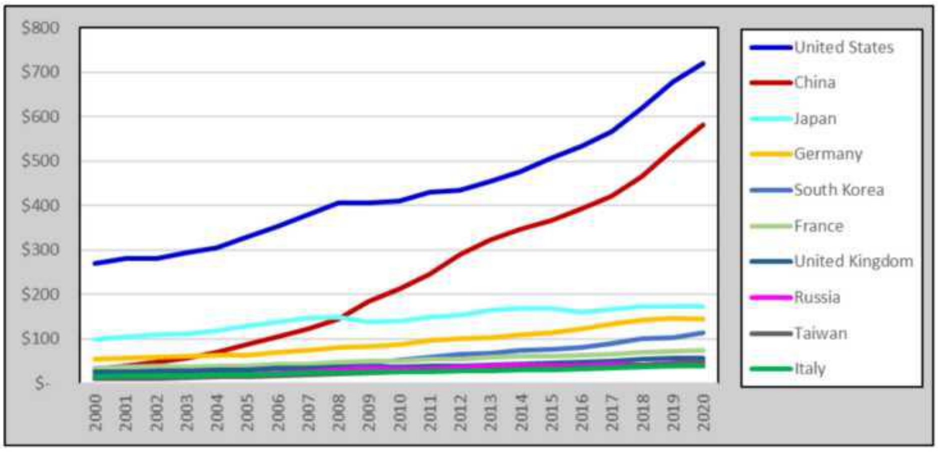


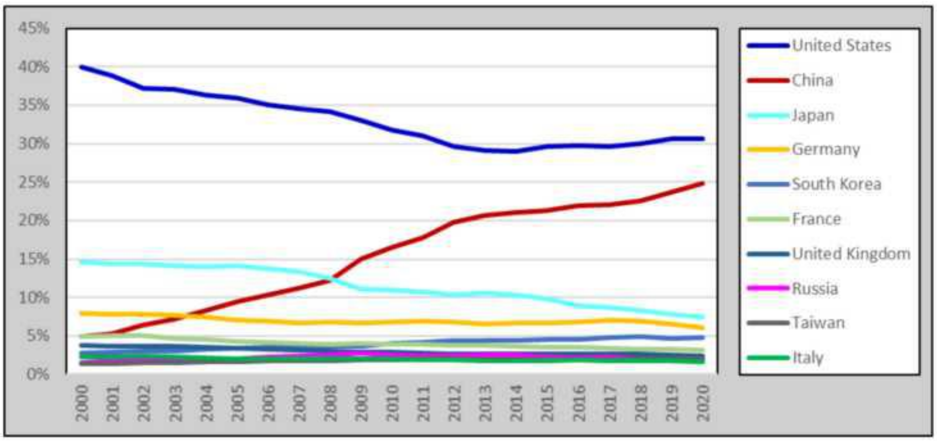

***Figure 3.4:*** *World Intellectual Property Organization (WIPO) Global Innovation Index 2022 Rankings [430].*

***Table 3.1:*** *Countries with the Highest Expenditure (in billions of current Purchasing Power Parity dollars) on R&D (2020), SOURCE: CRS Analysis of Organisation for Economic Development and Cooperation, OECD Stat Database [433]*

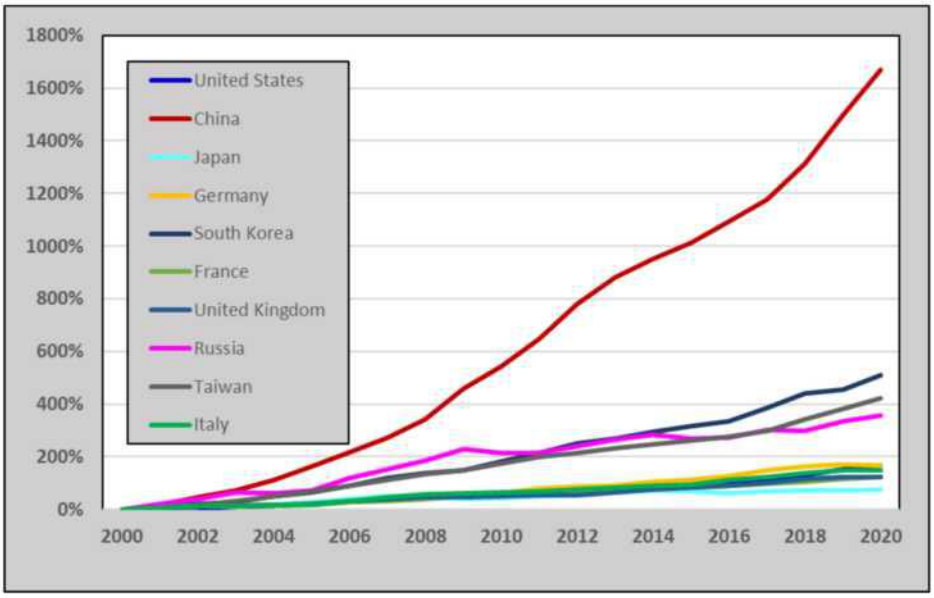
| RANK | COUNTRY | AMOUNT | RANK | COUNTRY | AMOUNT |
|---|---|---|---|---|---|
| 1 | United States | 720.9 | 11 | Canada | 30.1 |
| 2 | China | 582.8 | 12 | Spain | 25.1 |
| 3 | Japan | 174.1 | 13 | Turkey | 25 |
| 4 | Germany | 143.4 | 14 | Australia | 24 |
| 5 | South Korea | 112.9 | 15 | Netherlands | 23.7 |
| 6 | France | 74.6 | 16 | Belgium | 21.3 |
| 7 | United Kingdom | 56 | 17 | Sweden | 20.1 |
| 8 | Russia | 48 | 18 | Israel | 19.8 |
| 9 | Taiwan | 47.9 | 19 | Switzerland | 19.4 |
| 10 | Italy | 38.2 | 20 | Poland | 18.1 |




*(a) R&D Expenditures of Selected Countries, 2000-2020 (in billions of current Purchasing Power Parity dollars) (Source: CRS Analysis of Organisation for Economic Development and Cooperation, OECD Stat Database [433]).*




***(b)** Share of Global R&D of Selected Countries, 2000-2020 (Source: CRS Analysis of Organisation for Economic Development and Cooperation, OECD Stat Database [433]).*




***(c)** Growth in R&D Expenditures Since 2000 for Selected Countries (Source: CRS Analysis of Organisation for Economic Development and Cooperation, OECD Stat Database [433]).*

***Figure 3.5:** National R&D Funding (SOURCE: OECD, RDS Database) [433].*

such developments [434]. Therefore, the level of such investments and those from industry are vital factors in determining the long-term technological and capability development rate.

As noted by [435] and [436], there are growing investments in AI, quantum computing and information, commercial space, synthetic biology, cloud computing, cybersecurity and (big data) analytics. These investments are key drivers of new military capabilities [437, 438]. For example, global investment in AI research is set to exceed $1 trillion by 2030, driven in no small measure by Chinese investment and a stated goal to become the world's leader in AI by 2030 [439]. The US and the EU have also pledged billions of dollars & euros to support AI research, with more than 2 billion dollars set aside for defence-related AI research.

Global investment in S&T has changed substantially over the last few decades [440]. For example, in the 1960s, the USA's share of global research and development was 69%. By 2016 this share had fallen to 28%, with Chinese investment rising substantially as a function of purchasing power and as a percentage of Gross Domestic Product (GDP) (see Figure 3.5).

On a less positive note, the Organisation for Economic Co-operation and Development (OECD) [441] observes that:

> *"The share of government in total funding of R&D decreased by four percentage points (from 31% to 27%) in the OECD area between 2009 and 2016 ... But current trends in public research and development (R&D) spending may not be commensurate with the similar ambition and challenges delineated in mission-oriented policies. Since 2010, government R&D expenditures in the OECD and almost all Group of Seven countries have stagnated or decreased, not only in absolute amounts and relative to gross domestic product but also as a share of total government expenditure."*

At the same time that government funding has been decreasing, some patent and impact research suggests that technological innovation is slowing down [442, 443, 444, 445, 446, 447, 448, 447]. Since the publication of the last trends report more extensive research has highlighted this as a serious issue [445]. Others, such as Microsoft's Bill Gates, disagree strongly [449]. Both perspectives may be correct given the ambiguity in defining *innovation* and the long lead times between national investments, the serendipitous nature of scientific discovery, ultra-specialisation in academia, a publish-or-perish career paradigm, and the difficulty of finding practical applications.

***Figure 3.6:*** *NATO's Innovation Challenge - Government, Industry, Academia, Venture Capital and the Crowd.*

*Innovation* (e.g. novelty for a purpose) should not necessarily be conflated with *emerging* nor is *disruption* necessarily *game-changing technology* [450]. Other aspects of the innovation ecosystem are equally important, such as access, design, motivation, costs, intent, culture and societal expectations. Further, advances in mathematics, engineering and human factors are not necessarily technological but may be highly disruptive and innovative. Serendipity and synergy often play a critical role in bringing together ideas, people and technology to create *disruption*. On the other hand, low-cost, widely available technologies used creatively, employing innovative designs, or addressing problems that facilitate easy adoption can be highly disruptive (e.g. the Apple iPhone [451]). Therefore, in seeking military innovation, it is essential to distinguish between *innovation* and *disruption* and to appreciate the critical nature of these additional factors, which range across all aspects of DOTMLPFI (Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities, and Interoperability).

As noted in Figure 3.5, the US maintains a small lead in public sector R&D, although China's investments in public sector research exceeded that of the US in 2013. If one considers the Alliance as a whole, the R&D investment nearly doubles. Similarly, the US (and Alliance countries) dominate the world's top universities and colleges [452, 453], although China's Tsinghua University ranks 23rd. However, the methodology underlying this analysis [453] rests strongly on reputation and output factors built upon decades of investment. As noted by [454], investment by government in technology began in a very limited fashion only in the 1700s, gradually developing in strength until the 1940s when public investment increased dramatically. In this context, militarily useful science arose predominantly as a natural outgrowth of developments in industry and academia, e.g. dual-use in nature.

Over centuries the scientific community evolved from *Scientiae Latinae* to a *Scientia Americana* [454], or perhaps more accurately *Scientia Anglicus*. Perhaps we are well on our way to transitioning to *Scientia Sinica*. Starting around the 1940s, the US, and to a lesser extent the USSR, grew as scientific superpowers, focused on large, targeted, ambitious and often collaborative R&D activities. Much of the focus of this investment was directly or indirectly defence and security-oriented, with substantial spillover to the private and academic sectors. Well before the cold war ended, the focus on strategic priorities had begun to wane. At the same time, industry and academia were able to build upon the results of these earlier investments to create the digital world that we live in today and one enabling NATO's current technological edge.

Unfortunately, with its reliance on the self-interest of industry and academia, this lack of strategic focus has had real consequences. As noted by [32], *"In international competition, nations unable to identify and prioritise strategic technologies for action will fall behind and suffer from the resulting vulnerabilities."*

China, in particular, has been clear in its five-year plans on its technological priorities and has invested heavily to succeed in these areas (e.g. [455]). This focus has paid off handsomely. As noted by [32]:

> *"In our judgment, China leads the United States in 5G, commercial drones, offensive hypersonic weapons, and lithium battery production. The United States has modest leads in biotech, quantum computing, commercial space technologies, and cloud computing, but these could flip to the China column. The United States has a small lead in the AI competition, with China catching up quickly across the AI stack. China is making massive investments in all critical emerging technology sectors to catch up or take the lead."*

In his recent speech at the 2022 RUSI Annual Security Lecture [456], Sir Jeremy Fleming, Director of the GCHQ UK's intelligence security and cyber agency, spoke of the evolving technological environment in the context of national security and geopolitics under the heading of *"If China is the question, what is the answer?"*. In his words:

> *"So, we must also be clear that when it comes to technology, the politically motivated actions of the Chinese state is an increasingly urgent problem we have to acknowledge and address. That's because it's changing the definition of national security into a much broader concept. Technology has become not just an opportunity for international competition and collaboration but a battleground for control, values and influence. Of course, first and foremost, this is about science and engineering. But ultimately, it's about our way of life. We and our like-minded allies see technology as a way to enable greater freedoms, prosperity, and global collaboration. And yes, fair competition. But the Chinese leadership's approach is to also see it as a tool to gain advantage through control: of their markets, of those in their sphere of influence and course of their citizens."*

Paraphrasing the GCHQ Director, international multi-stakeholders, like-minded peers, and allies must address such an endeavour collectively. Counter-balancing divergent values creation and dissemination through more democratic, ethical, moral and legal technology shall be a NATO priority.

Therefore, Sir J. Fleming stated:

> *"So, if China is the question, and science and technology is part of the answer, what should we do next? Our task as a community is to understand the challenge, to know that Chinese tech domination is not inevitable. To take action."*

Ensuring that NATO maintains a technological edge and, consequently, a credible deterrence posture means more than simply significant investments. Such a posture requires clarity of objective and a sense of urgency, as articulated by heads of state at the Madrid Summit in June 2022 [457].

## 3.4 Strategic Drivers

The following key strategic drivers will likely affect technology trends over the next 20 years. This section offers some thoughts and assumptions regarding these drivers.

### 3.4.1 The Operational Environment (Space, Info-sphere, Arctic, and Urban)

The range of potential NATO operations is expanding and evolving as the geopolitical, military, economic, social, climatic, and technological landscapes change [458]. Space, the info-sphere, the arctic, and urban domains are particular areas of rapid evolution. At the same time, multi-domain operations will test the resilience and adaptability of NATO Allied troops.

#### The Space Domain

Space has been a critical military enabler since it became a *human* domain over 60 years ago. Today, space is experiencing a technological revolution as the space industry is transitioning from **old space** into **new space**. This change is characterised by a swift in the Space business model, from large public investments towards commercially-driven private funding. The growth of private actors and the stark increase of space activity [459], especially around the satellite communication industry, is empowering major technology developments (e.g. new propulsion options, novel materials, miniaturisation of sensors and electronics, and agile manufacturing have issued in a new era of rapid growth) which are significantly driving down the cost of space access. As a result, space is increasingly contested, congested, competitive and commercial. In the next 20 years, new space applications will also be expected to stretch beyond terrestrial orbits into cislunar space or even further.

***Figure 3.7:*** *An Illustration of a Fission Lunar Surface Power on Mars [460] (CREDIT: NASA).*

The increased reliance on space technologies for civilian and military use encourages nations to protect critical space-based assets. In this sense, many countries have declared space as a war-fighting domain (e.g. Russia, China and the United States). They are focusing on developing offensive and defensive space capabilities [461], which translates into an increased risk of the weaponization of the space domain [462]. This risk includes the use of anti-satellite (ASAT) (hard or soft kill) weapons [463, 464], which have the potential to *pollute* the near-earth environment, significantly increasing the risk of collision with space debris. The Prevention of an Arms Race in Outer Space (PAROS) is an active topic amongst the international community. The body of international law that governs space activity declares that *"the Moon and other celestial bodies shall be used exclusively for peaceful purposes"* and explicitly forbids the use of weapons of mass destruction [465]. However, these international norms are still vague and leave room for interpretation. In the past few years, some nations have been aiming to reduce that ambiguity by developing internationally accepted standards of responsible behaviour within space [466, 467]. However, as space activity develops, many questions will have to be addressed to provide legal certainty.

NATO has acknowledged the increasing importance of space. In 2019, Allies adopted NATO's Space Policy and recognised space as a new operational domain alongside air, land, maritime and cyberspace. In 2022 NATO published a public release version of this policy which guides NATO's approach to space and ensures the right space-based support to the Alliance's operations and missions in such areas as space situational awareness; intelligence, surveillance and reconnaissance; space-based monitoring of the atmospheric, oceanic and space environments; satellite communications; positioning, navigation and timing; or shared early warning. With growing Alliance and global reliance on space-based technologies, the *control of space could become a significant flash-point* [468]. Given the Alliance's dependence on space-based systems, NATO will need to increase its vigilance and resilience in this domain.

#### The Infosphere (Cyber, Electronic Warfare (EW), and the Electromagnetic (EM) Spectrum)

The digitisation and virtualisation of individuals, organisations and societies underlie the information domain [469]. Nowadays, 66% of the world population can access the internet [470], 67% has a smartphone, and more than half are active social media users [471]. Moreover, the digital world will likely expand in the next 20 years as the world adapts to the fourth industrial revolution [472] and 5G/6G networks and the internet-of-things (IoT) grows to trillions of devices [473].

This increased digitisation and hyper-connectivity will bring many benefits and create new vulnerabilities that could be exploited for information warfare, electronic warfare, or cyber warfare. Near-peer competitors have found a voice in the info-sphere. They combine trolling, mob behaviour, and disinformation campaigns with new technologies to create competing narratives and *alternate facts*. Deep-fakes as the one produced during the beginning of the Ukrainian invasion where president Volodymyr Zelensky was supposedly telling his soldiers to surrender [474, 475] (see Figure 3.8); Or France's release of classified drone recordings to prove that their armed forces were suffering a disinformation campaign after leaving Mali [476]; are just some examples of such behaviours.

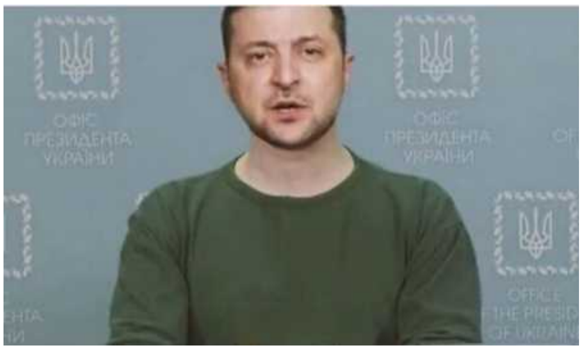


***Figure 3.8:*** *Zelensky's Deep-fake [475].*

Also, the increased digitisation of society has created new virtual communities that are unbound by geographic boundaries but increasingly defined by emergent virtual ones and associated *echo chambers* [477]. Social and individual empowerment so engendered have become in many ways as important to the modern world as food, water or shelter. This empowerment is true across the globe and at all levels of economic development, driven by the deep-seated human need for social contact. Nations are challenging such empowerment through national firewalls and social metrics to control. Emerging and Disruptive Technologies such as AI or Machine Learning are being used to enhance online censorship [478]. At the same time, the increasing amount of data being produced [479] is being leveraged by some to develop digital reputation rating systems [480] that are meant to shape and constrain social discourse and individual expressions of discontent.

***Table 3.2:*** *Info-sphere Operations (Source: [481])*

| Characteristic | Cognitive Warfare | Cyber Warfare | Electronic Warfare | Information Warfare | Psychological Warfare |
|---|---|---|---|---|---|
| Use of data | X | X | | X | |
| Deals with thoughts and behaviour | X | | | | X |
| Capacity for extreme public reach | X | X | | | |
| Interest in circulation of information | X | | X | X | X |

At the same time, the transmission of information through wireless communication systems creates the need to defend against the use of the electromagnetic spectrum as a weapon [481]. Electronic warfare can provide invaluable insights into military operations and make a difference when defending or attacking an adversary [482]. Also, the increased reliance on computers and digital networks creates cyber vulnerabilities than can be exploited to generate harm [481]. The reality is that cyber threats to the security of the Alliance are complex, destructive and coercive and are becoming ever more frequent [483]. Overall, NATO operations in the info-sphere will require increasingly sophisticated cyber, EW and EM management approaches. Success in hybrid warfare will require winning the war in the info-sphere. This success will require the development of a competing Alliance narrative, trolling the increasingly deep and murky *data ocean* that such virtualisation and digitisation creates, and developing a *decision advantage* in terms of speed, accuracy and effect. The impact of EDTs in this area will be profound.

### The Arctic & the High North

Once Finland and Sweden join the Alliance, seven of the eight Arctic states will be members of NATO. For many years, changing environmental conditions due to climate change [484, 485] (e.g. Figure 3.9) and increased human activity have reshaped the High North's (Arctic territory and waters) geostrategic relevance to Alliance nations [486, 487, 488], partners [489], and others with interests in polar climate change and resource development [485, 490, 491]. This region has traditionally been an area of low confrontation [492]. Still, the current geopolitical situation and the increased military [493], and economic [494] activity of third actors in this domain are changing national position:

> *"NATO is a defensive alliance. Our purpose is to prevent conflict and preserve peace. Much of the High North (Arctic territory and waters) has traditionally been an area of low tensions. But unfortunately, this is changing due to the rapidly warming climate and rising global competition. Increasingly parts of the Arctic will be ice-free in summer. This unlocks opportunities for shipping routes, natural resources and economic development. But it also raises the risk of tensions. Authoritarian regimes are willing to use military intimidation or aggression to achieve their aims. At the same time, they are stepping up their activities and interest in the Arctic"* - **Jens Stoltenberg, NATO's Secretary General** [418]

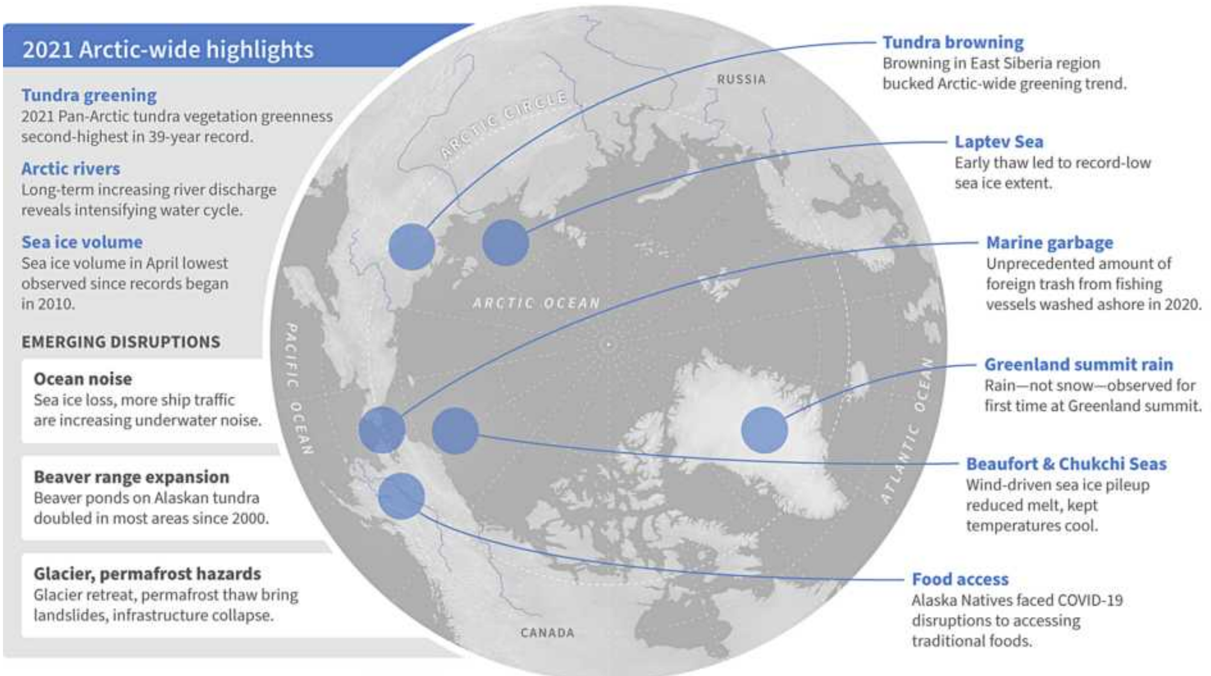



***Figure 3.9:*** *The Changing Arctic Environment (CREDIT: NOAA [495]).*

From a military perspective, the Arctic hosts Allied and Non-Allied key military and commercial infrastructure (e.g. missile defence facilities, radars, early warning sites, or commercial space ground stations...) [492, 496] and is home to a large proportion of Non-Allied nuclear deterrence forces [492].

From an economic perspective, this region is the gateway to the North Atlantic, hosting vital trade, transport and communication links between North America and Europe. Therefore, ensuring freedom of navigation and unfettered access is essential to keep our economies strong and our people safe. While some Alliance nations have considerable Arctic operational experience [497, 2], the reality is that an increase in military activity in the High North may present a capability gap for NATO [492]. This also applies to the S&T domain. For instance, concerning navigation in seas where ice is present, ongoing and new research will be needed to improve surface ship safety and operability in Arctic regions. At the same time, operations over vast distances, where few satellites regularly pass, will lead to sparse GPS and communication coverage. Weather conditions (atmospheric and space) will degrade sensor, communication and vehicle performance. The freezing winters, swarming insects, permafrost, short summers, muskeg and highly variable weather conditions pose an additional risk to human health and equipment not prepared to withstand such conditions. Technologies, including many of those considered in this report, will be challenged to operate successfully in the Arctic.

#### The Urban Theatre

Today, 56% of the world population lives in urban areas, and over 80% of global GDP is generated in cities [498]. According to the United Nations, by 2050, the world population will be close to 10 billion people [499] and urban areas will host almost 70% of the earth's population [500]. This scenario will impact urban development [501] as well as future military operations [502].

***Figure 3.10:*** *Street view in the city of Kyiv. The photo was taken when the president of Ukraine, Volodymyr Zelenskyy, visited the city on 2022-04-04. (CREDIT: WikiCommons [503])*

On the one hand, higher population densities and the need to mitigate the impact of climate change [504] may enhance the need for innovative S&T solutions [501]. For instance, **Artificial Intelligence** may be used for road traffic management [505, 506]; **Distributed Ledger Technology** may allow for secured and decentralised data exchanges amongst local services; **Digital twins** may be used as planning tools for urban modelling [507]; **3D Printing** will allow for on-site fabrication of components to provide services during crisis scenarios [508, 509]; **Renewable energy sources** and decentralised power grids will allow increasing sustainability; At the same time, it is important to be aware that these technologies may be applied simultaneously to enhance their potential impact [499].

On the other hand, increased urbanisation may create new security concerns and may make NATO operations in an urban environment more likely. The 5Cs have described the future character of conflict in the future urban battlespace: it will be more Congested, Cluttered, Contested, Connected, and Constrained [502]. The current war in Ukraine reminds us of the complexities of urban warfare and the need to understand, train for, and operate in complex urban environments (see Figure 3.10). This may necessitate providing key services to deny an adversary the opportunity to exploit a chaotic situation or weaponize a city against its population. The engagement space of the future urban operational environment will be highly multi-dimensional and hybrid, with strategic success depending on successful information, social, EM and cyber engagements. There will be an increased need to operate with minimal or no collateral damage in environments where the difference between combatants and non-combatants may be difficult to discern or change minute-to-minute. New technologies will be essential to ensure adequate situational awareness and (kinetic or non-kinetic) precision in these scenarios, with the internet-of-things providing millions of possible sensors and urban transportation systems increasing the complexity of operations [468].

### 3.4.2 Culture, Ethics & Law

In the last two decades, we have observed how technological innovation has outpaced government legislation. However, over time, culture, ethics, and law shape the integration of technology into society and define its effect and value. Some of the disruptive developments brought by technology have impacted primary constitutional values (e.g. Social media and data privacy) or have shaken the structure of the system itself (e.g. Blockchain technology and finance). However, technological progress has also impacted more mundane things (e.g. auto insurance liability shifting from the driver to the manufacturer). Ultimately, legal frameworks can create favourable technology ecosystems to foster innovation and favour economic growth [510, 511, 512] However, these can also be used as a weapon to hamper progress (e.g. Lawfare).

Overall, ethical and regulatory issues have surrounded the development of EDTs and have had a direct impact on the development of defence-related capabilities, in particular in the areas of autonomy, artificial intelligence [95, 513], cyber [514] and space [515]. As a result, Alliance nations have differing constraints around the operational use of EDTs and the capabilities they engender. These constraints ultimately impact the development, interoperability and employment of EDTs as part of Alliance military capabilities. However, NATO itself is well-positioned to ensure that such fundamental issues are addressed. As a result, EDT-derived military capabilities will be interoperable, used legally, and seamlessly integrated into Alliance operations.

In the upcoming years, technology will continue to develop, and it will bring new regulatory challenges such as:

- **The democratisation of technology** (e.g. reduced costs and increased access): This trend raises concern about how much regulation is needed to safeguard society from high-tech rogue actors whose capabilities are limited by their imagination. For instance, space has always been dominated by government activity. However, the decrease in the costs of access to space is changing this trend. In the next 20 years, private companies will be the key actors in space, and a lot of regulation is needed to understand the implications of their behaviours beyond terrestrial boundaries.
- **Artificial Intelligence**: Our world is governed by algorithms that support decision-making (e.g. insurance, credit scores, social media feeds...). However, these algorithms are very complex and usually not transparent (we don't know the reasoning behind their decisions). As society increasingly relies on machine learning and advanced algorithms, demands to see inside algorithms will likely increase. This will increase transparency and also help society understand algorithm bias discrimination.
- **Data, digital privacy and security**: The challenges of maintaining privacy in an increasingly digital and virtual world are profound. Regarding ethics and confidentiality, there is no single global social norm regarding how personal data is used. In the West, populations are generally resistant to the use of their data by governments. Nevertheless, even in Alliance countries, privacy concerns may be overridden in the name of security [516]. Some societies or governments see value in using such data to reinforce social norms (e.g. [517]). Having uninhibited access to an entire population's data gives a clear advantage for training AI and conducting advanced social analytics.

From a broad societal perspective, cultural resistance exists to integrating civilian capabilities into the military arsenal. For example, while non-lethal weapons may reduce casualties or collateral damage, even in high-intensity war-fighting scenarios, and increase operational effectiveness, they are seen by many as *not a military weapon*. This reluctance has slowed down their adoption and integration into the operational toolkit. Similarly, the military use of current information and cyber capabilities has been slower than expected, likely due to cultural resistance in civil and military societies.

### 3.4.3 The Environment

Climate change will be a major disruptive force in the upcoming decades, with many future studies and major climate impact assessments (e.g. [47, 434, 473, 495, 518, 519, 520, 521, 522] to name a few) highlighting the potential for climate change to drive future conflict. The 2021 Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) conducted a massive analysis concerning observed and projected climatic changes. Major highlights about projected changes include [523]:

- *Global surface temperature will continue to increase until at least mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO2 and other greenhouse gas emissions occur in the coming decades.*
- *Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, heavy precipitation, and, in some regions, agricultural and ecological droughts; an increase in the proportion of intense tropical cyclones; and reductions in Arctic sea ice, snow cover and permafrost.*
- *It is virtually certain that the Arctic will continue to warm more than global surface temperature, with high confidence above two times the rate of global warming.*
- *With every additional increment of global warming, extreme changes continue to grow. For example, every additional 0.5°C of global warming causes discernible increases in the intensity and frequency of hot extremes, including heatwaves (very likely) and heavy precipitation (high confidence), as well as agricultural and ecological droughts in some regions (high confidence).*
- *The proportion of intense tropical cyclones (Category 4–5) and peak wind speeds of the most intense tropical cyclones are projected to increase at the global scale with increasing global warming (high confidence).*
- *Continued global warming is projected to intensify further the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events.*
- *Many changes due to past and future greenhouse gas emissions have been irreversible for centuries, especially changes in the ocean, ice sheets and global sea level.*

All the conditions mentioned earlier have led NATO to accelerate its environmental security and protection efforts. For decades, NATO has been dealing with environmental security issues that can lead to humanitarian disasters, regional tensions and violence. In 2022 NATO published its Climate Change and Security Impact Assessment (CCSIA); to respond to the demand for increased Allied awareness concerning the impact of climate change on security. This report sets out the effects of various climatic hazards: **(1) on NATO's strategic environment** (e.g. increased accessibility to shipping channels and competition for natural resources in the High North); **(2) on NATO's assets and installations** (e.g. Rising sea levels and storm surges threaten the structure of ports and bases situated in low-lying coastal areas); **(3) on NATO's missions and multi-domain operations**(e.g. climate change makes military operations and missions in various regions more expensive and more technically challenging); as well as **(4) on NATO's resilience and civil preparedness** (e.g. Increased shortages and control of food, lack of fresh water, reduced biodiversity).

### 3.4.4 Gender and Technology

Over the next 20 years, the world will continue to undergo a major technological transformation, seeking to adapt to the ongoing fourth industrial revolution [524], as well as the scientific revolution that underlies it and the biotechnology-driven future beyond. This adaptation is not independent of humanity's biological, social and physical realities. Of particular note is the role of *gender* in S&T development. Gender impacts the relationship with technology in at least three major ways.

First, technology must adapt to unique mental, physiological, social and physical gender requirements. Such factors are often not considered when developing technology for military use [525]. This can mean designing equipment (e.g. space suits adapted to women) or physical spaces to adapt to gender-based physiological differences, developing physical biometric models more representative of the military population, and adjusting to gender and individual cognitive approaches. As noted in [526]:

> Women, on average, tend to have smaller frames than men, but women "were wearing the male version [and] that often it compromised a woman's ability to lift her arm appropriately to fire." This lack of mobility presents a serious risk to women since it prevents them from being able to defend themselves in combat situations.

These differences are especially important in the context of human enhancement technologies.

Second, access to technology is not equal. The International Telecommunication Union (ITU) estimates that in 2022 there were 2.7 billion people without internet access, of which the majority were women and girls. This phenomenon is known as the **gender digital divide** [527], and it may have a major impact in the upcoming years. As noted in [527], *"hurdles to access, affordability, lack of education as well as inherent biases and sociocultural norms curtail women and girls' ability to benefit from the opportunities offered by the digital transformation"*. In practice, a lack of internet access impedes the uptake and effective use of technology [528], including that used on the battlefield. Considering that over 90% of jobs worldwide have a digital component [529], and that military systems are becoming more dependent on technology, addressing this issue will be of the utmost importance; It also generates a gap of professionals in science, technology, engineering, and mathematics (STEM) fields which are on great demand [530]; In fact, the shortage of STEM graduates may generate a manufacturing skills gap in the future [531], and millions of jobs could go unfilled in the next decade [531].

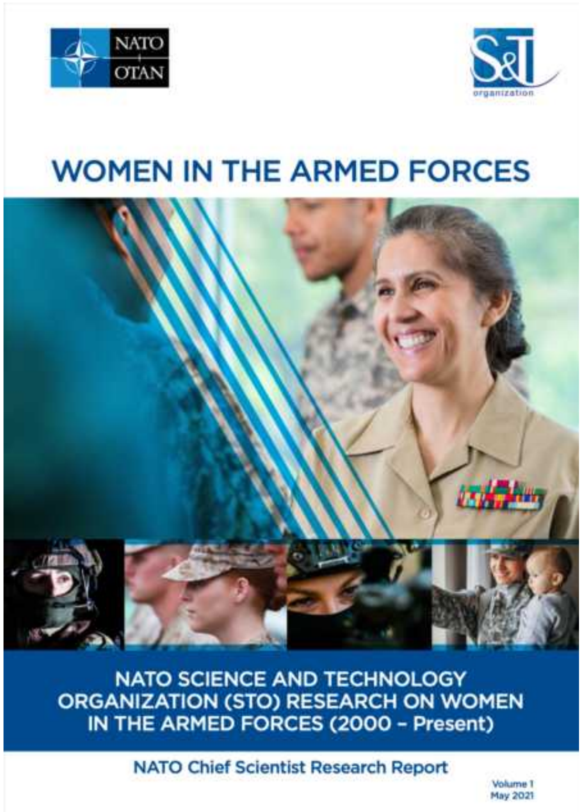



***Figure 3.11:*** *NATO Chief Scientist Report - Women in the Armed Forces [525]*

Finally, reality reflects that global workforce gender parity hasn't yet been achieved [532]. When looking into S&T specifically, the data shows that men outnumber women in most, but not all, STEM fields [533]. Women make up just one-quarter (28%) of tertiary graduates in engineering and 40% of those in computer sciences. Also, women represent just 22% of the professionals working in AI. Globally, women represent only one-third of the research workforce [533] and 18% of the authors of scientific publications [534]. On a more positive note, evidence suggests that equivalent scientific records yield similar career impact [535, 536], with current disparities tied to socio-economic factors that impact career length and publication numbers. Therefore, solving the skill and impact gap while ensuring a competitive workforce to sustain economic prosperity requires a better understanding of root causes. Nations will be faced with continuing to address this issue. As noted by [537] *"The shortage of women in STEM is widely recognised as detrimental to women, since science and technology occupations, particularly in engineering and computer science, are among the highest-paying jobs and fastest-growing occupations. Additionally, numerous analyses have found that greater diversity strengthens innovation and performance."*

NATO's common values of individual liberty, democracy, human rights and obligations under the Charter of the United Nations underpin the principle that women's full rights and participation are essential. As such, the NATO Science for Peace and Security (SPS) Programme promotes concrete, practical cooperation on gender-related issues among NATO members and partner countries through collaborative multi-year projects, training courses, study institutes and workshops.

### 3.4.5 Mistrust in Science

Public trust/mistrust in science is a recurrent question that has become more critical with the rise of social media, COVID-19 and a growing sub-culture of distrust [538, 539, 540, 541]. Climate change [542] or the recent COVID-19 pandemic [543] are tangible examples of this phenomenon. Some may argue that mistrust in science may be explained due to targeted misinformation campaigns. However, other factors such as preconceived beliefs [544], or underlying structural problems within the communication of scientific findings, may also explain it [545].

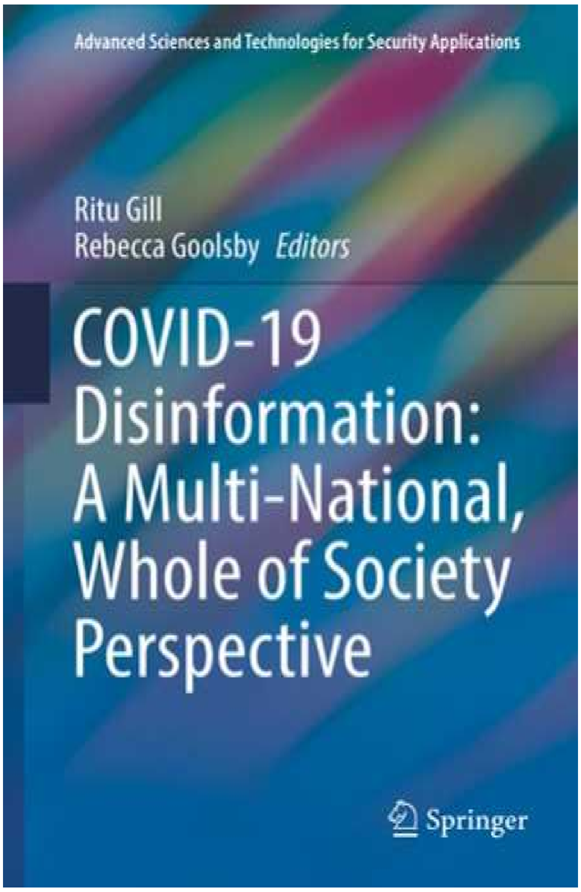



***Figure 3.12:*** *COVID-19 Disinformation: A Multi-National, Whole of Society Perspective [546].*

State and non-state actors have weaponized information for political or military gain for centuries. What has changed is the sheer scale and complexity of today's information landscape. Never before has it been easier for disinformation to spread through our societies, warp facts and influence perceptions. Over the last decade, a range of state actors have developed and implemented digital marketing techniques enhanced by cyber and psychological operations. The objective is to create an alternative worldview to undermine democratic values for their benefit. EDTs will increase the efficiency and effectiveness of disinformation by focusing attacks and automating cognitive warfare campaigns [547].

During the last decade, climate change has been questioned repeatedly [548]. While some of this criticism has been and is part of legitimate scientific discourse, much of this has been self-serving disinformation and misinformation following the earlier models used for anti-fluoridation, tobacco and lead additive disinformation campaigns [538, 549, 550, 551, 552] with their appeal to comfortable uncertainty [553]. While the scientific consensus is that climate change is a real phenomenon, the resulting disinformation campaign means there is still an evolving social consensus [554].

During the past few years, we have observed how state and non-state actors have exploited the COVID-19 pandemic to spread disinformation and propaganda, destabilising and undermining Western societies [543]. This situation was highlighted by the Director General of the World Health Organization (WHO), who, at the beginning of the COVID-19 pandemic, declared that *"we're not just fighting an epidemic; we're fighting an infodemic"* [555].

Many factors underlie this mistrust in science, including [556]:

> *"a public overwhelmed by too much information, growing polarization, disinformation campaigns by domestic or foreign corporations and governments, a media environment that rewards outrage and outlandishness, and the increasingly public nature of scientific research ... The motives behind disinformation ... include politics (arousing opposition to the other side), profit (making money by pushing bogus scientific products), social advocacy (raising support for a cause that cuts against the scientific consensus), and even foreign affairs (sowing distrust in an adversary's government)."*

One might add to this list a fundamental misunderstanding of how science is conducted, failures in scientific communication and a perceived reproducibility crisis [123, 557, 558, 559]. Indeed, outdated productivity metrics may cause researchers and institutions to over-hype their findings, leading to cynicism and disillusionment. Also, due to publication bias, research institutions may focus on publishing positive results while blurring negative ones. Other problems, such as citation misdirection or data and science distortion, may also impact how society perceives science [545].

In the next 20 years, multiple interdisciplinary challenges derived from climate change (e.g. food and water insecurity, reliable and alternative energy supplies...) and other threats that may have not yet arisen may demand a more permanent integration of science into policy-making. Therefore, ensuring society's trust in science will be key to good governance [538].

### 3.4.6 Miscellaneous

Following [47, 49, 402, 469, 473, 562, 563, 564, 565, 560, 561], we also note that several other strategic trends have the potential to impact future NATO capabilities or operations. These include:

- **The Changing Nature of Work**: Increased reliance on AI and Autonomy will redefine work; On one hand, technology is changing the skills that employers seek. Nowadays, almost 30% of tasks of 60% of current jobs could be performed by computers [566]. By the end of the next decade, almost 10% of the global workforce will work in new professions [566]. On the other hand, technology is also changing traditional work models. Indeed, the digital economy is changing traditional business models and is allowing companies to scale up more quickly than ever. Also, new digital platforms are bringing more flexibility to working arrangements. At the same time, new productivity models are centred around the well-being of individuals (e.g. remote working, life-work balance, shorter work weeks). Overall, all of these changes will generate challenges for society but will also open new opportunities.

- **Education**: Before COVID-19 educators already agreed on the value of Education Technology [567]. However, the pandemic forced academic institutions to either fully close or to adopt an all-virtual teaching model (e.g. virtual lessons, cloud sharing, digital collaboration, etc.) [568, 569]. While returning to a 'normal' lifestyle has gotten students back to the traditional learning frames, it is obvious that it will be hard to return to pre-pandemic teaching standards [456]. In the upcoming years, the use of virtual realities, AI, big data etc., will enable personalised on-demand training; at the same time, some companies are committing large investments to expand the use of the metaverse as an immersive tool to enhance the student's experience. These new learning tools will also support military preparation. The complexity of future operating and security environments suggests improving training and leveraging commercial developments for defence gains. AI is already being used for pilot training [570]. At the same time, Augmented Reality and Virtual Reality allow military training for combat operations, equipment maintenance, or moral well-being. Finally, it is worth mentioning that various STO Scientific and Technical Committees (e.g. Human Factors and Medicine (HFM) Panel and NATO Modelling and Simulation Group (NMSG)) are conducting several activities aligned to this topic.

- **Supply Chains**: In the past few years, major key events have tested the resiliency of global supply chains [571]. In the upcoming years, AI, Data and Autonomy will increasingly enable automated transportation and logistics [572]; In fact, these technologies will be key to ensuring a stable supply of materials such as Rare Earth Elements, which are strategically important due to their inclusion in many military systems [573, 574]. For this purpose, the STO's Applied Vehicle Technology (AVT) Panel has been conducting activities on this subject.

- **Energy, Water and Food Security**: Russia's brutal and unprovoked war of aggression against Ukraine has reminded us of the importance of ensuring a stable energy supply [575] and the vulnerability of the global food supply chain [561]. Indeed, the disruption of energy supply due to natural or artificial factors could affect security within the societies of NATO members and partner countries and impact NATO's military operations. Also, food and water security shouldn't be taken for granted. Climate change, natural disasters or military conflict could challenge water and food availability, ultimately generating security concerns. On the other hand, applying novel materials and techniques and bio-engineering and bio-technologies may increase water, energy and food supplies.

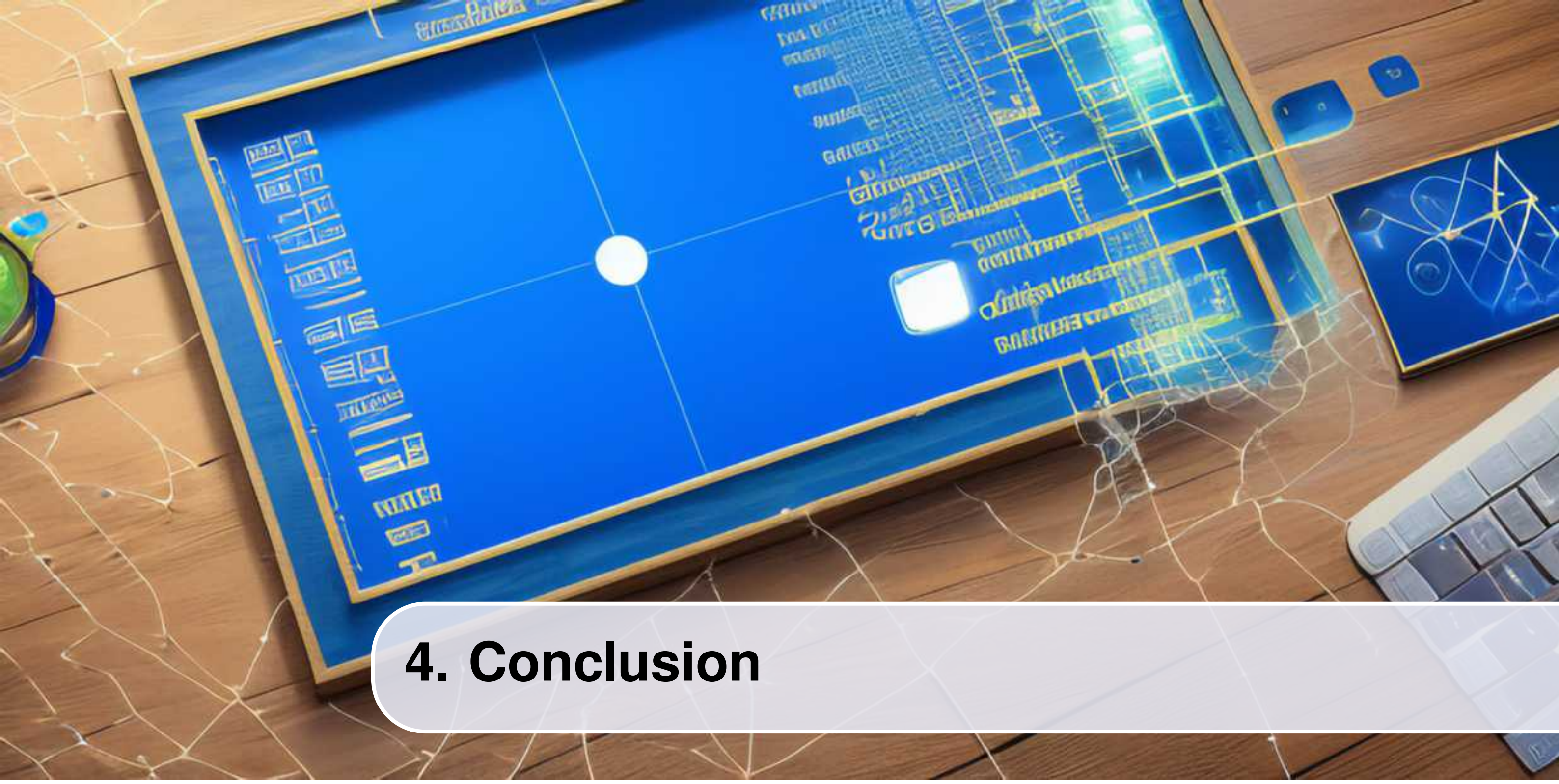
- **Human Capital**: An ageing global population, economic migration patterns and uneven nations' development will challenge societies and recruitment efforts by military forces. Further, a society's ability to exploit and absorb new technologies is limited by the availability of talented and skilled individuals able and willing to take on the challenge. Demographic shifts, job losses due to AI and autonomy, globalisation of talent and a growing skills mismatch may ultimately challenge the Alliance's ability to manage and absorb the disruption and exploit the opportunities presented by EDTs.

- **Changing Global Economic Framework**: Increased pressure on and decoupling of the international economic framework into protected technological silos (bifurcation) will hamper technological and economic development [576, 577]; and,

- **Infectious Diseases and Pandemics**: New diseases, reduced vaccination rates and growing resistance to countermeasures (e.g. antibiotics) will challenge global health & development and Alliance operations.

## 3.5 Contextual Trends - Conclusion

The world in which S&T is developing and, in turn, influencing has changed dramatically over the last three years. NATO is adapting, but the challenge should not be underestimated. New investments, innovation accelerators, a refocused defence planning process, and outreach on EDTs to the broader innovation community are all necessary steps. However, the need to maintain the essential technological edge that NATO has enjoyed for over 70 years has come face-to-face with renewed strategic competition and fundamental existential challenges.



# 4. Conclusion

**Technology and Society**

"Technology is a very human activity and so is the history of technology." - *Kranzberg's Sixth Law of Technology*

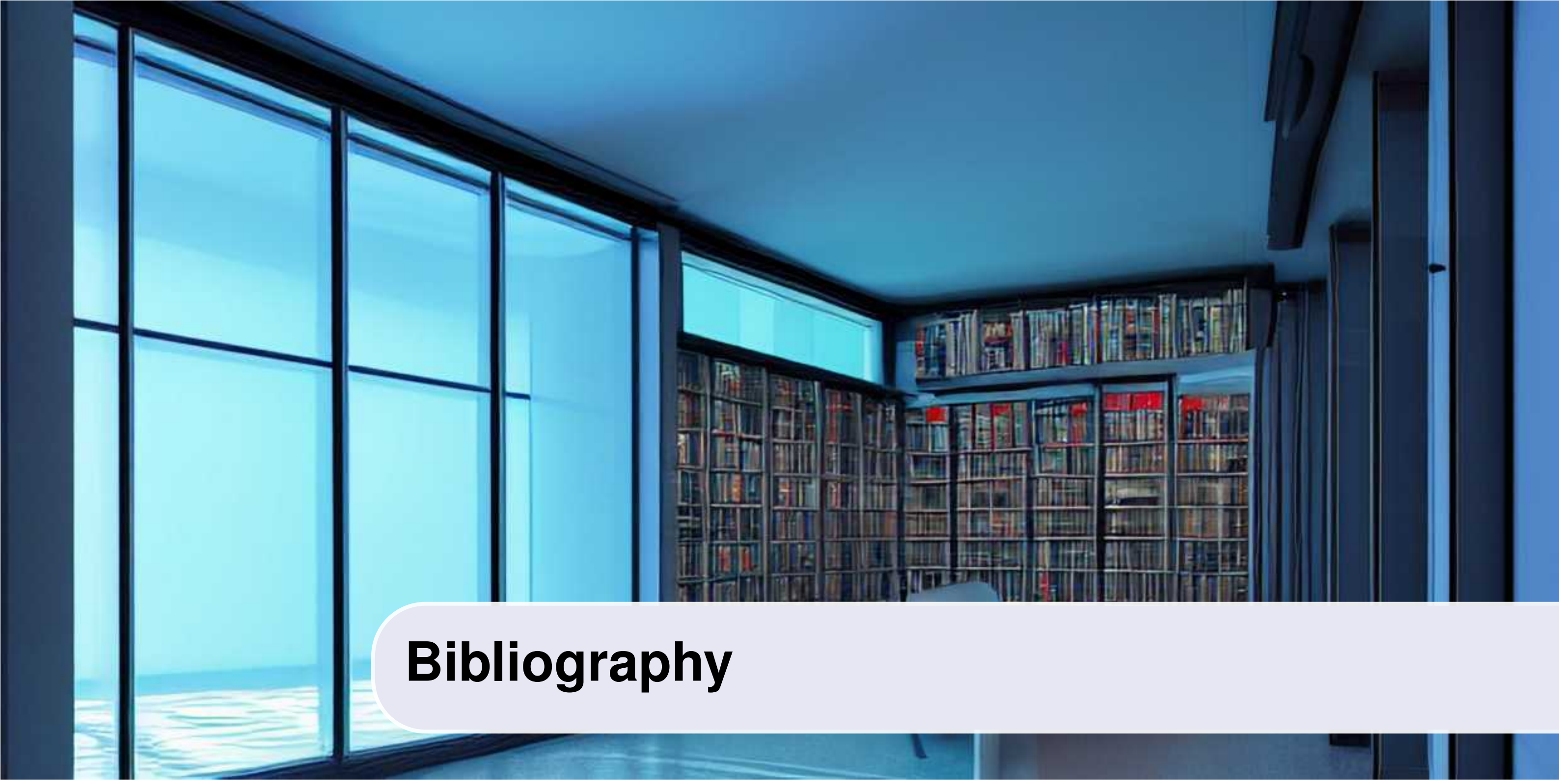
EDTs will expand NATO's ability to respond at an enterprise level, operate in rapidly evolving operational environments (such as space, cyber and the cognitive domain), and respond to operational challenges due to climate change and urbanisation. Recent innovation initiatives, increased NATO common funding, a new Strategic Concept, and a renewed focus on capability development support NATO's adaptation challenges. However, EDTs will stress NATO's ability to collectively innovate while ensuring legal, policy, economic, and organisational constraints are properly considered early in developing these technologies.

The Alliance has been and will continue to be defined by its technological choices. These choices underpin the military and enterprise capabilities necessary to ensure the effectiveness of the Alliance in a world of rapid change and development. Whether in the human, information, or physical domain, organised conflict is an enduring aspect of all societies, as is the need to respond to extraordinary crises. Technology and the science that underlies it provides the edge required by Alliance forces to respond to security, crisis response, and collective defence challenges. The nature of that conflict is changing, driven in no small measure by advances in technology, tools, and scientific understanding.

This evolution will be a vital feature of the future battlespace or zones of conflict, whether physical or virtual. These evolving multi-domain complex operational spaces will have significant implications for the development and future employment of the Alliance's instruments of power. If NATO is to develop a new *strategy of technology* it must do so in the context of evolving geographic, geopolitical, and military domains, which in themselves are driven in no small part by technologies that are increasingly intelligent, interconnected, distributed, and digital.

This report has considered how EDTs will disrupt, degrade, and enable NATO military capabilities in the 2023-2043 timeframe. Such characteristics of modern technologies are drivers of the current evolution and revolution in data, AI, autonomy, space, quantum, hypersonics, biotechnologies, materials, energy and electronics. Alone or in combination, they define the technological edge necessary for NATO's operational and organisational effectiveness. How quickly, in what order, and ultimately how successful these technologies will be, or what threats they will present, is yet to be determined. However, long-term forecasts of military technologies provide a useful exercise while offering a guide to prioritising capability and technology investments. The techno-policy, legal and ethical challenges that they present to NATO cannot be overstated. Understanding *why* they present a problem or opportunity, *how* they are expected to manifest, and *what* this will mean to the Alliance is an excellent first step and will ensure NATO remains technologically prepared and operationally relevant.

# Appendices



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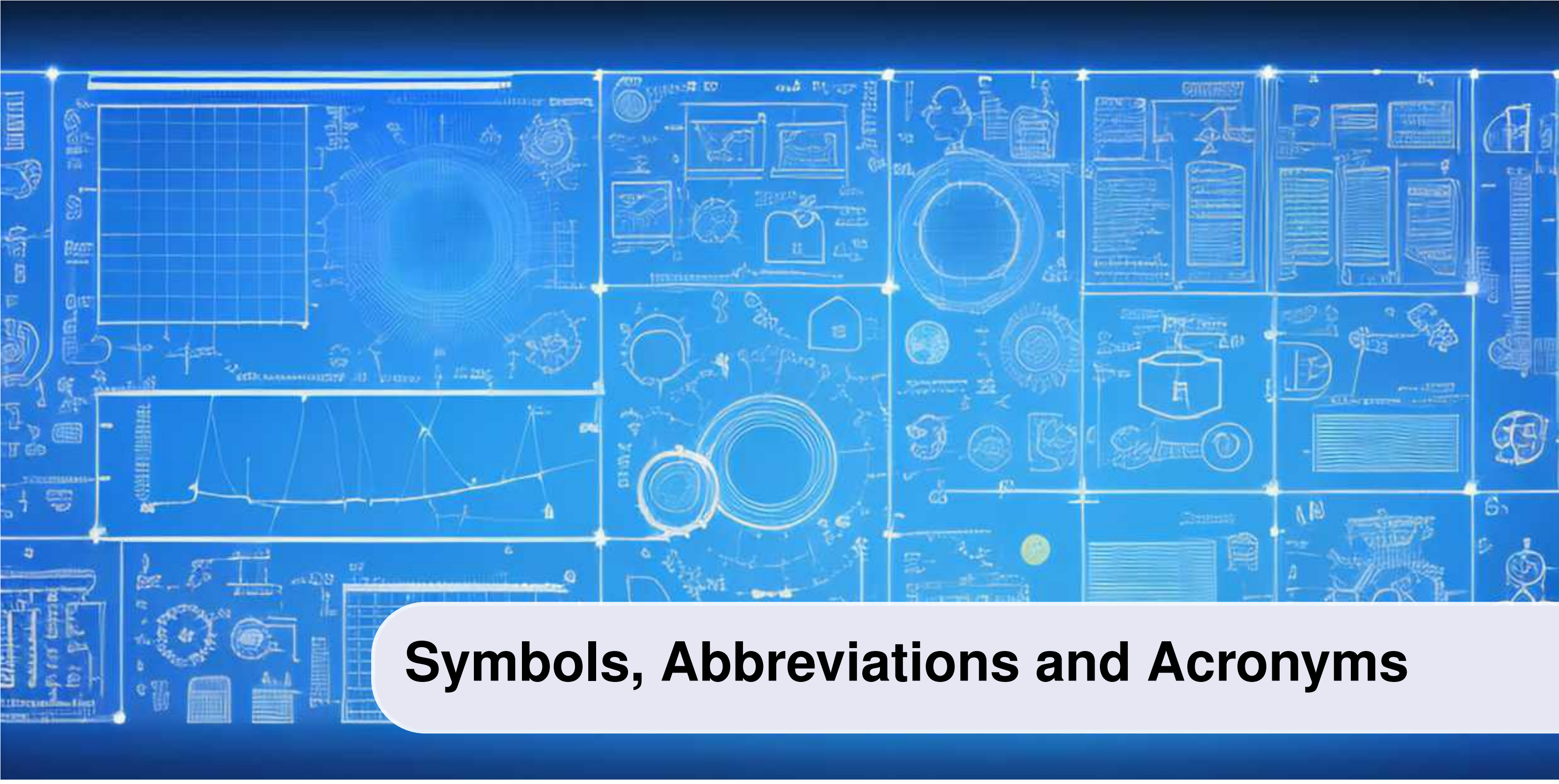

# Symbols, Abbreviations and Acronyms

| | |
|---|---|
| $\hbar$ | $h/(2\pi)$ |
| $c$ | Speed of Light in a Vacuum ($2.99792458 \times 10^{+8} m/s$) |
| $h$ | Planck Constant ($6.62607004 \times 10^{-34} m^2 kg/s$) |
| 2-D *or* 2D | 2-Dimensional |
| 3-D *or* 3D | 3-Dimensional |
| 4-D *or* 4D | 4-Dimensional |
| 5G | Fifth Generation (Wireless Technologies) |
| 5V | Volume, Velocity, Variety, Veracity and Visualisation (Challenges of Big Data) |
| A2AD *or* A2/AD | Anti-Access and Area Denial |
| ACT | Allied Command Transformation |
| ADF | Australian Defence Force |
| AFRL | Air Force Research Lab (USA) |
| AGI | Artificial General Intelligence |
| AI | Artificial Intelligence |
| AI HLEG | Artificial Intelligence High Level Experts Group |
| AIoT | Artificial Intelligence of Things |
| AIS | Automatic Identification System |
| AM | Additive Manufacturing |
| AMRG | Additive Manufacturing Research Group |
| ARL | Army Research Lab (USA) |
| ASAT | Anti-Satellite Weapons |

| | |
|---|---|
| ASW | Anti-Submarine Warfare |
| BDA | Battle Damage Assessment |
| BDAA | Big Data and Advanced Analytics |
| BHET | Bio and Human Enhancement Technologies |
| BLUE | Friendly Forces |
| C2 | Command & Control |
| C3 | Consultation, Command and Control |
| C4ISR | Command, Control, Communications, Computers (C4) Intelligence, Surveillance and Reconnaissance (ISR) |
| CBRN | Chemical, Biological, Radiological and Nuclear |
| CBRNE | Chemical, Biological, Radiological, Nuclear, and Explosive |
| CI | Computational Imaging |
| CMRE | Centre for Maritime Research and Experimentation |
| COA | Courses of Action |
| COP | Common Operating Picture |
| CPoW | Collaborative Program of Work |
| CRISPR | Clustered Regularly Interspaced Short Palindromic Repeats |
| CSBA | Center for Strategic and Budgetary Assessments |
| CWA | Chemical Warfare Agent |
| DARPA | Defense Advanced Research Projects Agency (US) |
| DCDC | Development, Concepts and Doctrine Centre |
| DEW | Directed Energy Weapon |
| DGA | Direction Générale de L'armement |
| DGRIS | Direction Générale des Relations Internationales et de la Stratégie |
| DIA | Defense Intelligence Agency |
| DIM | Deception, Identification & Monitoring |
| DIME | Diplomatic, Information, Military and Economic |
| DNA | Deoxyribonucleic Acid |
| DND | Canadian Department of Defence |
| DOD | US Department of Defence |
| DOTMLPF-I | Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities and Interoperability |

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|---|---|
| DRDC | Defence Research and Development Canada |
| DST | Defence Science and Technology Group (AUS) |
| Dstl | Defence Science and Technology Laboratory (UK) |
| DSTO | Defence Science and Technology Organisation (AUS) |
| E&EM | Electronics & Electromagnetics |
| EDA | European Defence Agency |
| EDT | Emerging And/Or Disruptive Technology |
| ELINT | Electronic Intelligence |
| EM | Electromagnetic |
| EO | Electro-Optical |
| EOD | Explosive Ordnance Disposal |
| EW | Electronic Warfare |
| FAS | Federation of American Scientists |
| FLIA | Foundation for Law & International Affairs |
| fm | Femtometer $(10^{-15}m)$ |
| FOI | Foi Totalförsvarets Forskningsinstitut / Swedish Defence Research Agency |
| GAI | Generalised Artificial Intelligence |
| GAN | Generative Adversarial Network |
| GAO | (US) General Accounting Office |
| GDP | Gross Domestic Product |
| GEO | Geosynchronous Equatorial Orbit |
| GNSS | Global Navigation Satellite System |
| GoC | Government of Canada |
| GPS | Global Positioning System |
| HALE | High Altitude Long Endurance |
| HCM | Hypersonic Cruise Missile |
| HDMS | His/Her Danish Majesty's Ship |
| HEO | Highly Elliptical Orbit |
| HET | Human Enhancement Technologies |
| HGV | Hypersonic Glide Vehicle |
| HT | Hypersonic Technologies |
| I2D2 | Intelligent, Interconnected, Distributed & Digital |

| | |
|---|---|
| IED | Improvised Explosive Device |
| IoT | Internet of Things |
| IP | Intellectual Property |
| IR | Infrared |
| IS/ESC | NATO International Staff / Emerging Security Challenges |
| ISR | Intelligence, Surveillance and Reconnaissance |
| ISTAR | Intelligence, Surveillance, Targeting and Reconnaissance |
| ITW&AA | Integrated Tactical Warning and Attack Assessment |
| JAIC | (NATO) Joint Artificial Intelligence Center |
| JALLC | (NATO) Joint Analysis and Lessons Learned Centre |
| JAPCC | (NATO) Joint Air Power Competence Centre |
| LEO | Low Earth Orbit |
| LIDAR | Light Detection and Ranging |
| M&S | Modelling and Simulation |
| Mach 1 | Speed of Sound (340.3 $m/s$; 1,235 $km/s$; 767 $mph$) In Dry Air at Mean Sea Level and Standard Temperature of 15°C) |
| MASINT | Measurement and Signature Intelligence |
| MC | Military Committee |
| MCM | Mine Countermeasures |
| MEO | Medium Earth Orbit |
| MIMO | Multiple-Input and Multiple-Output, |
| MIoP | Military Instruments of Power |
| ML | Machine Learning |
| MOD | (UK) Ministry of Defence |
| mTBI | Mild Traumatic Brain Injury |
| NAC | North Atlantic Council |
| NASC | Naval Air Systems Command |
| NATO | North Atlantic Treaty Organization |
| NCIA | NATO Communication and Information Agency |
| NDPP | NATO Defence Planning Process |
| NGO | Non-Governmental Organisations |
| nm | Nano-Metre ($10^{-9}m$) |

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|---|---|
| NOAA | National Oceanic and Atmospheric Administration |
| NRC | National Research Council (Canada) |
| OCS | NATO Office of The Chief Scientist |
| OECD | The Organisation for Economic Co-Operation and Development |
| OGD | Other Government Departments |
| ONR | Office of Naval Research (USA) |
| OODA | Observe, Orient, Decide, and Act |
| OR&A | Operational (Operations) Research & Analysis |
| OTH | Over-The-Horizon |
| PAL | Phase Alternating Line |
| PCE | Physiological and Pharmacological Cognitive Enhancements |
| PCL | Passive Coherent Location (Radar) |
| PLA | People's Liberation Army |
| pm | Picometer ($10^{-12}m$) |
| PNT | Positioning, Navigation and Timing |
| PRC | People's Republic of China |
| PTSD | Post-Traumatic Stress Disorder |
| QC | Quantum Communication |
| QIS | Quantum Information Science |
| QKD | Quantum Key Distribution |
| QO | Quantum Optics |
| QT | Quantum Technologies |
| R&D | Research and Development |
| RAP | Recognised Air Picture |
| RAS | Robotics and Autonomous Systems |
| RCAF | Royal Canadian Air Force |
| RDDC | Recherche et Développement Pour La Défense Canada |
| RDS | Research and Development Statistics |
| RED | Hostile Forces |
| RF | Radio Frequency |
| ROE | Rules of Engagement |
| RSGB | Royal Society (Great Britian) |

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|---|---|
| S-AIS | Satellite - Automatic Identification System |
| S&T | Science and Technology |
| SA | Situational Awareness |
| SACEUR | Supreme Allied Commander Europe |
| SACT | Supreme Allied Commander Transformation |
| SAR | Synthetic-Aperture Radar |
| ST | Space Technologies |
| STO | Science & Technology Organization |
| SWaP-C | Size, Weight, Power and Cost |
| TBM | Theatre Ballistic Missile |
| TCPED | Tasking, Collection, Processing, Exploitation, and Dissemination |
| TFA | Technology Focus Area |
| THz | Terahertz ($10^{12} Hertz$) |
| TOE | Targets of Emphasis |
| TRADOC | U.S. Army Training and Doctrine Command |
| TRL | Technology Readiness Levels |
| TSTO | Two State to Orbit |
| TWC | Technology Watch Card |
| UAV | Unmanned Air Vehicles |
| UCAV | Unmanned Combat Aerial Vehicle |
| UGV | Unmanned Ground Vehicle |
| UK | United Kingdom |
| UMS | Unmanned Maritime Systems |
| UNESCO | United Nations Educational, Scientific and Cultural Organization |
| US | United States |
| USA | United States of America |
| USD | US Dollars |
| USV | Unmanned Surface Vehicle |
| UUV | Unmanned Underwater Vehicles |
| UV | Ultraviolet |
| UxV | Unmanned Vehicles |
| vKHS | Von Kármán Horizon Scan |

| | |
|---|---|
| vKI | Von Kármán Institute |
| VV&A | Verification, Validation, & Accreditation |
| WEF | World Economic Forum |
| μm | micrometer ($10^{-6}m$) |


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