The Central Research institute
of the Armed Forces of Ukraine

Military Science. Vol. 2 No. 1 (2024)

DOI: 10.62524/msj.2024.2.1.15

Implementation of the emerging and disruptive technologies as the key to technological superiority in modern warfare

Kostiantyn Kulahin
PhD in engineering, senior researcher
senior researcher
Ivan Kozhedub Kharkiv National Air Force University
61023, Sumska Street, 77/79, Kharkiv, Ukraine
e-mail: k.kulagin@ukr.net
ORCID: 0000-0003-1189-5623

Ivan Nos
PhD in engineering
head of scientific research department
Ivan Kozhedub Kharkiv National Air Force University
61023, Sumska Street, 77/79, Kharkiv, Ukraine
e-mail: 171a16@gmail.com
ORCID: 0000-0003-1501-0503

Oleksiy Solonets
PhD in engineering, senior researcher
leading researcher
Ivan Kozhedub Kharkiv National Air Force University
61023, Sumska Street, 77/79, Kharkiv, Ukraine
e-mail: alex_solonez@ukr.net
ORCID: 0000-0001-6223-5022

Kostiantyn Kvitkin
researcher
Ivan Kozhedub Kharkiv National Air Force University
61023, Sumska Street, 77/79, Kharkiv, Ukraine
e-mail: kosta_kit@ukr.net
ORCID: 0000-0002-8330-5023

Abstract. The relevance of article is due to the fact that in the conditions of confrontation between countries different in terms of resources, strength of the army and number of weapons, military superiority over the enemy are achieved by using asymmetric and hybrid actions with using innovative high-tech weapons and C4ISR. The search for innovative approaches to the management of troops, new methods of using both traditional types of weapons and new ones created on unconventional physical principles, the introduction of the emerging technologies is an urgent need for the development of the Ukraine defense capabilities - the key to technological superiority in modern warfare. Today, most of the developed countries pay considerable attention to scientific research on the emerging and disruptive technologies, strive to maintain advantages in this field. Based on this, the research of promising scientific and technical trends and determining the potential of their application in military affairs is an important scientific and practical tasks that must be solved. The leading approach to solving this problematic issue is the use of the results of the analysis of scientific publications, reports of leading international security institutions, the use of statistical

methods of scientometric and patent analysis, as well as the assessment of the level of attention or expectations. The article presents the results of a systematic analysis of existing technological trends, the most significant new and breakthrough technologies, as well as an assessment of their impact on the sphere of security and defense. A certain author's view on the possibilities of using such technologies is offered. The materials of the article are of practical significance for specialists who are responsible for the formation of directions of scientific and scientific-technical activity, the introduction of innovations and the emerging technologies in the activities of the defense-industrial complex.

Keywords: innovation, emerging and disruptive technologies, artificial intelligence, robotic and autonomous systems, novel materials, defense capabilities

Introduction

Currently, humanity is facing a dangerous, unpredictable and unstable world with non-traditional challenges and threats, such as asymmetric and hybrid wars, space militarization, international terrorism, cyber threats, information and psychological operations, climate change and bioterrorism. The ability to respond promptly to current and future challenges can be improved through the active and driving role of emerging and disruptive technologies (EDTs), which can be implemented within the next 10-20 years and will have a significant impact on the economic, socio-political and, of course, defense capabilities of those countries or security associations of countries that will timely and correctly assess the potential of such technologies and take a leading position in their practical application.

Under the newest (emerging) technology we will understand a radically new innovative technology characterized by relatively rapid development and a certain degree of consistency that has been maintained for a long time, the technical and value potential of which is largely uncertain, ambiguous and not fully realized, but which is assessed as having a significant impact on the socio-economic, military-technical and other spheres of society in the future. Such technologies will reach maturity and find implementation within 10-20 years, and, as of today, they are not widely used or their impact on defense, security and industry is not sufficiently analyzed and fully understood. A breakthrough technology is a relatively new innovative technology, the degree of development of which allows us to assess its technical and value potential as unequivocally capable of quickly and radically changing existing norms and processes in certain areas of life or in society as a whole, destroying established business models, traditional markets and relationships between governance entities, institutions and consumers, to dramatically displace old technologies, products or services by overcoming technical barriers, applying new ways of solving problems and meeting needs that were not previously available or underdeveloped, significantly reduce costs, improve productivity and increase accessibility to a wider audience, changing the demand for goods and services and consumer preferences.

Emerging and disruptive technologies have several generalized characteristics that help experts identify and categorize them promptly, including innovation, synergistic potential, ability to develop, impact on the future, and ability to change traditional business models. These characteristics help to identify the latest and most disruptive technologies, and understand their future potential and likely impact on various areas.

Often, emerging and potentially disruptive technologies present opportunities for integration with each other and with other existing established technologies, which can lead to more complex and powerful technological solutions called convergent technologies. They are defined as innovative technologies that combine several technologies in a certain way to create a synergistic effect.

Over time, the latest, breakthrough and convergent technologies may become critical for the state - technologies that require protection and guaranteed preservation, are of fundamental

importance for sustainable economic development, ensuring economic and national security and defense of the state, maintaining existing and acquiring new defense capabilities, creating high-tech competitive energy-efficient and environmentally friendly products. When compiling a list of critical technologies, each country relies on the specifics of its own goals, needs, capabilities, and ambitions.

The driver of EDT implementation in the military sphere is NATO. Within its structure, the NATO Science & Technology Organization (STO) is active, and several specialized bodies, agencies and working groups have been established, including the NATO Advisory Group on Emerging and Disruptive Technologies (AGEDT), NATO's Data and Artificial Intelligence Review Board (DARB), The Defense Innovation Accelerator for the North Atlantic (DIANA), which cooperate with public and private defense sector, international organizations, including the European Union (EU) and the United Nations (UN), academia and civil society to develop and, most importantly, implement EDT and establish international principles for the responsible use of these technologies.

EDTs and other innovative technologies will be used in the military sphere, regardless of where and why they were created. At the same time, they may create entirely new operational domains (e.g., cyberspace) or re-apply traditional ones. Rapid changes in the technological landscape are driving the Fourth Industrial Revolution “Industry 4.0”, and the seventh-generation military revolution.

German economist Klaus Schwab is considered to be the developer and ideologist of the Fourth Industrial Revolution concept. He outlined his vision of “Industry 4.0” in his books “The Fourth Industrial Revolution” (2017) and “Technologies of the Fourth Industrial Revolution” (2018). The main technological driver of this revolution is considered to be disruptive innovation and its synthesis in three main areas: physical, digital, and biological. And this, in the author's opinion, determines the fundamental difference between the Fourth Industrial Revolution and all previous industrial revolutions. The ability of innovative technologies to breakthrough (critical change) sustainable technologies was first discussed by Clayton Christensen in his book "The Innovator's Dilemma: How New Technologies Kill Strong Companies" (2004), and breakthrough innovations and corresponding breakthrough innovative technologies were identified as the main catalyst for changes in consumer values in the market and sustainable business processes.

In recent years, experts from various fields have explored the essence and prospects of the latest and most disruptive technologies. In particular, (Rotolo, Hicks, Martin, 2015) discusses terminological aspects in detail, (Küfeoğlu, 2022) reveals the essence and principles of organization of the most well-known emerging technologies at the moment, (Mariette, Bernard, Meyerson, 2023) analyzes the top 10 emerging technologies of 2023 and considers the methodology for assessing their impact on society and the economy. Armstrong (2017) considers various concepts, methodologies, tools and areas of application of disruptive technologies, Manners-Bell and Lyon (2022) describes the peculiarities of the application of disruptive technologies in the field of logistics and supply chain management, and Slyusar, Sotnyk, Kupchyn, 2020) proposed a definition of critical and breakthrough technologies, as well as an approach to their structuring, as well as a conceptual approach to structuring the most important critical and breakthrough technologies for the state defense sector using a decision-making model based on fuzzy logic. Aspects of the selection and application of critical technologies in the defense sector are discussed in (Slyusar, Sotnyk, Kupchyn, 2020), (Sotnyk, Rastryhin, Kupchyn, 2020), and the study of the potential and possibilities of introducing convergent technologies in Ukraine is discussed in (Matyushenko, 2016). Some publications present the results of applying statistical methods of scientometric and patent analysis to study global technological and scientific trends (Pysarenko and Kvasha, 2021), assessing the level of attention of scientific and technical communities, defense companies, and individual countries to new, disruptive, and critical technologies (Pysarenko and Kvasha, 2020).

By far the most significant source for EDT analysis is the NATO Science & Technology Organization (STO) report "Science & Technology Trends 2020-2040" (Reding, Eaton, 2020) and the 2023 report "Science & Technology Trends 2023-2043. Across the Physical, Biological, and

Information Domains" in two parts (Reding, Lucia, Blanco, Regan, Bayliss, 2023), in which NATO experts identified the main strategic priorities in the development of weapons and military equipment, which should be based on ten closely interrelated EDTs, which are considered to be the main strategic disruptors over the next 20 years. Other important documents are two reports prepared by AGEDT, with advice on how to optimize their innovation efforts. The first one (Chana, 2020), published in March 2021, provided four main initial tips for NATO: improve technological literacy, create an effective network of innovation centers; develop and facilitate new mechanisms for financing innovation with the participation of private sector actors, and create innovative partnership initiatives with external stakeholders. In its second annual report (Chana, 2021), published in April 2022, the group reviewed three critical ongoing areas of work to ensure that NATO and Allies can rapidly adopt new technologies and maintain technological advantage through the DIANA project, the NATO Innovation Fund, and the Human Capital Innovation Policy, which provides guidance to NATO on how to attract, retain, and develop talented people with technical skills and innovative thinking. Since June 2020, Ukraine, as a NATO Enhanced Opportunities Partner, has been able to participate in almost all initiatives and studies conducted by NATO working groups, organizations, and agencies.

An analysis of publications shows a sharp increase in the interest of scientists and defense program (project) managers in the tools for identifying EDT and assessing (predicting) the results of their implementation, both on the positive side and taking into account the negative risks of their use. Most publications are devoted to economic, transport and logistics, information, technical, and environmental aspects, and only a small share of works is devoted to defense and technical aspects, which makes this study relevant.

Therefore, the purpose of this article is to define the essence of EDTs and the potential for their use to acquire new defense capabilities in the context of the war with the Russian Federation and possible future hybrid and asymmetric wars, to systematize the identified technological trends, to focus the attention of the scientific community on the need for accelerated analysis of potential technological advantages that EDTs can provide, especially in the security and defense sector of the state, to expand the discussion around urgent technological needs to acquire the necessary equipment for the troops to win.

Methodological Framework

According to the results of studies (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023), (Chana, 2020), (Chana, 2021) conducted by NATO experts, it is believed that by 2043, four main characteristics will determine the emergence and implementation of the latest and most disruptive technologies in the military sphere:

intelligence (ensured by the use of symbiotic artificial intelligence, its integration at all levels using machine learning technologies, and analytics of large amounts of structured and unstructured data);

interconnectedness (ensured by the use of a distributed network of primary sources of information (virtual and physical) using new encryption methods and Distributed Ledger Technology (DLT));

distributed (ensured by large-scale decentralized and ubiquitous use of various sensors and sensors, collection and processing of large amounts of data);

digitalization (ensured by the digital combination of human, physical and information domains to create breakthrough effects).

The implementation of EDT should ensure the implementation of the five main imperatives of the NATO Warfighting Capstone Concept (NWCC) (2023): cognitive superiority, multilevel resilience, sustained impact and demonstration of power, cross-domain command and control, and integrated multilayer defense in five operational environments (domains), including space and cyberspace.

As of the end of 2023, NATO experts have identified 10 main groups of advanced and disruptive technologies:

1) technologies for processing and advanced analytics of large data sets (Big Data and Advanced Analytics, BDAA) and information and communication technologies (ICT))
2) artificial intelligence technologies (Artificial Intelligence, AI);
3) Robotics & Autonomous Systems (RAS);
4) Space Technologies (ST);
5) Hypersonic Technologies (HT);
6) Quantum Technologies (QT);
7) Biotechnology and Human Enhancement Technologies (BHET);
8) Novel Materials & Advanced Manufacturing;
9) energy and advanced energy propulsion (Energy & Propulsion);
10) electronic and electromagnetic technologies (Electronic & Electromagnetic, E&EM).

The main defining characteristics of these technologies are: the symbiosis of human and artificial intelligence, interconnectedness (combination) of virtual and physical dimensions, distributed storage and processing of large data sets, global digitalization of physical, human and information spaces.

Technological developments in the areas of artificial intelligence, autonomy, space, some areas of big data, energy, electrical engineering and electromagnetic effects are considered by NATO experts to be predominantly (but not exclusively) disruptive, as developments in these areas are based on a long history of support for scientific and technological development. Activities in these areas are centered around their effective implementation and impact on other technologies. Thus, a significant or revolutionary disruption of military capabilities is either already underway or will have a significant effect within the next 5-10 years. New developments in quantum technologies, biotechnology, materials with new properties, and some aspects of data analytics (e.g., next-generation 6G communication networks) are assessed as emerging technologies because previous development cycles have had a significant impact on previous technological revolutions. They will require significantly longer development time (10-20 years) before their disruptive nature is fully realized into a specific technological or military capability.

Results and Discussions

Let's analyze the main 10 groups of the latest and most disruptive technologies in more detail.

The "BDAA & ICT" technology group provides advanced analytical tools for analyzing data that is large in volume, variety, structured, reliable, timely, and visualized, and accelerated digitalization, the proliferation of new sensors, new modes of communication, smart things technologies, and the virtualization of social and cognitive spaces greatly contribute to the development of advanced analytics of large distributed data sets. The most well-known new technologies for processing large data sets (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023) are: Advanced Computing & Methods (advanced computing technologies and methods of high-performance computing); Novel Applications & Decision Making (new software and algorithmic applications for decision support with improved interface and visualization and methods of multi-criteria group decision making); Distributed Ledger Technologies (distributed ledger technologies that provide simultaneous access, verification and updating of records in a network database); Advanced Networks (advanced fault-tolerant and cyber-resilient data transmission networks that integrate satellite, cellular, wired and wireless communication channels into a single network); Networked Sensors & Sensing (sensor network and network sensing technologies that allow collecting and analyzing information from various traditional and advanced sensors connected to the network in all operating environments); Data Storage (new data storage technologies); Cyber & Cyberphysical Systems (cyber resilience and cyber defense technologies).

The introduction of BDAA technologies will increase the efficiency of military structures, reduce costs, improve logistics, real-time monitoring of resources and predictive assessments of plans and programs. At the same time, it will generate much greater situational awareness at the strategic, operational, tactical, and defense-industrial levels.

It should be noted that to operate with big data and use it effectively, it is necessary to use faster, more reliable and distributed new-generation communication and data transmission networks. In this area of innovation, the development of mobile broadband networks is becoming increasingly important, allowing for continuous communication and combat control functions during high-speed maneuver operations in wide theaters of war. The required highly efficient and secure military communications can be provided by the latest commercial fifth (5G) and sixth-generation (6G) mobile technologies, which continue to evolve rapidly due to improved technologies and new cellular models (Keller, 2020). Key advances over previous generations include multi-interface access, spectrum expansion, network software based on Network Function Virtualization (NFV), Software-Defined Networking (SDN), and Internet of Things (IoT) features.

The introduction of next-generation military communications technology will ensure high-performance mobility, flexibility and adaptability, data security, cognitive control of bandwidth, frequency, and speed of information transmission to ensure reliable and uninterrupted communication in congested and complex electromagnetic environments, invulnerability to jamming, attacks on fiber-optic cables and satellite communication channels, resistance to cyber attacks on radio software and to electromagnetic pulses caused by electromagnetic munitions or a nuclear explosion at high altitude. To ensure high defense capabilities, military communication systems must become smaller, and lighter, cover multiple operating radio wave bands, and be capable of transmitting any data, including geospatial and video data.

The BDAA & ICT technology group is the core technology group for all EDTs and is central to their use for the development of military operational capabilities, which should be defined in the defense planning process (Slyusar and Kulagin, 2019). However, the greatest synergistic effect is obtained through the combination of these digital technologies with intelligent technologies, in particular artificial intelligence.

The group of technologies "Artificial Intelligence (AI)" is a technology that provides human-made intelligent systems (machines) with the ability to act and perform tasks in a physical or digital environment that usually require human intelligence (e.g., recognizing patterns, learning from experience, drawing conclusions, making predictions, or taking action), taking into account a complex goal and choosing the best actions (according to predefined parameters and algorithms), and that need to be performed to achieve the goal based on the perception of its operating environment, interpretation of collected structured or unstructured data, justification of knowledge gained from this data, analysis and selection of possible action strategies that may rely on learning or adaptation to the environment (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023). AI has been called the most influential technology ever invented and is expected to play a significant disruptive role in defense and security.

There are two generalized types of artificial intelligence: "weak" or narrow artificial intelligence (Artificial Narrow Intelligence, ANI) and "strong" artificial intelligence, which consists of general artificial intelligence (AGI) and artificial super intelligence (ASI). ANI is a type of artificial intelligence for solving a certain specialized group of tasks that makes decisions only based on the limited data used for its training. Examples of such systems are: Natural Language Processing (NLP) systems, object or face recognition systems, chatbots, conversational or recommendation assistants, powerful lexicographic systems, machine translation programs and electronic dictionaries, Predictive Maintenance (PdM) models, specialized autonomous platforms, etc. AGI can learn and reason based on experience, solve problems and communicate by imitating generalized human-level intelligent behavior. In addition, it can plan any task. ASI is a type of artificial intelligence that is expected to

exceed the intelligence and abilities of the human brain.

Artificial intelligence is based on Machine Learning (ML) and Deep Learning technologies. ML is a type of artificial intelligence that uses big data and statistical methods of processing it, capable of recoding itself in accordance with constantly growing new data. DL is a subclass of machine learning algorithms based on artificial neural networks (e.g., Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), Residual Neural Network (ResNet), Quaternion-Valued Neural Networks (QVNN)), with Long Short-Term Memory (LSTM), both algorithmic and biological (Disentangling AI, Machine Learning, and Deep Learning, 2021), and uses a multi-layer filter system for hierarchical extraction of useful features.

A separate class of RAS is the Lethal Autonomous Weapon System (LAWS), which selects and engages targets that meet certain predefined criteria without human intervention, after a human decision to deploy the weapon with the understanding that the attack, once initiated, cannot be stopped by human intervention (Robotic and Autonomous Systems in a Military Context, 2021).

The ultimate goal of integrating robotic and autonomous systems into military activities is to combine humans and RAS into a powerful, well-coordinated team, allowing RAS to perform boring, dirty, dangerous and expensive tasks while utilizing the unique talents, experience and intuition of humans.

NATO experts have grouped the areas of RAS development into four broad areas (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023): Advanced RAS, RAS Application, Counter-RAS, and RAS Man-Machine Teaming (combining human, robotic, and autonomous systems into a working team).

The widespread introduction of RAS, especially those with artificial intelligence, in the military sphere creates significant moral and ethical challenges, but also opens up new opportunities to increase the efficiency, effectiveness and flexibility of the armed forces by

the speed of decision-making and prioritization of threats, much higher than the human reaction time, which allows to significantly reduce the cycle of observation, orientation, decision-making and implementation of appropriate actions - the OODA cycle (Observe, Orient, Decide, Act)

high reliability and efficiency in performing specific tasks;

accuracy of image recognition and sensory perception of RAS that exceeds the level of human capabilities;

increased range and endurance, ability to control swarming and self-healing of the swarm structure in case of failure of individual elements;

Increased resistance to weather and climatic conditions, pollution, intentional and unintentional mechanical and electromagnetic factors, and combat damage;

reducing the cost of production of mechanical, electronic and software components and services, especially through additive manufacturing;

Increased time of functioning as intended (RAS can perform tedious and repetitive high-level monitoring tasks 24/7 without the need for "rest", logistics planning can be solved efficiently, and the limits of human multitasking can be quickly exceeded);

increasing the flexibility and adaptability of RAS throughout the system's life cycle through scalability, functionality expansion, component and software upgrades, AI training and self-improvement, etc.)

Robotic and autonomous systems represent a transformation of forces and capabilities in the military sphere. They provide a significant military potential to expand the quality, coverage, efficiency and security of military operations and change the forms and methods of armed struggle in future wars and conflicts.

Space Technologies (ST) - technologies developed through space exploration sciences and space vehicles created by the aerospace industry, which necessarily take into account the unique and extreme characteristics of near-Earth, middle and deep space.

Over the past decade, interest in the use of space and space technologies for military purposes has grown significantly, driven by two interrelated trends:

First, over the past few years, the share of commercial space programs has increased significantly, private financial assets have radically changed the directions and intensity of space exploration and contributed to changes in the forms and methods of armed struggle (for example, the use of commercial satellite communications by Starlink (USA), satellite imagery from private American companies Maxar Technologies Ltd, Planet Lab, and BlackSky Technology Inc. as well as Argentine Satellogic, Spanish Deimos Space, and Finnish ICEYE by the Armed Forces of Ukraine in the war against the Russian Federation has significantly increased situational awareness and decision-making support). In addition, the global commercial space industry continues to lead the way in drastically reducing launch costs, new options for deploying space assets, and commercial availability of high-quality space-based information;

second, new technologies and production methods have changed the nature, availability and cost of space utilization (e.g., new propulsion options such as advanced solar-powered electric propulsion systems (Advanced Electric Propulsion System, AEPS) (Peterson, 2021), electromagnetic acceleration technologies for moving payloads into space (SpinLaunch) (Jeffrey, 2022), on-board AI, advanced robotics, remote maintenance of satellites in orbit, reduction of size, weight, power consumption, and cost (SWaP-C) of systems, advanced and new sensors, 3D printing, improved energy storage and efficiency, and next-generation encryption technologies. As a result, outer space is becoming a strategic driver of technological development and geostrategic competition.

In 2019, NATO foreign ministers recognized space as the fifth operational domain of military activities, in January 2022, NATO's Overarching Space Policy (2022) was published, and at the Brussels Summit in 2021, it was recognized that harmful activities in space could lead to the application of Article 5 of the North Atlantic Treaty (Brunner, 2021). Therefore, the use of space in the interests of the system of operational (combat) command and control, communications, computerization - intelligence, surveillance and reconnaissance (Command, Control, Communications, Computers - Intelligence, Surveillance, Reconnaissance, C4ISR), as well as navigation and defense against threats in and from space, are central to many of NATO's existing defense capabilities, and it is the basis on which NATO is building a technological edge that partner countries can join.

Thus, we can confidently expect an increase in the number of space programs, the use of space technologies and the amount of data received from space over the next 20 years. In combination with BDAA & ICT, AI and RAS technologies, space technologies can significantly improve situational awareness at all levels, space-based support for operations, protection of space-based military and commercial infrastructure, reliable missile and space defense, and operational effectiveness of military and humanitarian missions around the world. However, the issue of sustainability of space assets and systems is becoming no less relevant than the benefits provided by such systems.

The Hypersonic Technologies (HT) group of technologies is the technology that enables advanced hypersonic weapons systems (HWS) (missiles, gliders, aircraft, cruise missiles, maneuverable warheads) to reach and maintain a speed of more than Mach 5 (6125 km/h) in the Earth's atmosphere or at its boundary, and to maneuver at such speeds. These systems are particularly strategically disruptive given the reduced reaction time available for Integrated Tactical Warning/Attack Assessment (ITWAA), maneuverability, reduced time to target, difficulty in developing countermeasures, and the threat they pose to critical targets individually or en masse (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023). Systems of this origin can rely on the kinetic effect of use alone or on the use of various types of warheads, including nuclear ones. Countermeasures against such hypersonic systems are particularly challenging due to their speed, maneuverability, and altitude.

The main advantages of HWS are: limited time for detection and warning of use, due to the

high speed and specific flight profile of hypersonic weapons; rapid response to the need to quickly reach and guarantee the destruction of a critical target, especially a moving one or one with temporary vulnerability; high ability to overcome enemy missile defense, due to the combination of high speed, low altitude, maneuverability and stealth; unpredictability for enemy assessment, due to the difficulty of predicting the trajectory of the missile. The main challenges in the design of HWS are the selection of materials that can withstand extreme loads and temperatures, as well as control systems that can operate in extreme conditions, in particular, due to the plasma created around the object moving at hypersonic speeds through dense layers of the atmosphere and isolating the aircraft from signals from the outside. However, new materials, improved modeling and simulation, and more efficient propulsion devices (jet engines) have contributed to certain technological breakthroughs in hypersonic research and significantly increased the likelihood of their widespread operational use (Tirpak, 2018).

Currently, China, Russia, the United States, the United Kingdom, France, India, Iran, Japan, and Australia have openly recognized the research, testing, and experimental use of hypersonic systems (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023), (Speier, Nacouzi, Lee, Moore, 2017), (Mizokami, 2019), (Bernstein, Hancock, 2021), (Hypersonic Weapons, 2024), and the Armed Forces of Ukraine destroyed modern Russian hypersonic missiles X-47M2 Kinzhal and 3M22 Zircon for the first time with the MIM-104 Patriot anti-aircraft missile system during their combat use in the capital of Ukraine in 2022-2024 (Lendon, 2024).

The Quantum Technologies (QT) group of technologies is a group of technologies that use quantum physics and related phenomena at the atomic and subatomic levels, in particular quantum entanglement and superposition (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023), (Amerongen, 2021), (Krelina, 2021). These effects support significant technological advances primarily in cryptography and unbreakable encryption systems, quantum computing, precise navigation and time synchronization, sensing using ultra-sensitive sensors and sophisticated visualization, communication, and the creation of new materials. Quantum phenomena underpin modern technologies, including the transistor, nuclear energy, electron microscopes, superconductivity, photoelectric detectors, medical imaging (functional magnetic resonance and positron emission tomography), lasers, and solid-state devices. Such technologies use the rules of quantum behavior of matter on the atomic scale (less than 10 nm), strong encryption and communication, and hitherto impossible levels of computing power (for some classes of problems).

Quantum technologies can be grouped into five main overlapping groups:

Quantum computing - a type of computing that does not operate according to standard mathematical algorithms, but takes advantage of quantum mechanical phenomena such as superposition, quantum entanglement, and interference (Amerongen, 2021), (Krelina, 2021);

Quantum communication - communication that uses subatomic particles, such as photons, to transmit data using the principles of quantum mechanics, provides the use of secure or cryptographic communication methods using quantum properties, Quantum Key Distribution (QKD) and Post-Quantum Cryptography (PQC) (2023). The Quantum Internet can also be considered part of this field of research, defined as a (theoretical) network built through entangled quantum communication networks and computers;

Quantum sensing and metrology is a field of knowledge about the use of quantum systems, quantum properties or phenomena to measure physical quantities with high accuracy (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023), (Krelina, 2021). For example, the measurement of magnetic or gravitational fields using quantum sensing technologies is used for precise positioning, navigation, and timing synchronization in inertial high-precision navigation systems in combat platforms where the use of global satellite navigation systems such as GPS is impossible or difficult;

quantum materials - materials whose properties can be explained only with reference to

quantum phenomena. Two-dimensional materials, such as graphene or graphene, are often referred to as quantum materials, as are quantum topological materials, whose electronic structures are different (and much more complex) than those of metals or insulators.

Quantum optics - technologies for applying quantum mechanics to understand and exploit the interaction of light with matter. This applies to a variety of applications such as interferometry, photonics, quantum computing, communications, sensing, etc.

Today, three groups of quantum technologies are already considered by military experts as having the potential to revolutionize military operations (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023).

First of all, these are quantum sensors. The use of ultra-sensitive gravimetric, magnetic, or acoustic sensors will significantly increase the effectiveness of underwater warfare capabilities, potentially making the oceans transparent (Roblin, 2019). Quantum radar (O'Donnel, 2019) could make stealth technologies obsolete, provide more accurate target identification, and allow for covert detection and surveillance. Precision clocks will allow for the development of (accurate) PNT systems for use in places inaccessible to GPS (e.g., under ice).

Second, there is quantum computing, potentially the most disruptive quantum technology of all, which could make classical computing tasks that were previously unattainable viable in areas such as optimization, BDAA&ICT, AI, and simulation and testing. This computational advantage can greatly enhance the decision-making and operational effectiveness of any armed force, and for the first time make the most robust modern encryption methods and encrypted data possible to break and steal.

Thirdly, quantum communication and cryptography technologies are used to create ultra-secure communications with a high degree of intrusion detection and low probability of interception. Achievements in quantum communications are considered essential for the development of efficient next-generation wireless communication technologies such as 6G.

Although new quantum technologies have the potential to revolutionize military operations (missions), most of them are still in the early stages of development, and significant technical challenges remain to be addressed before real operational systems can be developed.

The BHET group of technologies includes biotechnologies that use organisms, tissues, cells, or molecular components derived from living things to affect living things or to affect the functioning of cells or molecular components of cells, including their genetic material, and human enhancement technologies that apply biomedical interventions to the human body that improve physical fitness or cognitive, physiological, sensory, or social functions beyond baseline. These technologies cover the spectrum of biological technologies such as genetic manipulation (e.g. CRISPR) for the development of new pathogens or medical countermeasures, manufacturing methods using biological processes, human enhancement technologies using integrated robotics (e.g. exoskeletons, artificial limbs or internal organs), neurointerfaces, vision enhancement technologies, socio-technical symbiosis with AI and RAS, pharmacological approaches to cognitive and physical enhancement, increased virtualization of the socio-cognitive environment that supports the development of new social, information

NATO experts have grouped breakthrough areas of BHET technology research into eight groups (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023), (Ladisch, 2001):

Biowarfare and Heath (biological warfare and military health) - technologies for identifying pathogens, slowing or stopping the pathophysiological processes of bioagents, creating new classes of drugs, means for the prevention and prophylaxis of diseases, biometrics, wound care and tissue regeneration.

Genetics and Microbiology – technologies for gene editing and means to mitigate accidental or intentional misuse of gene editing, development of personalized medicines and therapeutic/prophylactic treatments for military personnel, as well as discovery of genome-based

medical and biotechnological applications.

Bioengineering is a technology that applies engineering principles of design and analysis (with the support of AI/ML technologies) to biological systems and biomedical technologies, their operation (e.g., biomanufacturing) and problem solving in the interaction of such systems. Over the next twenty years, bioengineering is expected to become much easier and cheaper, thanks to new developments that will reduce the cost of biotechnology for reading, writing, and editing genes. In addition, new research efforts are improving and expanding the ability to create complex multicellular systems for enhanced capabilities and functional materials with integrated biological functions. This includes 3D bioprinting, AI/ML-enabled bioengineering, hybrid materials, synthetic biomimetic materials, smart materials, and organoids ("brain balls").

Systems Biology and Bioinformatics – technologies that study complex biological systems through large-scale quantitative analysis of dynamic interactions between multiple components of a biological system. Areas of particular interest include novel chemical, biological, radiological and nuclear biological sensors and computational biology.

Cognitive Enhancement - technologies for improving human cognitive abilities, monitoring and manipulating neural activity in the brain to improve cognitive performance and neurological and psychiatric care in military medicine, as well as for creating new methods and technologies for the treatment of brain injuries, neurodegenerative diseases and certain mental illnesses, including the treatment of post-traumatic stress disorder.

Social Enhancement – technologies for studying social networks, analyzing, modeling and simulating their dynamics, as well as the corresponding social behavior of individuals, certain social groups and society as a whole. The research is being conducted in two directions: predicting new properties of social networks and targeting social consequences, such as disinformation, cognitive and hybrid warfare campaigns, and using "virtual reality" to expand and improve social interaction.

Physical Performancet - technologies for increasing human physical performance and the efficiency of individual biological systems of the body (e.g., strength, endurance, tolerance to pain or fatigue).

Human-Machine Symbiosis – technologies for increasing human productivity with the help of mechanical or electronic means, the use of artificial intelligence, computer vision, augmented reality and human-machine interfaces. Improving SWaP-C characteristics will facilitate the use and eventual development of sensory and motor augmentation capabilities, such as virtual reality contact lenses or exoskeletons.

BHET technologies are expected to become available within the next 20 years. The most breakthrough scientific and technical areas of BHET that should be of interest to the military are: bioinformatics and biosensors, the use of genetic modifications, pharmacological agents, electromechanical devices or neurological interfaces to improve human physiological and neurological performance, medical countermeasures and technologies, synthetic biology, etc.

The Novel Materials & Advanced Manufacturing group of technologies combines technologies for creating artificial materials with unique and novel properties that can be produced using nanotechnology or synthetic biology methods, as well as technologies focused on the design, development, assembly and optimization of manufacturing processes required to create such materials and microelectronics.

Modern advances in BDAA, AI, ST, QT, BHET and new discoveries in materials science (e.g., graphene, one of the thinnest, strongest, stiffest and most extensible crystalline materials (The wonder material graphene may have found its killer app, 2022) have significantly influenced the technological field of creating extremely heat-resistant, high-strength materials for combat platforms, stealth coatings, or coatings capable of collecting and storing energy, superconducting materials, 2-D materials, and topological materials. Interesting research is being conducted on new 2D materials (e.g., graphite, a multilayer allotropic modification of carbon), new polymers, nanomaterials, and

meta-materials (Yiming, 2022). Recently, eight new materials have been discovered that have a structure similar to graphene (Reding, Eaton, 2020): antimonene, arsenene (a single-layer bent honeycomb structure of arsenic), bismuth, boron, borophane, boronene, fagraffen, phosphoren, and stannene. Other similar two-dimensional materials, such as ferromagnetic chromium triiodide, rhenium disulfide, titanium carbides, and molybdenum ditelluride, have unique optical, ferromagnetic, physical, or electrical properties. Polymeric materials are an integral part of the modern economy and military. There are several notable areas of research (Young, 2021): the creation of complex topological structures, functional polymeric materials, sustainable materials, biopolymers, and self-healing polymers. Nanomaterials are nanoscale (one billionth of a meter) materials that exhibit unique optical, electronic, biological, or mechanical properties. Two critical areas of research are (Hecht, 2022): bionanomaterials and quantum dots.

Additive manufacturing, often used synonymously with three-dimensional printing (3D printing) (Additive Manufacturing Research Group, 2018), is the process of creating an almost arbitrary three-dimensional solid object from a digital model by adding materials in layers. Additive manufacturing can be used for: rapid prototyping; rapid production and repair in the field; and the production of precision, customized, or unique parts.

Advanced manufacturing methods encompass many techniques, but two of them deserve special attention because of their potentially disruptive impact on military capabilities: 3D/4D printing and biomanufacturing (reproduction of biological structures using 3D printing for rapid aid to the wounded and their rehabilitation). Unlike 3D printing, 4D printing transforms materials under the influence of changing environmental stimuli, such as pressure, heat, pH, light, humidity, or temperature. Such materials are promising for new structures or sensors, especially in biomedical applications such as biomedical robots, tissue engineering, or bioscaffolds (two- or three-layer tissue-cell structures grown in vitro on the basis of a vascular scaffold that serves as a support for layering cellular structures).

While additive manufacturing methods such as 3D/4D printing continue to evolve, new nano- and microfabrication techniques are being explored to synthesize, assemble, and create materials from the atomic to macro-scale with potential applications in energy, optics, electronics, therapeutics, and genetic engineering (Bechelany, 2022).

Technologies for creating new materials can significantly increase the efficiency and sustainability of combat platforms, provide new more powerful, reliable and safe equipment for military personnel, equip the army with state-of-the-art compact means of communication, reconnaissance and navigation, ensure the creation of protective coatings and stealth coatings, materials for space and hypersonic flights, and additive manufacturing technologies will allow to organize the production of unique parts and structures, rapid restoration and repair of equipment in the field.

Energy & Propulsion Technology Group – technologies for creating new ways to generate energy and store it, as well as building efficient power units (engines).

Social and political interest in combating the effects of anthropogenic climate change, transition to the concept of sustainable economic development, active implementation of green energy technologies, research in the field of renewable energy, environmentally friendly engines, and clean energy generation methods are of significant commercial, social and military interest. In particular, research for NATO defense is focused on four areas (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023): creation of new batteries and energy storage devices (Batteries and Energy Storage); new power generation technologies (Power Generation); search for new ways of energy transmission (Power Transmission); new propulsion systems (Propulsion).

In the field of creating efficient energy storage devices for military needs, work is underway to optimize the traditional technology of lithium-ion batteries and introduce new technologies of potassium-ion and zinc-ion batteries, as well as to study new technologies based on double carbon,

lithium-carbon, lithium-iron-phosphate, sodium-iron, magnesium-sulfur, etc. Some of these technologies are focused on large-scale energy storage, while others are targeted for use in transportation platforms.

Another option for energy storage with significant advantages in weight, safety, lifetime, energy density, charging speed, and toxicity is provided by supercapacitors or ultracapacitors that do not rely on electrochemical storage, or hybrid systems that combine electrochemical energy storage with supercapacitors (Reding, Eaton, 2020), (McFadden, 2020).

Research on clean energy technologies is important to support the climate policy of NATO and European countries. First of all, these are renewable energy sources based on solar energy storage or the use of environmentally friendly biofuels with neutral carbon emissions (e.g., bioethanol, biodiesel, and biobutanol) or hydrogen. Another promising area is the creation of compact (on-site) nuclear power plants based on safer and more environmentally friendly nuclear fuel, such as thorium (David, 2023), (Barry, Santoso, 2022).

Two promising areas are being considered in the field of energy transmission: Wireless Power Transmission (WPT) (for short distances, power is transmitted by magnetic fields using inductive coupling or by electric fields using capacitive coupling, and for long distances, by narrowly focused electromagnetic radiation) and localized power grids (Microgrids) of military camps or ships that can be disconnected from large power grids, thereby increasing the sustainability and localization of power generation.

The development and widespread deployment of efficient propulsion systems or powering military vehicles is a major technical challenge that is being explored in three main areas: electrification of combat platforms, new aerospace engines, and environmental operations.

Examples of the electrification of combat platforms include the replacement of traditional fossil fuel engines with electric or hybrid propulsion systems on aircraft, ships, tanks, and other combat and transportation platforms, and the transition to low-carbon fuels. At the same time, new propulsion systems and fuels should be unified with civilian standards and be compatible with the commercial production sector. For example, the Tactical Vehicle Electrification Kits (TVEK) developed for the U.S. Army's ground forces reduce average fuel consumption by 25%. The first prototype of an all-electric light reconnaissance vehicle, the Electric Light Reconnaissance Vehicle (eLRV), is being tested, and the full transition of military and transport equipment to hybrid powerplants is planned by 2035, and to all-electric ones by 2050 (Kulagin, Solonets, Kvitkin, Medved, Gubareva, 2023).

E&EM Technologies Group – technologies for the creation of microelectronic and microelectromechanical devices and other electronic component base, search for new circuitry solutions and new architecture of integrated circuit crystals, improvement of semiconductor technologies and materials, as well as creation of devices for generating and emitting powerful pulses of electromagnetic radiation, powerful pulsed power supplies with high specific energy density, development of new approaches to generating powerful microwaves.

Technological progress and the implementation of EDT technologies depend heavily on the development of new microelectronics and electromagnetic spectrum management. However, the constant scaling of the silicon-based electronic component base, according to NATO experts (Reding, Eaton, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023), will face severe physical limitations over the next ten years. This will require new approaches to electronic systems that use new materials, designs, architectures (combining memory and computing), physics (magnetic states, electron spin properties, topological insulators, phase-shifting materials, trapped ions, and photonic quantum circuits), photonics, artificial intelligence-enabled design tools, and neuromorphic chip designs (Budget Estimates Justification Book, 2022). The electromagnetic spectrum is becoming an increasingly competitive and congested area. Therefore, research is constantly underway to maximize

and optimize it (e.g., cognitive radios and frequency management) while taking into account the challenges of electronic warfare.

It is expected (Reding, Lucia, Blanco, Regan, Bayliss, 2023) that over the next 20 years, development will occur in the following areas:

Advanced Electronics and Electromagnetics – technologies for creating new microelectronics based on traditional and innovative materials. A significant part of this research is grouped into three broad categories (Reding, Lucia, Blanco, Regan, Bayliss, 2023), (Budget Estimates Justification Book, 2022): Materials (new silicon-free compounds (e.g., gallium, gallium arsenide or nitride, silicon carbide, etc.) and 2D materials), Architecture (rethinking the architecture of silicon-based microchips and boards, specialized circuits built with artificial intelligence, circuits for biomimetic, neuromorphic, and hyperdimensional computing), and Design (improving chip performance, design, and layout using AI/ML technologies);

Antennas (new antenna designs) – technologies for creating new antenna designs and sensor systems with improved SWaP-C characteristics and performance, as well as long-distance wireless communication systems, including underground and underwater. Promising research is in the following areas: antennas with mechanical control of magnetic/electric fields at ultra-low frequency (ULF), from 0.3 to 3 kHz, and ultra-low frequency (VLF), from 3 to 30 kHz, for long-range wireless communications, as well as underwater and underground communication channels antennas for ultra-wideband emitters and receivers to provide reliable and secure communication channels that are resistant to electronic warfare; 4D antenna arrays for multi-channel transmission and intelligent electromagnetic beamforming;

Photonics and Lasers – technologies for manipulating electrons and photons for information transmission, signal processing, spectroscopic sensing and imaging, as well as for the development of microchips modeled on the basis of neural processes (neuromorphic photonics), ideal for AI/ML applications. In addition, the development of silicon chips for light control and nanolasers on a chip allows us to move to quantum computing;

Spectrum (electromagnetic spectrum) – technologies for the efficient use of the available electromagnetic spectrum, its control and counteracting access to such spectrum by hostile parties. Promising research is focused on three areas: Adaptive camouflage (developments aimed at adapting the optical and near-optical signatures of humans, transport platforms or objects to the existing background or environment), high-frequency high-power redundant matching (development of powerful amplifiers designed to organize communication at high-frequency millimeter-wave waves to provide high-speed communication, increased sensitivity and increased sensor resolution) and adaptive spectrum management (development of cognitive radios or sensors using

Directed Energy Weapons (DEW) – technologies for creating laser, microwave, beam and sound weapons to blind the sensors of combat platforms and satellites, suppress the functioning or physical destruction of an enemy target (manpower, missiles, aircraft, unmanned platforms, vehicles, etc.

The most promising DEW developments are the High-Energy Laser (HEL) and High-Powered Microwave (HPM) weapons, which have the potential to generate effects over a wider area, disabling any electronics within their electromagnetic cone than laser weapons. While hardly a new technology, directed energy weapons (DEWs) have evolved and demand for them has increased dramatically around the world. These lasers and high-powered microwave weapons are already a devastating force on the battlefield, and are expected to be used even more widely over the next few years.

The current global DEW market is estimated to be worth USD 14.3 billion and will grow to USD 72.1 billion by 2028 (Global Directed Energy Weapons Industry, 2022). This growth is largely driven by improvements in energy storage systems, AI/ML and new material technologies. Many

DEW systems have been commissioned or have a very high level of technological readiness (Reding, Lucia, Blanco, Regan, Bayliss, 2023), (Kelley, Feickert, O'Rourke, 2023), (Hoffman, 2021), (Klontsak, Kamalov, Stetsyura, 2022).

The combination of these technologies and new mechanisms of interaction between them allow for the creation of new convergent technologies that may later become breakthroughs. For example, the synergistic combination of big data analytics and artificial intelligence technologies using intelligent, widespread and cheap sensors together with autonomy technologies should provide a potential military strategic and operational advantage, the addition of quantum technologies will expand the capabilities of data collection, processing and use (C4ISR) by significantly increasing the capabilities of sensors, secure communication and computing, the addition of new materials creation technologies will facilitate the development of materials with unconventional In turn, the development of exotic materials, new structures, miniaturization, new ways of generating and storing energy, additive manufacturing methods, and improved powertrain and engine designs will contribute to the full utilization of all five operating environments, including cyberspace and space, by reducing costs, increasing reliability, improving performance, and facilitating production.

To understand the status and pace of development of EDTs or combinations of EDTs, the importance and prospects of each technology group, certain evaluation criteria are used: potential military impact, the level of attention or excitement surrounding a particular technology or scientific field, the current level of technological readiness, the time horizon in which the science or technology is expected to be fully mature, the fit with defined operational capabilities, and the areas of science and technology that are significantly impacted by the introduction of EDT technologies.

The first step is to assess the potential probable impact of the introduction of a technology or several technologies on changing the defining characteristics of defense capabilities or carriers of these capabilities (military organizational structures, models (complexes, systems) of weapons and military equipment), such as speed, range, accuracy, lethality, survivability, availability, etc. This impact can be moderate (10-50%), high (50-100%) or revolutionary (a fundamental change in the characteristics of existing capabilities or the acquisition of completely new capabilities that were previously unattainable or underestimated).

The second stage assesses the level of attention and enthusiasm for the technology, as well as the ability of the technology to go through all the stages of integration into a sustainable technological environment. At this stage, experts should analyze many different factors that reflect the level of attention to the technology, its innovation potential and investment attractiveness: the list of countries that pay attention to a particular technology, their military potential rating and the dynamics of revenues from the sale of military technologies; inclusion of research on a particular technology in overall defense spending; the level of investment in technology development and the demand for training and qualification of personnel; the number of scientific publications and patents; the results of the risk analysis of the reassessment of the technology; and the inclusion of research on a particular technology in total defense spending; the level of investment in technology development and the demand for training and qualification of personnel; the number of scientific publications and patents; the results of the analysis of the risks of overestimating or underestimating the potential of technology and many other factors.

An interesting tool introduced by the American company Gartner, Inc, the so-called "Hype Cycle for Emerging Technologies" – a cycle that shows how a potentially successful new technology goes through five key phases (Slyusar, Sotnyk, Kupchin, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023): trigger of innovation, peak of high expectations, disappointment, enlightenment, and plateau of performance. A unique aspect of this tool is its ability to summarize information from a variety of technologies that Gartner, Inc. annually reviews, identifying only the most transformative

ones that analysts predict will revolutionize certain industries within 10 years. For example, Figure 1 shows the Gartner cycle for 2023.

Technologies do not always progress from the beginning to the end of such a cycle, many areas of science or technological discoveries never create breakthroughs for innovation, or they disappear from public consciousness after the initial fascination as unproductive areas of development, or they may appear later as new convergent developments that give rise to an old idea. The development of most new technologies can be predicted only with a certain degree of probability, but the evolutionary process built on creative failures and mistakes is essential for scientific and technological progress, as lessons learned and fantastic ideas lead to entirely new areas of research, discovery and innovation. Balancing the peak of high expectations with the low point of the disillusionment problem is a critical task in making decisions about investments and long-term capabilities. The Gartner cycle is useful for this purpose, but there are notable shortcomings in its use as a tool for evaluation and decision-making, in particular, the placement of a technology on the Gartner curve is determined by the level of expectations (hype) assessed by experts, rather than by quantitative indicators of technology development.

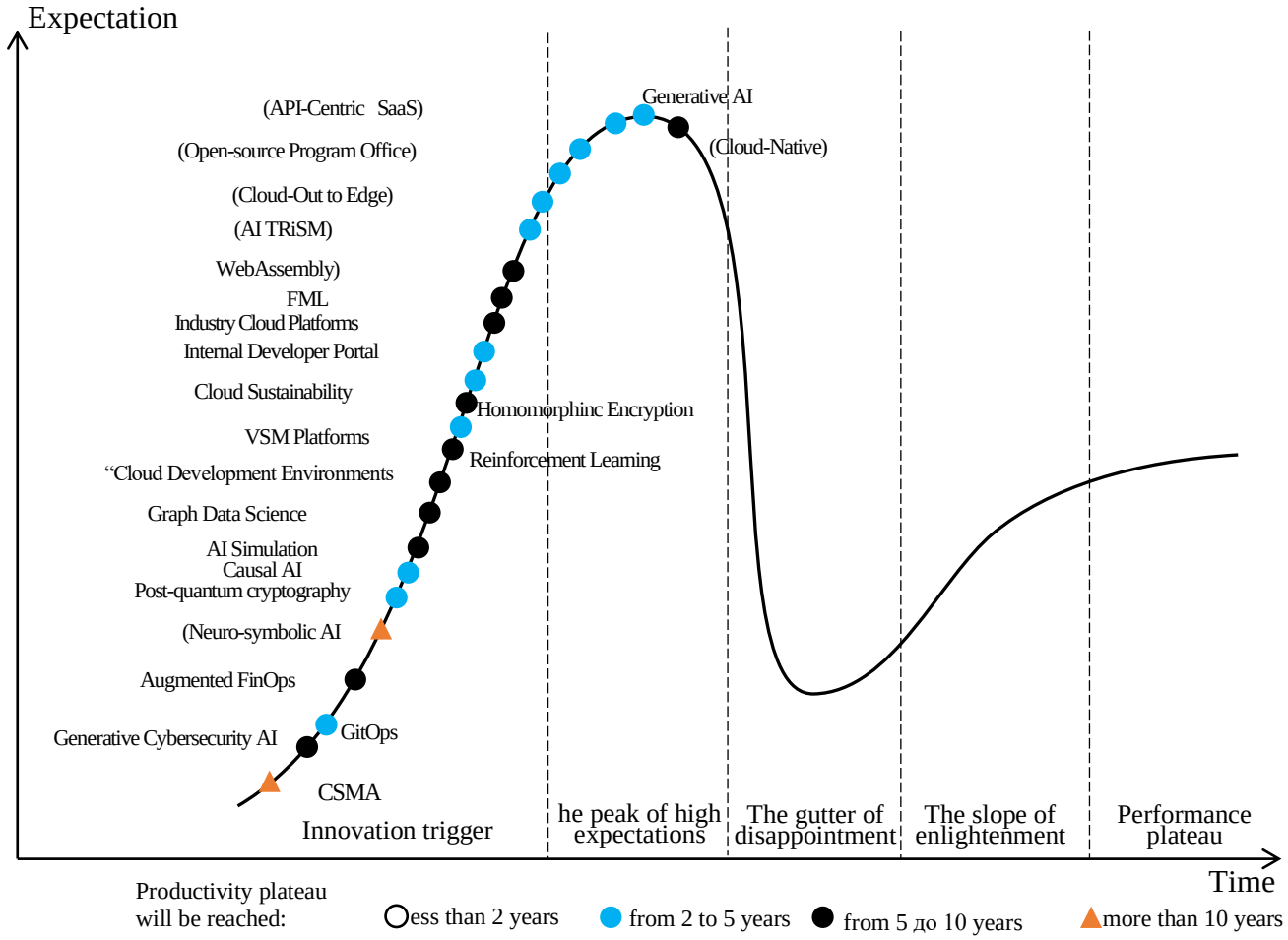


Figure 1. Gartner cycle for the latest (emerging) technologies for 2023

The third stage is the assessment of the technology's maturity level (Technology Readiness Level, TRL). The assessment system is based on a scale of nine levels, where 1 is the lowest, basic level of readiness, and 9 is the highest. There are 9 levels of technology readiness in total. The US National Aerospace Agency (NASA) first proposed such an assessment scale, and later the European Commission advised EU-funded research and innovation projects to adopt this scale (From the lab to

commercialization: the path of knowledge-intensive products through the levels of technological readiness. Innovation Cases, 2023).

At the lowest level of maturity (TRL1), scientific research is transformed into applied research and development, the basic principles of the technology are developed and described, research results are published and peer-reviewed, but the technology exists only "on paper". At TRL2, the principles of the technology have been studied, the concept of the technology has been formulated, and the initial results can be applied in practice, the practical application has been identified, but it is of a general nature. At the stage of reaching TRL3, active research and development, both analytical and experimental studies, begin to verify the viability of the technology, experimental proof of concept and its readiness for further development. After a successful proof of concept at TRL3, the main components of the technology must be integrated to ensure that the individual elements can work together successfully, the technology is tested in the laboratory, and test results are documented to demonstrate compliance with analytical predictions. At the TRL5 stage, testing prototypes of the technology allows us to predict the tasks for the next stages of development. A fully functional prototype or representative model is demonstrated and operated in an appropriate use environment at TRL6. TRL7 level - demonstrates the operation of a real prototype of the technology in the working environment and its performance in real operating conditions. The demonstration should be a prototype of a real-world application. If it is a physical prototype, it is a high-precision engineering unit that adequately addresses all critical scaling issues, built and operated in an appropriate environment to demonstrate performance in a real-world operating environment and platform (land, sea, air or space), and if it is software, there is a prototype with all key functions available for demonstration and testing. All technologies used in real systems go through TRL 8. In almost all cases, this level is the final stage of technology development. At this level, the final product in its final configuration has been successfully demonstrated through testing and analysis for a defined operating environment and the corresponding platform. All software is debugged and fully integrated with all existing hardware and software systems. All user documentation, training and maintenance documentation is complete. The TRL9 level in almost all cases is the final correction of bugs and major aspects of operation in real conditions. It can also be about integrating a new technology into an existing system. At this level, the technology can be used by customers, ongoing technical support has been established, and the technology or product is ready for mass production.

Figure 2 summarizes the levels of technological maturity of the main groups of new and disruptive technologies discussed above.

The fourth stage assesses the time horizon for reaching the level of technological maturity (TRL8-TRL9). This is a rather important time indicator, especially for investors. The time horizon for technology maturity is estimated in various foresight studies (Slyusar, Sotnyk, Kupchyn, 2020), (Reding, Lucia, Blanco, Regan, Bayliss, 2023).

At the fifth stage, the impact on current and future defense capabilities is assessed and proposals are formulated as part of the defense planning process (Slyusar and Kulagin, 2019). Each technology is assessed for its potential impact (low, medium or high). Almost all of the technology groups reviewed were assessed by NATO experts as having a high or even revolutionary level of impact on the Alliance's defense capabilities.

Defense science is divided into three broad areas, covering research in the human (including biological), information and physical domains of science and technology. Therefore, the sixth stage links EDT to these three major research areas, which helps to ensure a holistic approach to EDT research, development and exploitation.

Assessing the potential impact of emerging or disruptive technologies is therefore not a straightforward process. It requires consideration of the threat environment (current and future), legal and policy constraints, political factors, investment decisions, and an assessment of economic and entrepreneurial potential, risk tolerance and willingness.

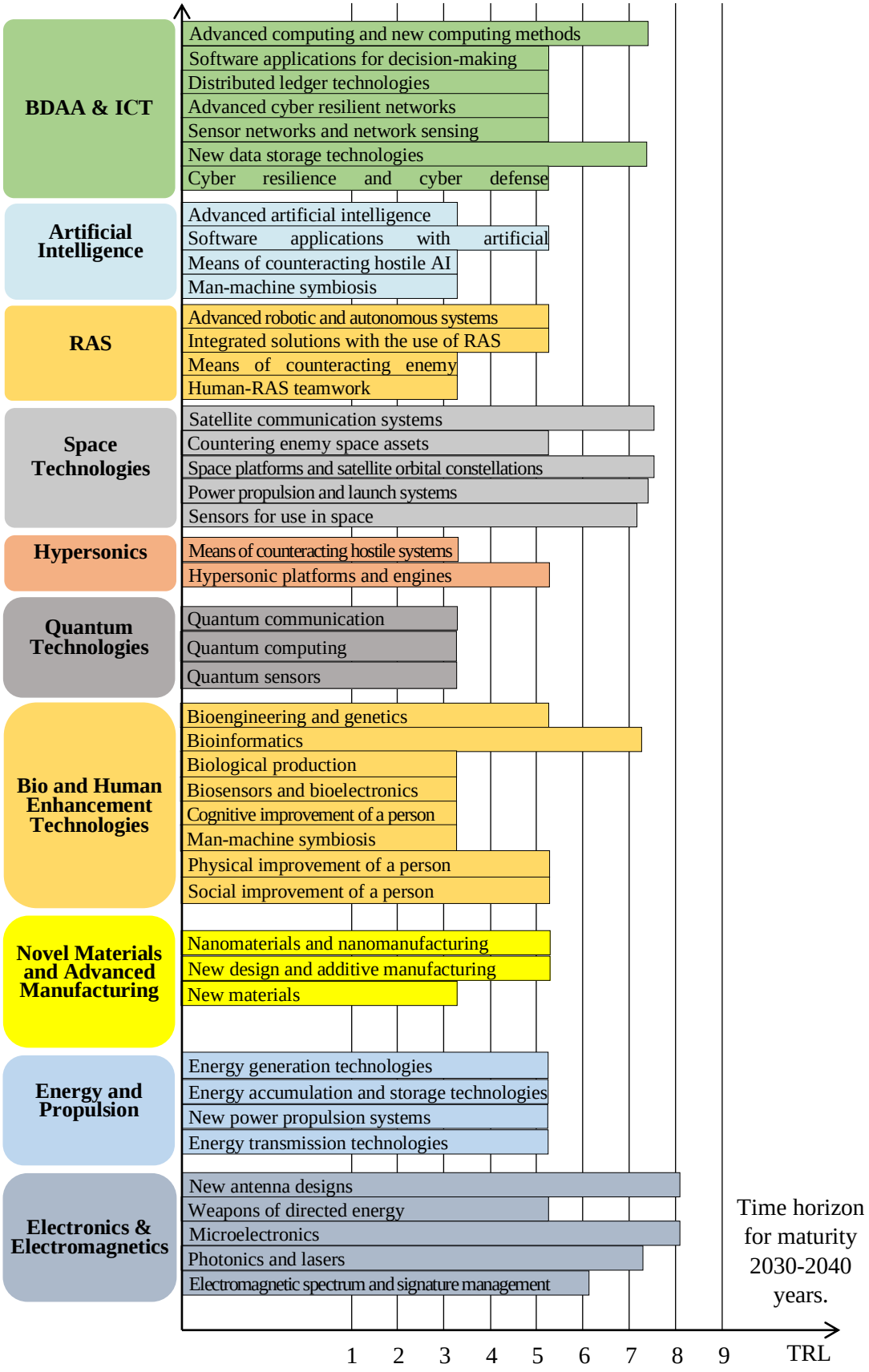


Figure 2. Summarizing the levels of technological maturity of the main groups of new and disruptive technologies discussed above

Conclusion

This article examines how new and disruptive technologies can enable or influence military capabilities in a timeframe of up to 20 years. Individually or in combination, they define the technological frontier necessary for the effectiveness of operational and organizational forces in the security and defense sector. How quickly, in what order, and ultimately how successful these technologies will be, or what risks they will pose, is not yet fully understood. The range of potential military operational domains is constantly expanding and evolving, just as the geopolitical, military, economic, social, climate, and technological landscapes are changing. However, long-term forecasts of military experts, in particular from NATO countries, provide useful information and professional advice on prioritizing new opportunities and technological investments, provide a basis for selecting promising areas for further research in the field of economic security and national defense, and contribute to technological awareness and preparedness for effective investment policy and development of the defense industry.

The systematic analysis of the ten main groups of new and breakthrough technologies recognized by NATO experts, which are expected to reach technological maturity in the next 15-20 years and significantly affect the defense capabilities of NATO member states and, accordingly, partner countries, can be useful for specialists who formulate the military-technical and defense-industrial policy of the state.

In order to develop military capabilities that meet current and future geostrategic challenges, countries must be at the forefront of innovation, science and technology, design and production of the most modern and technologically advanced weapons and military equipment. This also requires a sound assessment of the potential security environment in the future, especially with regard to military challenges and security threats arising from new scientific and technological discoveries and the implementation of breakthrough technologies in an open globalized world.

Continuous monitoring of scientific and technological trends, determination of their breakthrough military potential, and the risks of both overestimation and financial miscalculations, as well as underestimation and expected vulnerability of the security and defense system, is one of the tools for increasing the defense technological advantage or at least maintaining military-technological parity with an equal adversary, and it also accelerates the introduction of innovations, new and breakthrough technologies in the defense industry.

The results obtained will allow to focus the attention of the scientific community on the main innovation trends in the defense sector and to involve the widest possible range of experts in discussing and justifying promising and priority areas for Ukraine to introduce the latest and most disruptive technologies, risk analysis and reasonable selection of technologies that have the potential to become critical for the state.

Recommendations

The materials of the article are recommended for use by the scientific and scientific-pedagogical staff of scientific institutions and higher educational institutions of the Armed Forces of Ukraine and the Ministry of Defense of Ukraine, experts of other ministries that support the security and defense sector, and specialists of the defense industry.

In the future, it is advisable to focus on a more detailed definition of the list of the latest and most breakthrough technologies that have the potential to be implemented in Ukraine independently or with the support of partner countries, their deeper analysis and evaluation, in particular, the degree of criticality for the national security of the state and technological superiority to bring victory in the aggressive war unleashed by the Russian Federation.

References

1. Schwab, K. (2017). The fourth industrial revolution. Exmo. http://loveread.ec/

contents.php?id=66348.
2. Schwab, K. (2018). Technologies of the Fourth Industrial Revolution. Exmo. http://loveread.ec/view_global.php?id=73865.
3. Christensen, K. M. (2004). The innovator's dilemma. How strong companies die because of new technologies. Alpina Business Books.
4. Rotolo, D., Hicks, D., Martin, B. (2015). *What is an emerging technology?* University of Sussex. (Version 1). https://hdl.handle.net/10779/uos.23420075.v1.
5. Küfeoğlu, S. (2022). Emerging Technologies. *Sustainable Development Goals Series.* Springer, Cham. 11-21. https://doi.org/10.1007/978-3-031-07127-0_2.
6. Mariette, D., Meyerson, S.B. (2023). *Top 10 Emerging Technologies of 2023, Flagship Report, Centre for Fourth Industrial Revolution*. World Economic Forum. https://www.weforum.org/publications/top-10-emerging-technologies-of-2023/.
7. Armstrong, P. (2017). *Disruptive Technologies. Understand, evaluate, respond*. Kogan Page Publishers.
8. Manners-Bell, J., Lyon, K. (2022). *Logistics and supply chain innovation. A practical guide to disruptive technologies and new business model*. Kogan Page Publishers.
9. Slyusar, V. I., Sotnyk, V. V., Kupchyn, A. V. (2020). Breakthrough technologies in the defense sphere of Ukraine. *Armament and military equipment*, Kyiv. 4 (28). 13-23.
10. Sotnyk, V. V., Rasstrygin, O. O., Kupchyn, A. V. (2020). Methodology of selection of critical technologies. *Modern information technologies in the field of security and defense*. 1(37). 67-76. http://doi.org/10.33099/2311-7249/2020-37-1-67-76.
11. Matyushenko, I. Yu. (2016). Development and implementation of convergent technologies in Ukraine in the conditions of the new industrial revolution: organization of state support. FOP Alexandrova K. M.
12. Pisarenko, T., Kvasha, T., Havrys, T. (2021). Analysis of global technological trends in the military sphere. UkrINTEI. http://doi.org/10.35668/978-966-479-127-1.
13. Pisarenko, T., Kvasha, T. (2020). Global technological trends in the field of weapons and military equipment. UkrINTEI. http://doi.org/10.35668/978-966-479-117-2.
14. Reding, D. F., Eaton, J. (2020). *Science & Technology Trends 2020-2040. Exploring the S&T Edge*. March, 2020. NATO Science & Technology Organization, Office of the Chief Scientist, Brussels. https://www.nato.int/nato_static_fl2014/assets/pdf/2020/4/pdf/190422-ST_Tech_Trends_Report_2020-2040.pdf.
15. Reding, D. F., Lucia, A. D., Blanco, A. M, Regan, L. A., Bayliss, D. (2023). *Science & Technology Trends 2023-2043. Across the Physical, Biological, and Information Domains. Overview.* 1. NATO Science & Technology Organization, Office of the Chief Scientist. https://www.nato.int/nato_static_fl2014/assets/pdf/2023/3/pdf/stt23-vol1.pdf.
16. Reding, D. F., Lucia, A. D., Blanco, A. M, Regan, L. A., Bayliss, D. (2023). *Science & Technology Trends 2023-2043. Across the Physical, Biological, and Information Domains. Analysis.* 2. NATO Science & Technology Organization, Office of the Chief Scientist. https://www.nato.int/nato_static_fl2014/assets/pdf/2023/3/pdf/stt23-vol2.pdf.
17. Chana, Deeph. (2020). *NATO Advisory Group on Emerging and Disruptive Technologies. Annual report.* North Atlantic Treaty Organization. https://www.nato.int/nato_static_fl2014/assets/pdf/2021/3/pdf/210303-EDT-adv-grp-annual-report-2020.pdf.
18. Chana, Deeph. (2021). *NATO Advisory Group on Emerging and Disruptive Technologies. Annual report.* North Atlantic Treaty Organization. https://www.nato.int/nato_static_fl2014/

assets/pdf/2022/7/pdf/220715-EDT-adv-grp-annual-report-2021.pdf.
19. *NATO Warfighting Capstone Concept.* (2023). Allied command transformation NATO'S Strategic Warfare Development Command. https://www.act.nato.int/wp-content/uploads/2023/06/NWCC-Glossy-18-MAY.pdf.
20. Keller, J. (2020). What 5G means to the military. *The Military & Aerospace Electronics*. December 2. https://www.militaryaerospace.com/rf-analog/article/14188341/military-5g-communications.
21. Slyusar, V. I., Kulagin, K. K. (2019). Peculiarities of NATO's defense planning process. Science and technology of the Air Force of Ukraine. 3(36). 47-59. http://dx.doi.org/10.30748/nitps.2019.36.06.
22. *Disentangling AI, Machine Learning, and Deep Learning.* (2021). April 5. Exxact Corporation. https://www.exxactcorp.com/blog/Deep-Learning/difference-between-ai-machine-learning-and-deep-learning?gclid=Cj0KCQiA47GNBhDrARIsAKfZ2rALRgE7vtm XoqQx_-fWly40_XMl_Q-esKbaEzfx5Rbw5M2mVRwIk0QaArYaEALw_wcB.
23. Robotic and Autonomous Systems in a Military Context. (2021). Jstor.org. https://www.jstor.org/stable/pdf/resrep29554.3.pdf.
24. Peterson, P. (2021). September 26. *Advanced Electric Propulsion System (AEPS) Enabling a Sustainable Return to the Lunar Surface through NASA Gateway. 74th Annual Gaseous Electronics Conference*. NTRS – NASA Technical Reports Server https://ntrs.nasa.gov/citations/20210022011.
25. Jeffrey, C. (2022). *Here's what it looks like to get flung from a centrifuge at 1,000 mph.* Techspot. May 4. https://www.techspot.com/news/94466-here-what-looks-like-get-flung-centrifuge-1000.html.
26. *NATO's overarching Space Policy.* (2022). North Atlantic Treaty Organization. January 17. https://www.nato.int/cps/en/natohq/official_texts_190862.htm.
27. Brunner, Karl-Heinz. (2021). *Space and Security – NATO'S Role. Preliminary Draft Special Report.* October 10. https://www.nato-pa.int/download-file?filename=/sites/default/files/2021-04/025%20STC%2021%20E%20-%20SPACE%20AND%20SECURITY%20-%20BRUNNER_2.pdf.
28. Tirpak, J.A. (2018). The Great Hypersonic Race. *The Great Hypersonic Race – Air Force Magazine*. June 27. https://www.airandspaceforces.com/article/the-great-hypersonic-race/.
29. Speier, R. H., Nacouzi G., Carrie Lee and Moore, R. (2017). *Hypersonic Missile Nonproliferation: Hindering the Spread of a New Class of Weapons*. CA: RAND Corporation. June 27. https://www.rand.org/pubs/research_reports/RR2137.html.
30. Mizokami, Kyle. (2019). Russia's New Hypersonic Weapon Flies at Mach 27. *Popular Mechanics*. Dec. 30. https://www.popularmechanics.com/military/weapons/a30346798/russia-new-hypersonic-weapon-mach-27/.
31. Bernstein, P., Hancock, D. (2021). China's Hypersonic Weapons. *Georgetown Journal of International Affairs*. January 27. https://gjia.georgetown.edu/2021/01/27/chinas-hypersonic-weapons/.
32. Hypersonic weapons. (2024). *Deep State*. Vanguard. Feb. 20. https://deepstateua.com/hypersonic_missiles/.
33. Mizokami, K. (2022). Russia Is Using Hypersonic Weapons to 'Put Fear Into the Hearts of Ukrainians. *Popular Mechanics*. Apr. 05. https://www.popularmechanics.com/military/weapons/a39600945/why-russia-is-using-hypersonic-weapons-in-ukraine/.

34. Lendon, Brad. (2024). Russia used an advanced hypersonic missile for the first time in recent strike, Ukraine claims. *CNN Business*. Feb. 13. https://edition.cnn.com/2024/02/13/europe/ukraine-russia-zircon-hypersonic-missile-intl-hnk-ml/index.htm.
35. Amerongen, M. (2021). Quantum technologies in defense and security. June 03. https://www.nato.int/docu/review/uk/articles/2021/06/03/kvantov-tehnolog-v-oboron-bezpets/index.html.
36. Krelina, M. (2021). Quantum technology for military Applications. *EPJ Quantum Technology*. https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-021-00113-y.
37. Post-Quantum Cryptography. (2023). National Institute of Standards and Technology. Computer Security Resource Center. 22nd of November. https://csrc.nist.gov/projects/post-quantum-cryptography.
38. Roblin, S. (2019). No More "Stealth" Submarines: Could Quantum "Radar" Make Submarines Easy to Track (And Kill)? *The National Interest*. 27th of April. https://nationalinterest.org/blog/buzz/no-more-stealth-submarines-could-quantum-radar-make-submarines-easy-track-and-kill-54547.
39. Wes O'Donnel. (2019). Quantum Radar a Game Changer for Offensive Stealth Operations. American Military University EDGE. Sept. 11. https://amuedge.com/quantum-radar-a-game-changer-for-offensive-stealth-operations/.
40. Ladisch, M. (2001). *Opportunities in Biotechnology for Future Army Applications*. National Academies Press. June 11. https://doi.org/10.17226/10142.
41. The wonder material graphene may have found its killer app. (2022). *The Economist*. May. https://www.economist.com/science-and-technology/2022/05/18/the-wonder-material-graphene-may-have-found-its-killer-app.
42. Yiming, Hu. (2022). Synthesis of γ-graphyne using dynamic covalent chemistry *Nature Synthesis.* 1. 449–454. May 09. https://www.nature.com/articles/s44160-022-00068-7.
43. Young, J. (2021). *What are the most important areas in polymer research?* https://www.hindawi.com/post/what-are-most-important-areas-polymer-research/.
44. Hecht, J. (2022). Nanomaterials pave the way for the next computing generation. *Nature 608.7922*. Aug. 10. https://www.nature.com/articles/d41586-022-02147-3.
45. *Additive Manufacturing Research Group* (AMRG). (2018) The 7 categories of Additive Manufacturing, Additive Manufacturing Research Group, Loughborough University. Loughborough University. https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/.
46. Bechelany, M. (2022). Nanofabrication and Nanomanufacturing. *Nanomaterials 12*(3). https://www.researchgate.net/publication/358202961_Nanofabrication_and_Nanomanufacturing.
47. McFadden, C. (2020). Could Ultracapacitors Replace Batteries in Future Electric Vehicles? June 6. https://interestingengineering.com/science/could-ultracapacitors-replace-batteries-in-future-electric-vehicles.
48. David, E. (2023). Power Electronics Handbook by Muhammad H. Rashid. *Cosmic Journal of Phisics. 2*(1). 38-60. https://www.researchgate.net/publication/375598117_Power_Electronics_Handbook_by.
49. Barry, N., Santoso, S. (2022). Modernizing Tactical Military Microgrids to Keep Pace with the Electrification of Warfare. *Military Review*. https://www.armyupress.army.mil/Portals/7/military-review/Archives/English/ND-22/Barry/Barry%20November-December-

UA.pdf.

50. Kulagin, K. K., Solonets, O. I., Kvitkin, K. P., Vedmid, O. I., Gubareva, O. P. (2023). Impact of climate change on the safety of military operations and the life cycle of weapons and military equipment. *Systems of Arms and Military Equipment.* 2 (74). https://doi.org/10.30748/soivt.2023.74.06.
51. Budget Estimates Justification Book. (2022). Defense Advanced Research Projects Agency. Department of Defense Fiscal Year. https://www.darpa.mil/attachments/U_RDTE_MJB_DARPA_PB_2023_APR_2022_FINAL.pdf.
52. *Global Directed Energy Weapons Industry*. (2022). ReportLinker. October. https://www.reportlinker.com/p05798382/Global-Directed-Energy-Weapons-Industry.html?utm_source=GNW.
53. Kelley, M., Feickert, A., O'Rourke, R. (2023). Background and Issues for Congress. August 22. https://sgp.fas.org/crs/weapons/R46925.pdf.
54. Hoffman, R. (2021). High Power Microwaves High Power Microwave (HPM) 6.1 Programs. *NVAL Science & Technology*. https://www.nre.navy.mil/media/document/directed-energy-weapons-dew-high-power-microwave-hpm-61-programs-fy21-annual-report.
55. Klontsak, M.Ya., Kamalov, E.V., Stetsyura, I.R. (2022). Prospects for equipping the Armed Forces of Ukraine with directed energy weapons. *Collection of scientific works of the Center for Military and Strategic Studies of the National Defense University of Ukraine named after Ivan Chernyakhovsky*. 3(76). http://znp-cvsd.nuou.org.ua/article/view/274787/269951.
56. *From the laboratory to commercialization: the path of science-intensive products through the levels of technological readiness. Innovative cases*. (2023). NEF (New Economy of Ivano-Frankivsk). September 10. https://neweconomy.if.ua/innovations/innovation-cases/z-laboratoriyi-do-komerczializacziyi-shlyah-naukoyemnyh-produktiv-kriz-rivni-tehnologichnoyi-gotovnosti/.