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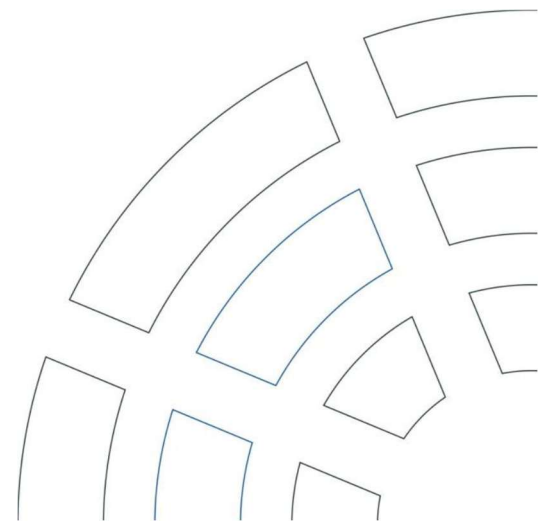
SCIENCE AND TECHNOLOGY COMMITTEE (STC) SUB-COMMITTEE ON TECHNOLOGY TRENDS AND SECURITY (STCTTS)

A DOUBLE-EDGED SWORD: WHY NATO MUST EMBRACE THE PROMISE AND AVOID THE PERILS OF SYNTHETIC BIOLOGY

Report
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059 STCTTS 24 E rev.1 fin – Original: English – 24 November 2024

Founded in 1955, the NATO Parliamentary Assembly acts as a consultative interparliamentary organisation which is institutionally separate from NATO. This report was adopted by the Science and Technology Committee at the 2024 NATO PA Annual Session in Montréal, Canada. It is based on information from publicly available sources or NATO PA meetings – which are all unclassified.



Synthetic biology is one of the most disruptive emerging technologies. This third-generation biotechnology is a multi- and interdisciplinary field that applies engineering principles to biology. It enables the modification of existing organisms and the creation of new ones and is, therefore, no longer limited to the gene sequences found in nature. The technology has a wide range of potential applications and commercial products are already available in agriculture, food, medicine, and electronics. However, technological, scalability, and funding challenges, as well as ethical regulatory issues, still need to be resolved before synthetic biology can be widely used.

These observations from the civilian sector also apply to the area of security and defence. Synthetic biology brings new possibilities for armed forces in areas such as energy storage and generation, novel and advanced materials, sensing, medical treatments and human enhancement. As is the case for most emerging disruptive technologies, there are security risks because actors can use the technology for malicious purposes. These risks include, for example, the possibility of using synthetic biology to (re)create and modify pathogens. As in the civilian sphere, many of these opportunities and risks still lie in the future. There is, nonetheless, no time to lose in accelerating synthetic biology innovations.

This report contributes to the quest of embracing the promise and avoiding the perils of synthetic biology. Building on existing efforts, NATO and its Allies should pursue a set of measures that follow several guiding principles: act in a forward-looking manner; recognise the dual-use characteristic of the technology; balance synthetic biology's opportunities and threats; place ethical questions at the centre of any debate; and draw on the resources and expertise of NATO, the NATO Science for Peace and Security Programme (SPS Programme) and the NATO Science and Technology Organization (NATO STO). Against the backdrop of NATO's Biotechnology and Human Enhancement (BHE) Technologies Strategy, NATO, Allies and NATO Parliamentarians should work towards a joined-up approach, engage in awareness-raising efforts, prepare the ground for the future, monitor developments and engage with external actors.

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Acknowledgement: The Rapporteur extends appreciation to the Committee's Director, Bryjna Oskardottir, and its Researcher, Moritz Neubert, for their research contributions to this report.

I- INTRODUCTION

1. Synthetic biology is considered amongst the most disruptive of technologies. This third-generation biotechnology is a multidisciplinary field that applies engineering principles to biology. By modifying existing or creating novel organisms, synthetic biology is no longer confined to genetic sequences that already exist in nature. The technology, therefore, allows for changes to be made to organisms so that they produce certain substances or acquire new abilities. It allows, for instance, for the engineering of *E. coli* bacteria to produce biofuel. The usage of synthetically altered organisms has increased in recent decades and commercial products are available in sectors such as agriculture, food, medicine and electronics. At the same time, the introduction of entirely novel and artificial products and materials still lies largely in the future. Both existing and future applications of synthetic biology depend on technological advancements. Whereas past progress was driven by advancements in DNA sequencing, editing and synthesising, future innovation will rely on machine learning, artificial intelligence and computing power. Yet, technological obstacles, scalability challenges, funding shortfalls and ethical, as well as regulatory, questions remain.

2. These broader developments are not confined to the civilian sphere but also apply to the security and defence domain. Synthetic biology brings new possibilities for armed forces in areas such as energy storage and generation, the development of novel and advanced materials, sensing, as well as medical treatments and human enhancement. At the same time, there are security risks, including the possibility of using synthetic biology to (re)create and modify pathogens. Even if many of these possibilities are not yet a reality, there is no time to lose in accelerating synthetic biology innovations/advancements. The Alliance and NATO member countries have identified biotechnologies, including synthetic biology, as priorities and are working towards embracing the technology's promise, whilst avoiding its perils. This is reflected in NATO's Strategy on Biotechnology and Human Enhancement (BHE) Technologies which was adopted during the meeting of NATO Defence Ministers in February 2024. However, other players have not stood by idly: the Russian Federation is active but lags behind technologically, and the People's Republic of China (PRC) will be a key player that will be ready to use the technology for security and defence purposes.

3. Against this background, NATO and Allies should pursue a set of measures that follow several guiding principles. Namely, to act in a forward-looking way, to recognise the dual-use characteristic of synthetic biology, to balance the technology's opportunities and threats, to centre ethical questions in any debates, and to draw on the resources and expertise of NATO, its Science for Peace and Security Programme (SPS Programme), and the NATO Science and Technology Organization (NATO STO). With the recently adopted BHE Strategy serving as a foundation, NATO, Allies, and NATO Parliamentarians should work towards a joined-up approach, engage in awareness-raising efforts, prepare the ground for the future, monitor developments, and engage with external actors. Such steps play a significant role in ensuring that NATO embraces the promise and avoids the perils of synthetic biology. This report contributes to this endeavour by summarising what synthetic biology is and why it matters, elaborating upon the enabling technological advancements and remaining challenges, outlining the ethical considerations and regulatory landscape, taking stock of synthetic biology in the security and defence domain, and mapping defence-related research and development by Allies and external actors.

II- WHAT SYNTHETIC BIOLOGY IS AND WHY IT MATTERS

4. Understanding what synthetic biology is and why it matters is no easy task. To begin with, there is no agreed-upon definition of synthetic biology (DoD, 2015; O'Toole et al., 2020). There are different reasons for this lack of a common definition. Synthetic biology encompasses a broad scope of activities and it continues to evolve rapidly, implying that boundaries with other areas are at times fluid (CRS, 2022a; Parks et al., 2017). Some definitions focus on the features distinguishing synthetic biology from other technologies and disciplines. Other definitions look at the purpose and potential

applications to demarcate the field of synthetic biology. The Convention on Biological Diversity's (CBD) definition does, for instance, emphasise the multidisciplinary nature as well as the objectives whereby "synthetic biology is a further development and new dimension of modern biotechnology that combines science, technology and engineering to facilitate and accelerate the understanding, design, redesign, manufacture and/or modification of genetic materials, living organisms and biological systems" (CBD, 2023). Accordingly, it is necessary to approach a definition of synthetic biology from different angles to provide a holistic understanding of what the technology is and how it matters.

5. Synthetic biology is a multidisciplinary technology that transcends boundaries and encompasses various fields, including biology, chemistry, computer science, and engineering (Mauroni, 2018; NATO STO, 2023c). Synthetic biology is a third-generation biotechnology that follows and builds on breeding and domestication (first generation) as well as gene editing (second generation), both of which sought to alter organisms (NASEM, 2018; NATO STO, 2023c; Stanford University, 2023). Unlike genome editing, synthetic biology does not attempt to change an existing organism's DNA but seeks to insert longer DNA sequences into a genome that may be entirely artificial (NHGRI, 2019). In its essence, "[s]ynthetic biology involves the precise genetic manipulation and engineering of organisms for scientific research and developing unique characteristics and capabilities not seen in nature" (NATO STO, 2023c, p. 62). In doing so, synthetic biology applies engineering principles such as the design-build-test cycle (Parks et al., 2017; Stanford University, 2023). At the same time, it goes beyond genetic engineering since it not only modifies existing systems but aims to create entirely new and artificial ones (EGE, 2009; Hammes, 2010).

6. Synthetic biology is, therefore, no longer confined to genetic sequences that already exist in nature (Stanford University, 2023; *The Economist*, 2019). Its purpose lies in the creation of modified or novel genetic combinations to design and build new systems, whereby DNA segments are treated as building blocks (DoD, 2015; Parks et al., 2017). Synthetic biology can follow a bottom-up approach that builds systems from the ground up or a top-down approach that recomposes existing organisms (PCSBI, 2010). In either case, synthetic biology allows for the modification of existing traits that organisms exhibit or the creation of novel characteristics. It "can yield new organic molecules, novel materials that cannot be manufactured directly" that possess unique features and abilities (NATO STO, 2023c, p. 62). Hence, synthetic biology can be used to alter organisms so that they produce certain substances or acquire new abilities, for instance sensory ones (NHGRI, 2019).

7. Accordingly, synthetic biology offers a wide range of possibilities. Many existing commercial applications focus on novel ways to produce existing products or materials, such as nylon (Lin et al., 2023). Companies use genetic engineering and synthetic biology for packaging, commodity and specialty materials, as well as the provision of materials and services for research and development (R&D) and laboratories (DoD, 2015). Commercial products are available in sectors such as agriculture, food, medicine, and electronics (Voigt, 2020). In the area of agriculture and food, the application of synthetic biology can enhance food security through the creation of more resilient rice and other crops (Ekström et al., 2019; NHGRI, 2019; Stanford University, 2023). It can also contribute to food safety by facilitating the identification of contaminated products (Stanford University, 2023), and by making microorganisms available that can clean water, soil, or air from pollutants (NHGRI, 2019; OECD, 2023). Companies and start-ups also use synthetic biology for novel ways of re-creating flavours or materials found in nature (Parks et al., 2017). Examples include engineered yeast that produces meat flavours or rose oil for perfumes (NHGRI, 2019; OECD, 2023).

8. Medicine is another field where synthetic biology has made significant contributions. The most prominent applications have been the rapidly developed COVID-19 mRNA vaccines (Dolgin, 2020). Researchers have also used synthetic biology in an attempt to develop a vaccine against African swine fever (IDRC, 2020), and as the basis for an innovative cancer treatment (Gronvall, 2018). In addition, modified yeast cells offer new ways to produce medicinal opioids (Ekström et al., 2019). Further, the spread of mosquito-borne diseases, such as Zika, could be stemmed through the design of infertile mosquitoes unable to produce disease-transmitting offspring (Parks et al., 2017).

9. Yet, the introduction of entirely novel and artificial products and materials still lies largely in the future (Parks et al., 2017). Synthetic biology is, nonetheless, expected to have ramifications for a variety of products through substitution, process improvements, and changes to raw materials over the course of the coming decades (Candelon et al., 2022). Accordingly, the market for synthetic biology is set to grow significantly (Crotty, 2023; Stanford University, 2023). Estimates vary but some foresee a global market worth USD 37 billion in 2028, and others forecast a value of USD 100 billion in 2030 (CRS, 2022a). Some experts argue that it can aid decarbonisation in the areas of food, clothes, construction, and travel (Abdur-Rahman et al., 2024), thereby contributing to energy security and transition. Potential use-cases include modified microbes that replace fossils in the production of fuels, plastics, and chemicals, or non-oil jet fuels and bacteria-run batteries (Mauroni, 2018; Morhard, 2022). Synthetic biology may also enable more localised, sustainable, and cost-efficient supply chains that are less dependent on external providers for input materials (Morhard, 2022). Moreover, the technology holds the promise to treat and cure diseases through novel approaches in the future (*The Economist*, 2019). It may, in case of technological advancements, even be used for human enhancement by altering human physiology through new ways of delivering biochemicals or by modifying the microbiome and immune system (NASEM, 2018).

III- ENABLING TECHNOLOGICAL ADVANCEMENTS AND REMAINING CHALLENGES

10. Both existing and future applications of synthetic biology depend on technological advancements. In previous decades, several developments enabled the increased adoption of synthetic biology. The methods of DNA sequencing improved in accuracy, speed, and price (GAO, 2023). Deriving the sequence of a human genome used to cost approximately USD 10,000 a decade ago and is today available for a price of around USD 600 (Stanford University, 2023). Moreover, the methods to edit and synthesise genes advanced significantly. Today, a synthetic biologist can draw on various methodologies, including CRISPR¹. Further, it became possible to synthesise longer DNA segments in less time and the costs for such procedures dropped significantly in the last twenty years (PCSBI, 2010; Stanford University, 2023; *The Economist*, 2019). These advancements have been crucial as they enable accurate changes to genetic sequences and made them more affordable (Crotty, 2023; *The Economist*, 2019).

11. Synthetic biology benefits from advances in machine learning, artificial intelligence, and increased computing power. These advancements are set to improve the design-build-test cycle by offering new possibilities for the design of organisms and the prediction of their behaviour (GAO, 2023; Miller, 2023; NATO STO, 2023c). It is unlikely to entirely alleviate the difficulty of predicting the behaviour of modified organisms, but enhanced modelling abilities would improve the forecasting of intended effects (EGE, 2009; PCSBI, 2010). Another helpful tool in this regard is pattern-recognition, which could aid in the detection of certain evolutionary rules within large piles of data (*The Economist*, 2019).

12. However, challenges remain. Many applications are not yet market-ready and the NATO STO observes that “[t]he scope and magnitude of the future contributions that synthetic biology will make to civil and national security sectors are currently quite speculative” (NATO STO, 2023c, p. 62). Amongst others, there are technological obstacles to the widespread adoption of synthetic biology (NATO STO, 2023c). In the mid-2010s, the United States Department of Defense noted that the

¹ CRISPR (short for “clustered regularly interspaced short palindromic repeats”) is a technology that research scientists use to selectively modify the DNA of living organisms. CRISPR was adapted for use in the laboratory from naturally occurring genome editing systems found in bacteria (NHGRI, 2024).

technology developed rapidly in the preceding years but that fundamental research is still required (DoD, 2015). In the US, the National Academies of Sciences, Engineering, and Medicine (NASEM) provides an extensive list of technological barriers (NASEM, 2018). The creation or alteration of viruses and bacteria struggles with the synthesis and assembly of larger DNA constructs, the engineering of complex traits and knowledge about the viability of newly created organisms. Creating small organisms within a laboratory and ensuring that they survive and act as intended in nature is another matter (DoD, 2015; O’Leary et al., 2020; PCSBI, 2010).

13. The large-scale application of synthetic biology can, furthermore, be held back by non-technological challenges. This includes shortcomings in the underlying infrastructure. In 2015, the United States Department of Defense noted the risk of bottlenecks due to the limited number of facilities that can create designs, make prototypes and test newly created organisms (DoD, 2015). Such facilities can face lengthy delivery times for input materials, creating scalability challenges (DoD, 2015; O’Leary et al., 2020). Moreover, R&D protocols can differ between facilities, thus hampering cooperation and interoperability (Parks et al., 2017). These issues could be addressed using ‘biofoundries’: facilities that offer an “integrated infrastructure enabling the rapid design, construction, and testing of engineered organisms for biotechnology applications and research” (CRS, 2022a, p. 5).

14. Insufficient funding and high costs pose further obstacles. Funding streams for fundamental scientific research are fragile and can be insufficient. When it comes to DNA synthesis, there is little public funding and costs have not been further reduced in recent years (Stanford University, 2023). Private funding is not necessarily a substitute. Commercial actors may refrain from investment, as synthetic biology products can represent risky ventures (Parks et al., 2017). Early efforts to derive fuels synthetically failed in the face of challenges scaling from lab- to mass-production, coupled with high cost compared to oil (*The Economist*, 2019). Even though investment by venture capital actors rose over the course of the last twenty years and surpassed USD 20 billion in 2021 (Abdur-Rahman et al., 2024), start-ups may struggle in their efforts to commercialise their products on the path to profitability as three prominent examples indicate. Amyris, focusing on cosmetics, Zymogens, working on plastic films, and Ginkgo Bioworks, producing bacteria for industries, faltered or had to scale down significantly (Service, 2024). Beyond technology, scalability, and funding, the questions of societal acceptance of synthetically derived products, their regulation and governance, and diverging legal assessments have the potential to cause uncertainty amongst potential producers (Parks et al., 2017).

IV- ETHICAL CONSIDERATIONS AND THE REGULATORY LANDSCAPE

15. Societal acceptance is crucial to the wider adoption of synthetic biology and rests, inter alia, on ethics, norms, and attitudes (NATO STO, 2023c). From the outset, ethical considerations accompanied technological advancements and sparked various reflection processes. In 2008, the European Commission’s European Group on Ethics in Science and New Technologies (EGE) was tasked with issuing an opinion on the technology’s ethical, legal, and societal consequences. The EGE noted that synthetic biology raises fundamental questions about life and nature, including the legitimacy of creating novel living organisms (EGE, 2009). In 2010, the Obama Administration asked the Presidential Commission for the Study of Bioethical Issues (PCSBI) to draw up a report on the ethics of synthetic biology (PCSBI, 2010). The PCSBI “recommended revisiting the moral objections to synthetic biology as the field advances, but we were not persuaded that synthetic biology currently fails to respect the proper relationship between humans and nature” (Gutmann, 2011, p. 20).

16. Other ethical considerations include the potential ramifications of releasing synthetic biology products into the environment. Concerns revolving around the environmental risk associated with the release of synthetic biology agents, whether intentional or unintentional, are central to discussions around biosafety and biosecurity (CRS, 2022a; EGE, 2009; Vergin, 2018). Questions of ethics and norms also relate to the societal acceptance of synthetically altered organisms. The

general reservations and resistance towards genetically modified organisms (GMO) offer a glimpse into potential public apprehension towards synthetic biology products.

17. As such, it does not come as a surprise that the increasing relevance of synthetic biology goes hand in hand with questions around governance and regulation. Regulatory questions centre on whether synthetic biology is covered by existing regulations, whether they are sufficient for its safe application, or whether new frameworks are required. Several countries draw on existing biotechnology frameworks to govern synthetic biology. For example, in 2018, the Central Committee on Biological Safety (ZKBS) in Germany concluded that synthetic biology can be covered by the regulations applicable to GMOs (Hamilton et al., 2021; Keiper & Atanassova, 2020). The United States regulates biotechnology on the federal level through the Coordinated Framework for the Regulation of Biotechnology, which tasks several agencies with regulatory oversight (CRS, 2022a). A review published in 2017 concluded that the Coordinated Framework continues to be sufficient, but questions remain as to whether the regulations in place are appropriate for the various future uses of synthetic biology (CRS, 2022a; NASEM, 2017). In April 2024, the Biden administration issued a “Framework on Nucleic Acid Synthesis Screening to encourage providers of synthetic nucleic acids to implement comprehensive, scalable, and verifiable screening mechanisms” that relates to its Executive Order on the Safe, Secure, and Trustworthy Development of AI (White House, 2024).

18. This overall picture, whereby synthetic biology is largely covered under existing biotech frameworks, chimes with the concerns of critics who are claiming that “the current regulatory frameworks are insufficient to cope with the complexities of engineering biology innovations and also do not take into consideration building and maintaining trust in the regulation of engineered organisms” (OECD, 2023, p. 2). Moreover, the shared assessments of governments that existing biotechnology frameworks are sufficient and applicable to synthetic biology do not imply regulatory coherence. Governments do not always reach the same conclusions when it comes to the balance between ensuring safety and allowing sufficient space for innovation (CRS, 2022a; Gronvall, 2018). Generally speaking, European regulators tend towards the precautionary principle and their counterparts in the United States look towards risk minimisation and cost-benefit analyses (DoD, 2015). Similarly, the United Kingdom (UK) has historically possessed more stringent regulations for GMOs than the United States (Parks et al., 2017). Other divergences emerge as the United States regulates products and European countries tend to focus on the regulation of processes (CRS, 2022a; Parks et al., 2017). Such differences in regulation, which are closely related to societal acceptability, carry implications for the adoption of synthetic biology. In the eyes of commercial actors, it is, for instance, more likely that the food and agriculture industry takes up synthetic biology products in the United States than in the EU (Parks et al., 2017).

19. Given those differences, some analysts describe the regulatory architecture for synthetic biology and biosecurity as “a ‘patchwork’ of international conventions, national laws, regulations, guidelines, etc.” (Hamilton et al., 2021, p. 54). On the international level, governance issues are discussed in various frameworks. Synthetic biology is a subject of interest for international organisations such as the World Health Organisation (WHO), the World Trade Organisation (WTO), and the International Union for Conservation of Nature (IUCN). The topic also surfaces in the UN Convention on Biological Diversity (CBD), the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), the Biological and Toxin Weapons Convention (BWC), and the Chemical Weapons Convention (CWC) (CRS, 2022a; Keiper & Atanassova, 2020; Trump et al., 2021a). Discussions within the IUCN as well as the CBD, and its subsidiary Cartagena and Nagoya Protocols, mirror more general debates regarding safety concerns and the suitability of existing regulations (Keiper & Atanassova, 2020). Most recently, the CBD “established a process for broad and regular horizon scanning, monitoring and assessment of the most recent technological developments in synthetic biology”, created an Ad Hoc Technical Expert Group to support this process, and invited various stakeholders to provide information on the technology (CBD, 2023).

20. The EU, as well as the Organisation for Economic Co-operation and Development (OECD), continues to consider the matter of biotechnology and synthetic biology as well (Keiper & Atanassova, 2020). Recent developments within the EU include, for instance, legislative discussions

around new genomic techniques (NGTs). In February 2024, the European Parliament (EP) “adopted its position for negotiations with members on the Commission proposal on New Genomic Techniques (NGTs) which alter the genetic material of an organism” (EP, 2024). Amongst others, this legislation would exempt some NGT plants from GMO requirements. However, EU members could not find agreement within the Council of the European Union in May 2024 as positions on patents diverged (Di Mambro, 2024). The file will, therefore, probably be picked up again during the 2024–2029 term of the European Parliament. The OECD established a focus group on synthetic biology in November 2023 that is active within the Global Forum on Technology. The group brings together more than 60 experts from governments, research and academia, industry, and non-governmental organisations “to inform policymakers of key areas where action is needed to foster a strong bioeconomy whilst mitigating potential risks” (OECD, 2024).

21. There are also several non-governmental multistakeholder initiatives that bring together different actors within the field of synthetic biology, some of which establish behavioural guidelines. The members of the International Gene Synthesis Consortium (IGSC) committed themselves to a code of conduct in 2009 which includes, amongst others, the screening of samples for potentially dangerous materials (MPG, n.d.). They can offer platforms to exchange views such as dialogues between the IGSC and the GBA, or the Engineering Biology Research Consortium (EBRC) Global Forum which brought together policymakers to discuss national approaches (Dixon et al., 2022). In fact, several researchers and practitioners called for a Global Forum to assemble policymakers and practitioners from the IGSC, the EBRC, the GBA, the Genome Project Write (GPW), the International Genetic Engineering Machine (iGEM) Foundation, the BioBricks Foundation (BBF), the Bioindustrial Manufacturing and Design Ecosystem (BioMADE), and the OECD. Moreover, there is a significant do-it-yourself (DIY) biology community that overlaps and can go beyond existing academic and practitioner initiatives (CRS, 2022a; OECD, 2023).

V- SYNTHETIC BIOLOGY AND THE SECURITY AND DEFENCE DOMAIN

A. SYNTHETIC BIOLOGY AS A CAPABILITY: USE CASES FOR ARMED FORCES

22. Synthetic biology offers armed forces a broad spectrum of possibilities, the potential of which will unfold in the coming years. Innovations in the areas of energy storage and generation, novel and advanced materials, sensing, as well as medical treatments and human enhancement are of particular importance and interest. The NATO STO observes that synthetic biology will advance capabilities in “sensing; computing; materials and chemical production; materials protection and repair; agriculture and environment; energy storage and generation; human performance augmentation; medicine and pharmaceuticals; and chemical, biological, radiological, and nuclear defence” (NATO STO 2023a, p. 14). A report by the United States Department of Defense from 2015 identifies “commodity materials, specialty materials, sensing, medical and human performance, and biological and chemical threats and defense” as relevant areas (DoD, 2015, p. 9). In short, synthetic biology promises advancements across the board that can be beneficial for armed forces.

23. To begin with, synthetic biology can help militaries increase energy efficiency. There is the potential of using microbes to produce fuels (Evans, 2016), and researchers in the United States have worked on biomanufacturing processes relying on yeast and sugar to produce novel fuels that can power missiles (Miller, 2023; NAVAIR, 2020). There is also the possibility of producing batteries that run on bacteria or are constructed virally (Mauroni, 2018; NATO STO, 2023a). Using fuels and batteries based on synthetic biology would not only lower the environmental footprint of armed forces but also increase operational resilience by reducing dependence on external supply chains, with the potential added benefit of reducing costs (DoD, 2015; EDA, 2016). The environmental footprint of defence operations could further be reduced through microbes that are engineered in a way which enables them to digest waste, thereby enhancing recycling efforts (NSCEB, 2023).

24. Synthetic biology can, furthermore, introduce new ways of producing and improving existing materials and enable the development of novel materials, relevant to armed forces. Given the military's need for advanced materials, the United States Department of Defense identified new processes for producing chemicals or assembling nanomaterials as particularly promising (DoD, 2015). A report by the Congressional Research Service (CRS) notes that biotechnology and synthetic biology can advance camouflage, cloaking, and strengthen armour (CRS, 2022b). Examples include protective gear that can resist high temperatures, including fire (DoD, 2015; Harding & Ghoorhoo, 2023). In addition, there is ongoing work to genetically alter silkworms so that they produce spider silk, a particularly suitable material for strong but flexible protective gear. It may not make materials such as Kevlar irrelevant, but it offers a protective material that is more elastic and flexible (Bourzac, 2023; Dieuliis, 2018; Freedberg Jr., 2023; Tucker, 2016).

25. A report by the Engineering Biology Research Consortium (EBRC, 2020) provides several discrete examples of ways in which synthetically derived materials might aid the different services of the armed forces. For the army, biologically engineered materials could have self-healing properties, help with signature management, and support water purification and desalination efforts. The navy may benefit from new optical materials, coatings that resist corrosion and fouling, and materials that resist fire or radiation. The air force may take advantage of improved and more resilient runways, eased construction, improved canopy life, and better detection of risks to aerospace infrastructure. There is, for instance, the possibility of self-healing concrete for frontline airfields, whereby bacteria fill cracks as they appear (Freedberg Jr., 2023). In addition, novel resins could help in the production of light and protective materials for drones or ships as well as coatings that are resistant to corrosion (Dieuliis, 2018; DoD, 2015).

26. The technology's promise for armed forces apply to sensing as well. Both naturally and synthetically derived systems can sense potential chemical and radiation threats (DoD, 2015). Synthetic biology facilitates the development of highly capable sensors that could detect and alert soldiers to pathogens, biological or chemical agents, decontaminated or dangerous chemicals, and even improvised explosive devices (IEDs) (EBRC, 2020; Evans, 2016; NSCEB, 2023). Researchers did, for instance, successfully use thale cress as a biosensor to detect fentanyl to a high degree of accuracy (Ekström et al., 2019). Naval and air forces could, equally, draw on sensors to detect changes in the maritime or aerospace environment and their respective infrastructures, including material fatigue (EBRC, 2020). In addition, sensors could be used to collect biometrical data from soldiers or monitor their biomarkers (EBRC, 2020).

27. The possibilities of biometrical sensing are closely related to the potential of synthetic biology in medicine and human performance (DoD, 2015; NATO STO, 2023a). For the armed forces, synthetic biology could provide engineered microbiomes that detect, identify, report, and diagnose potential hazards or complications early on, for instance through biosensors (EBRC, 2020; Nordraak & Horn, 2024). The technology also offers medical protections, treatments, and therapeutics that are particularly suited for militaries. It can enhance protection through engineered enzymes that are capable of breaking down chemical agents (Ekström et al., 2019; Nordraak & Horn, 2024). Engineered probiotics can offer protection against pathogens found in water (EBRC, 2020), and can help to deal with digestive health, stress and mental performance (Dieuliis, 2018; DoD, 2015). Lastly, synthetic biology can help to treat injuries and wounds by preventing infections and aid the healing process (DoD, 2015; NATO STO, 2023c; Nordraak & Horn, 2024).

28. Those possibilities point to the potential for human enhancement (Nordraak & Horn, 2024). The European Defence Agency's (EDA) Foresight Exercise mentions synthetic biology as one of the technologies that "can be used to enhance human being's [sic] cognitive and physical capabilities" (EDA, 2022). The EBRC report identifies, inter alia, engineered microbiomes to increase endurance or improve immune resistance. Furthermore, it notes that the navy could draw on engineered microbiomes to enhance the ability of withstanding high-pressure environments and cold (EBRC, 2020). Similarly, the air force could use personalised microbiomes to enhance fatigue resistance, increase nutritional uptake from food through probiotics and draw on engineered microbes to increase the resilience of soldiers in challenging environments (EBRC, 2020). The interim report by the United States National Security Commission on Emerging Biotechnology (NSCEB) notes that

“[a]n engineered human enzyme could deactivate nerve agents (e.g., sarin) in blood” and that “[m]edical synthetic biology research may enable the development of organisms that can produce treatments inside the body” (NSCEB, 2023, p. 8).

B. SECURITY RISKS: NEW WEAPONS, REGULATORY CHALLENGES AND PROLIFERATION

29. As is the case for most emerging and disruptive technologies, synthetic biology not only offers opportunities but can also become a threat if used for malicious purposes. The increasing availability of synthetic biology tools, the proliferation of actors working with this technology, including a sizeable DIY community, as well as regulatory challenges raise questions around biosecurity and biodefence. In 2016, the United States Director of National Intelligence, James R. Clapper, mentioned genome editing under the section of weapons of mass destruction and noted that due to “the broad distribution, low cost, and accelerated pace of development of this dual-use technology, its deliberate or unintentional misuse might lead to far-reaching economic and national security implications” (Clapper, 2016). The EDA’s potential scenarios for 2040 include a “[n]ew biohazard stemming from the use of synthetic biology and gene edition technologies” that “may be used as a bioweapon or biothreat”. Synthetic biology, therefore, can pose a risk for Allied security as well.

30. An analysis by the National Academies of Sciences, Engineering, and Medicine (NASEM) concluded that the most concerning threats are the re-creation of pathogenic viruses that are already known, increasing the danger of extant bacteria and using in situ synthesis to produce harmful biochemicals (NASEM, 2018). The assessment drew on four factors to assess the degree of concern: “Usability of the Technology, Usability as a Weapon, Requirements of Actors, and Potential for Mitigation” (NASEM, 2018, p. 3). Threats of comparatively lower concern include, amongst others, the modification of the human genome, microbiome, or immune system as well as the creation of new pathogens. A study published by the German Bundeswehr Office for Defence Planning provides two further threat scenarios (Vergin, 2018). The scenarios share the assumption that synthetic biology reached the stage of applied research but differ in their assumptions about the technology’s availability. The first scenario assumes the wide availability of synthetic biology and lays out the possibility of a super bacteria that can digest oil into water which could infect NATO fuel tanks. The second scenario assumes a narrower availability and describes a disease outbreak caused by a modified virus that affects peacekeeping forces.

31. These scenarios illustrate the security threats and concerns that synthetic biology may pose. As noted above, the BWC or the CWC generally appear to be applicable and would ban the creation of certain weapons based on synthetic biology (O’Leary et al., 2020; Trump et al., 2021a; Vergin, 2018). However, Allies and partners cannot rely on these frameworks to prevent the development of such weapons. On the one hand, the technology can obscure and transcend the boundaries between biological and chemical weapons (NASEM, 2018). In addition, the regulation of so-called biomimetics, or “nonbiological materials that can imitate biological processes and responses”, is less clear and such weapons may not be banned per se (Johnson & Kraska, 2020). On the other hand, repeated attacks on and disregard for the rules-based international order do not necessarily bode well for compliance with the BWC and CWC. Accordingly, actors with malign intentions that do not abide by those conventions might use novel pathogens or biological and chemical agents for their own purposes, thus posing significant threats (NATO STO, 2023a). Moreover, the BWC secretariat raised awareness that synthetic biology tools are increasingly accessible to a wide range of actors that are not necessarily subject to oversight (Trump et al., 2021a), an observation that speaks to the broader issue of proliferation and (non)compliance. It is, therefore, necessary to continuously monitor technological advancements that may lower entry-barriers (Miller, 2023). Yet, the ease of accessing and using synthetic biology should not be overstated (Hamilton et al., 2021). Nonetheless, armed forces need to prepare themselves to counter threats based on synthetic biology.

VI- MAPPING DEFENCE-RELATED RESEARCH AND DEVELOPMENT BY ALLIES AND EXTERNAL ACTORS

32. These examples show the wide range of potential applications and the ways in which synthetic biology can be both an opportunity and threat in security and defence. Given its promise, various countries prioritise this technology strategically and invest significantly in biotechnology and synthetic biology research and development. For example, Saudi Arabia finances research with a view to develop microbial cell factories and Singapore funds research centres at various universities (Trump et al., 2021a). China also invests heavily in the life sciences and has created research centres that are dedicated to synthetic biology (Crotty, 2023). The United Kingdom's policy paper on its national vision for engineering biology summarises the situation aptly by stating that “[t]his global momentum creates new opportunities for collaboration as well as healthy competition, increasing the need for the UK to act with pace” (UK Government, 2023).

33. This snapshot underlines the far-reaching efforts that countries in- and outside of the Alliance are pursuing in this field. Notwithstanding the dual-use characteristics of synthetic biology, not all research is necessarily related to the security and defence domain. Moreover, it is necessary to realistically assess the state of play. The opportunities of synthetic biology will materialise over the course of the next 20 years (NATO STO, 2023a). The risk of states using the technology for the development of novel biological weapon also faces obstacles (Mauroni, 2018). The same applies to non-state actors. A horizon-scanning exercise by the European Commission Joint Research Centre (JRC) noted that synthetic biology “was assessed as having a medium level of dual-use relevance/impact in the longer term, namely 10–15 years” (Bordin et al., 2020, p. 19). The following mapping exercise, therefore, emphasises the relevant actors in NATO's efforts to embrace the promise and avoid the perils of synthetic biology.

A. NATO AND ALLIES

34. NATO has identified biotechnologies and human enhancement (BHE) as one of the Alliance's nine priority technological areas (NATO, 2023). During a Defence Ministerial in February 2024, NATO member countries took another step by adopting the first international strategy covering the “responsible development and use of biotechnologies and human enhancement technologies” (NATO, 2024a). As such, “NATO has positioned itself as an ethical leader on biotech and human enhancement technologies by adopting an informed, value-based and gender-aware strategy” (NATO, 2024a). The strategy pursues the objective of making the most of this technology in a lawful and responsible manner, fostering trustful relationships between innovators and the wider public, and enhancing NATO's defence posture (NATO, 2024a). Concrete measures include impending research efforts by experts on the opportunities and challenges associated with applying these technologies in the defence field (NATO, 2024a).

35. The publicly available summary of the BHE Strategy, amongst others, defines biotechnologies and human enhancement technologies, lays out their opportunities and risks for the Alliance, formulates aims and desired outcomes, considers the strategic context, and lays out the Alliance's Principles of Responsible Use as well as the ways in which they can be operationalised (NATO, 2024b). In terms of opportunities, the strategy highlights the detection, identification, and monitoring of chemical, biological, radiological and nuclear (CBRN) threats through AI-enabled sensors, the reduction of strategic dependencies on external actors through synthetic biology and bio-manufacturing, and the usage of BHE-enabled materials. Risks are related to novel bioweapons and their potential proliferation as well as the ramifications of biological agents (NATO, 2024b). Moreover, it spells out and describes the six Principles of Responsible Use: lawfulness; responsibility and accountability; safety and security; human agency; informed consent; and sustainability, all of which include a gender perspective (NATO, 2024b). The strategy outlines concrete steps to operationalise these principles, notes that funding is provided through various instruments available to NATO and Allies, and that “Alliance work on BHE must not contradict or undermine the BWC or other related obligations and commitments made by Allies, both national and international” (NATO, 2024b).

36. An article published in the NATO Review by two members of the International Staff who worked in leading roles on the BHE Strategy provides further information. The analysis underscores the need for scientific collaboration across countries as the achievement of technological breakthroughs as well the protection against biotreats cannot be achieved in isolation (Reis & Stanley-Lockman, 2024). In addition, the authors highlight that the Principles of Responsible Use “were developed in public fora with experts from across NATO and partner countries, including from academia, the private sector and other international organisations” (Reis & Stanley-Lockman, 2024). As such, they are the product of multidisciplinary exchanges that assessed the technology from legal, ethical, cultural, and technological points of view (Reis & Stanley-Lockman, 2024). To operationalise the principles, the strategy formulates two focus areas: toolkits and education. The toolkits include learning from AI, risk and impact assessments, as well as testing, evaluating, validating, and verifying. Education should focus on end-users, innovators, and the public (Reis & Stanley-Lockman, 2024). The BHE Strategy also elicited a response by the United States NSCEB which stated that it “believes the Strategy openly addresses many important aspects of these technologies, including security and responsible use” (NSCEB, 2024). Moreover, the NSCEB called upon NATO and Allies “to share information and lessons learned about risks and benefits” and “to consider the broader contexts of these technologies for both military and civil use” (NSCEB, 2024).

37. NATO has, furthermore, been active in the field of synthetic biology through its Science for Peace and Security (SPS) Programme as well as its Science and Technology Organisation (STO). In July 2019, an Advanced Research Workshop took place within the framework of the SPS Programme at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland. The workshop brought together various experts and yielded a monograph, entitled: “Emerging Threats of Synthetic Biology and Biotechnology” (Trump et al., 2021b). The topic also played a role during the most recent Fall Science and Technology Board (STB) meeting in 2023 where Barbora Hrnčířová from the Masaryk University, Czech Republic, received the award for the best presentation after showcasing how bacteria can be engineered to break down resistant materials into sugars (Verner, 2023).

38. The NATO STO covers synthetic biology frequently in its reports and activities. The most recent overview and analysis reports on Science and Technology Trends 2023–2043 include assessments of the risks and opportunities associated with synthetic biology (NATO STO, 2023c, 2023d). The NATO STO identified synthetic biology as a focus area and studies the subject through a Research Task Group (RTG) in the Human Factors and Medicine (HFM) Panel. In March 2019, scientists from Belgium, Finland, Germany, the Netherlands, Norway, Türkiye, the United Kingdom, and the United States convened in Oslo as part of the HFM Panel “to explore how the field of synthetic biology and bioengineering will impact defence forces in the coming years” (NATO STO, 2019). The meeting covered various issues, such as materials, energy, sensing, and chemical and biological developments, and identified another meeting as well as a draft report as the next steps. The Research Task Group 305 in the HFM is tasked with “investigating emerging opportunities and threats as they relate to the NATO defence structure, NATO’s ability to prevent/assess, protect, and recover/mitigate during operations, and national security” (NATO STO, 2023a, p. 14). The study focused on various areas, such as “advanced applications of synthetic biology in medicine; human performance augmentation; CB defence; sensing; agriculture; environmental management; materials; energetics, propellants, and plasticizers; energy storage and generation; and coding and computers” (Nordraak & Horn, 2024, p. 14). Moreover, it formulated recommendations which include bi- and multilateral projects to scale up synthetic biology and biomanufacturing and to ensure interoperability and adoption of sensors that rely on synthetic biology (NATO STO, 2023a).

39. The emphasis on multilateral cooperation mirrors the observation that “[c]oordination between NATO nations over the next twenty years will be crucial to ensuring the security of our forces and protection of member states against harm that could be propagated through misuse of synthetic biology advances” (NATO STO, 2023b, p. 10). Other STO activities are highly relevant as well in this regard. Its long-term study on CBRN addresses medical countermeasures where synthetic biology can contribute (Nordraak & Horn, 2024). The HFM-335 team of specialists, which focuses on BHE, shared the observation that synthetic biology offers opportunities for medical applications (Nordraak & Horn, 2024). Lastly, the STB approved a new Scientific and Technical Committee in the STO. The STC Technology and Science Incubation Panel (TSI) will, amongst others, look at biotechnology.

These examples illustrate that NATO's activities, particularly within the SPS and the STO, position the Alliance to take on a pioneering role in synthetic biology.

40. The Alliance's activities are accompanied by efforts of various NATO members who are already actively engaged in the field of biotechnology and synthetic biology. For example, the Canadian government recently published a list of "Sensitive Technology Research Areas" which includes synthetic biology as one of the technologies that have "provided enhancements to existing weapons, such as biological/chemical weapons and autonomous weapons" (Canada, 2024, p. 10). It also mentions synthetic biology as part of its discussion on biotechnology and expresses the expectation that it "will enable advancements in many areas, such as antibiotic, drug and vaccine development, biocomputers, biofuel, novel drug delivery platforms, novel chemicals, synthetic food, and synthetic life" (Canada, 2024, p. 14). Some Allies are also raising the issue of synthetic biology within international organisations that are relevant for governing the technology. For example, Slovenia, Germany, and the EU hosted a side event in Geneva at the 9th BWC Review Conference where speakers "emphasized that advances in biotechnology and synthetic biology, [sic] demand additional attention devoted to efforts to detect, prevent and mitigate a wide spectrum of security risks" (Slovenia, 2022). During a thematic debate on other weapons of mass destruction in the UN General Assembly's First Committee, the Nordic countries noted in a joint statement that "[t]he potential for misuse of scientific innovations, for instance in synthetic biology, constitutes an ever-evolving security challenge" (Norway, 2019).

41. Turning to research efforts, a mapping of the synthetic biology landscape in Europe indicated that the continent is internationally competitive in terms of academic publications but trails the United States when it comes to patents and funds for innovation (Donati et al., 2022). Within Europe, France, Germany, and the United Kingdom stand out in terms of publications associated with their funding agencies which relates, at least in parts, to their size (Donati et al., 2022). Next to national efforts, the EU is a significant player in this field and funded 21 grant proposals on synthetic biology through the Horizon 2020 Programme (Donati et al., 2022). Recent examples of EU funding underscore the link of research to commercial applications as well as the linkage of synthetic biology with other EDTs. For instance, the EU granted funding for the two-year Synbee project that seeks to enhance "the entrepreneurial skills of young professionals across Europe, with a focus on synthetic biology" (European Commission, 2024a). In addition, a research centre at the University of Tartu (UT, Estonia), in cooperation with the Tallinn University of Technology (Estonia) and the Technical University of Denmark received funding from the European Commission and the Estonian government to "combine synthetic biology with digital technologies to facilitate big data-driven design of cells for the bio-industry" (UT, 2023). Taken together, this indicates that the United States leads in the field of synthetic biology but that European countries are undertaking steps to reap the rewards of this technology through research and development.

42. When it comes to security and defence more specifically, the NATO STO HFM-RTG-305 Team notes that the "[f]ocus across NATO Nations is now shifting towards demonstrating the viability of bioproducts in operational settings in order to reduce operational costs and increase operational flexibility" (NATO STO, 2023a, p. 41). The Norwegian Defence Research Establishment recently published a report entitled "synthetic biology and biotechnology for military medicine and chemical and biological defence – current state and future perspectives" (Nordraak & Horn, 2024). The report engages in horizon-scanning with a focus on applications in the fields of medicine and chemical and biological defence. However, there are general difficulties in identifying dedicated synthetic biology efforts by Allied nations in the security and defence domain. A potential reason could be that such activities are subsumed under the broader terms of biotechnology or biodefense. Analyses suggest that countries such as Germany recognise the specific risks associated with synthetic biology but that preparations are taking place within the broader field of CBRN defence (Herrmann, 2023; Vergin, 2018). At the same time, two NATO member countries stand out and have a leading role in the field: the United States and the United Kingdom.

43. The United States continues to be a leader in biotechnology and synthetic biology and recently published several strategies, policy documents, and initiatives. It created the NSCEB in 2022, which published its interim report in December 2023 and will produce a comprehensive report by the end

of 2024 (NSCEB, 2023). In March 2023, the US Department of Defense issued its Biomanufacturing Strategy which pursues several goals, such as providing guidance for investments (Freedberg Jr., 2023). In August 2023, the United States Department of Defense published its first Biodefense Posture Review (BPR) (DoD, 2023). Taken together, these steps can alleviate some of the shortcomings that experts had previously identified. Experts pointed to uncoordinated efforts as well as varying definitions of key terms and lamented that the focus on risk obscures the opportunities of synthetic biology (Dieuliis, 2018; Mauroni, 2018; NSCEB, 2023). The BPR provides guiding definitions for biodefense, bioincident, biothreat, and biohazard and can, therefore, remedy these concerns and help to streamline activities.

44. The United States Department of Defense and its subordinate entities and services are undertaking a range of activities that do not solely focus on potential threats but also the opportunities synthetic biology has to offer. The United States Department of Defense actively supports the build-up of biomanufacturing capacities by providing support to manufacturing sites (CRS, 2022a; Freedberg Jr., 2023). The United States Army Future Command's DEVCOM Army Research Laboratory made synthetic biology research a top ten priority. It has established an Army Center for Synthetic Biology supporting multi-stakeholder research projects and works on areas such as enhancing the survivability of soldiers, for example through innovative cloaking materials (Tucker, 2019; United States Army, 2024). The United States Department of Defense, furthermore, identified the need to build a pool of personnel with expertise in synthetic biology (DoD, 2015). Accordingly, several branches of the United States armed forces collaborate in the Synthetic Biology for Military Environment programme, which seeks to enhance the armed force's infrastructure, expertise and coordination (Alia-Novobilski, 2017; Dieuliis, 2018). Moreover, the United States Air Force Academy (USAFA) offers the possibility for its future officers to participate in a USAFA Synthetic Biology Education Program (USBEP) where they could join the USAFA iGEM team (Steel et al., 2019). However, these are long-term projects and research outputs need to prove themselves to be battlefield-ready and scalable (Tucker, 2019).

45. Another crucial actor is the Defense Advanced Research Projects Agency (DARPA). In charge of developing emerging technologies for the military's use, it is at the heart of many synthetic biology initiatives. For example, DARPA's Living Foundries project focuses on advancing synthetic biology, including through the creation of 1,000 molecules relevant to defence matters (CRS, 2022a; DARPA, 2021; Uppal, 2021). Moreover, DARPA provides a significant amount of funding for synthetic biology in the United States, with some reports suggesting that it accounts for up to 60% of total funding (CRS, 2022a; Wilson Center, 2015). The agency's funding expanded rapidly in the early 2010s, rising from almost no funding in 2010 to approximately USD 100–130 million annually in 2014 (Evans, 2016; Uppal, 2021). DARPA funds various projects, including efforts that seek to produce the highly durable polymer sporopollenin (Uppal, 2021).

46. The UK recognised the potential of synthetic biology early on and acted accordingly. It published "A Synthetic Biology Roadmap for the UK" in 2012 which entailed the creation of a Synthetic Biology Leadership Council as well as financial support amounting to GBP 70 million for six research centres (UK Government, 2023). These efforts provided the basis for the UK Synthetic Biology Strategic Plan issued in 2016. The United Kingdom Department for Science, Innovation and Technology (DSIT) published a "National Vision for Engineering Biology" in December 2023 which recognises, amongst others, that "[e]ngineering biology will be increasingly critical in achieving national resilience and preparedness for biological risks" (UK Government, 2023).

47. The National Vision also mentions several areas where the United Kingdom Ministry of Defence became active, namely research on materials and fuel. The United Kingdom evaluates the ways in which synthetic biology matters for defence through its Defence Science and Technology Laboratory (Dstl) and launched several funding competitions that focus on practical issues (Evans, 2016). The Centre for Defence Enterprise (CDE) and the Defence and Security Accelerator (DASA) launched two competitions in 2015 and 2016 offering funding for projects using synthetic biology for novel and transparent materials (UK Government, 2016, 2017). The DASA launched another two-phase competition in 2022 on "engineering biology for defence and security", focusing on power and energy technologies, materials for defence, and sensing (UK Government, 2022, 2024). In May

2022, the UK Research and Innovation (UKRI) and Dstl invested GBP 20.6 million in several projects in areas such as improved insect disease control or novel materials (UKRI, 2022).

48. These examples demonstrate the important work undertaken by NATO and Allies. The Alliance can and should be a platform to foster further cooperation that is critical to maintain a technological edge. The NATO STO observes that “[c]oordination between NATO nations over the next twenty years will be crucial to ensuring the security of our forces and protection of member states against harm that could be propagated through misuse of synthetic biology advances” (NATO STO, 2023b, p. 10). Accordingly, the NATO BHE Strategy states that the Alliance “will provide the transatlantic forum for BHE in defence and security” (NATO, 2024b). The United States Department of Defense’s BPR similarly stresses the importance of “[s]trengthening Biodefense Collaboration with Allies and Partners” and notes CBRN efforts within NATO in the context of biodefence (DoD, 2023, p. 37). There are several other examples of such cooperative efforts. The United States and the United Kingdom have a Biotechnology Working Group which could, according to the United States Department of Defense’s BPR, be used “to identify opportunities to optimize cooperation and collaboration” (DoD, 2023, p. 33). Another basis to foster cooperation between the United States and the United Kingdom is their Atlantic Declaration (UK Government, 2023). The action plan from 2023 includes collaboration on synthetic biology (NSCEB, 2023). The United Kingdom and Canada, furthermore, possess a Biomanufacturing Agreement (UK Government, 2023). In short, there is a solid basis for expanding cooperation amongst NATO Allies, which will be pivotal to maintaining the Alliance’s technological advantage.

B. THE RUSSIAN FEDERATION AND THE PEOPLE’S REPUBLIC OF CHINA

49. NATO and Allies are not the only actors that seek to reap the opportunities synthetic biology offers. In fact, analysts note that “advanced biological research is no longer overwhelmingly dominated by Europe and the US” (Trump et al., 2021a, p. 1). The Australian Strategic Policy Institute’s (ASPI) Critical Technology Tracker, which analyses the number and impact of research contributions, documents that China holds the lead ahead of the United States when it comes to published English-language research papers, both in terms of quality and quantity (Gaida et al., 2023). A recently published study by the European Commission’s JRC analyses patenting activities and shows that the United States lead ahead of Europe and China in this regard (European Commission, 2024b). Another mapping exercise observed that “synthetic biology research in China, India, and Australia has steadily been increasing in the last five years” and noted that “the European academic research ecosystem in synthetic biology appears to be overall competitive at a global level, rivalling research efforts carried out in the USA or China” (Donati et al., 2022, pp. 55–56). These examples indicate that external actors, be they partners, strategic competitors, or potential adversaries, are actively engaged in synthetic biology research.

50. Given its dual-use characteristics, such general progress in the field of biotechnology could enable external actors to use synthetic biology for security and defence purposes, potentially posing a risk to Allied security. As the aforementioned analysis of NATO’s BHE Strategy states: “[T]he Alliance’s strategic competitors and potential adversaries continue to invest in BHE technologies and are actively considering how they can be used in operational environments and in hybrid warfare tactics” (Reis & Stanley-Lockman, 2024). The United States Department of Defense’s BPR includes the evaluation that “North Korea and Russia maintain offensive biological weapons programs in violation of Biological Weapons and Toxins Convention (BWC) obligations and identifies concerns with Iran’s activities and its compliance with the BWC” (DoD, 2023, p. 6). In addition, it notes its concern about Chinese “military medical institutions’ toxin research and development given their potential as a biothreat” (DoD, 2023, p. 6). As such, it is worthwhile to briefly cover the activities of Russia and China in this technological area.

51. The Russian Federation presented its so-called BIO2020 strategy in 2020 which sought to enhance its biotechnological capacities across the board through a whole-of-government approach (CRS, 2022b). In addition, it launched a research programme entitled “Genetic Technologies

Development for 2019–2027” that includes, amongst others, a focus on genetic editing (Trump et al., 2021a). There is not much public information on whether Russia would use the technology for security and defence purposes, but its track record does not suggest full compliance with its obligations under the BWC or CWC (CRS, 2022b). Accordingly, NATO’s summary of its BHE Strategy holds that Russia continues its investments into BHE and that it seeks to weaken existing norms against proliferation and use of weapons of mass destruction. It concludes that “[t]he Alliance has grave concerns that Russia is considering further use of chemical or biological weapons in the future” (NATO, 2024b). At the same time, it should be noted that Russia is technologically less advanced than either the United States or China (CRS, 2022b). Whilst the Skolkovo Institute of Science and Technology (Skoltech) demonstrated advancements in using CRISPR, it does not match the improvements seen in China (Eastwood, 2017).

52. The PRC pursues the objective of being a leading nation in the field of biotechnology and of making use of it for both civilian and military purposes (NSCEB, 2023). The PRC’s 13th Five-Year Plan (2016–2020) provided a broad definition of sectors where biotechnology matters and formulated far-reaching objectives, demonstrating the importance the Chinese government attaches to this field (Moore, 2020). In comparison to previous plans, the focus lies more strongly on the development of Chinese companies that can compete on world markets. These efforts include, for instance, protective flanking measures (Moore, 2020). Despite these advancements, China faces challenges when it comes to research and development. It struggles, amongst others, to produce patented innovations that are picked up outside of the PRC. Notwithstanding the significant funding in recent years, investment challenges continue to prevail as well (Moore, 2020)

53. These broader efforts on biotechnology extend to synthetic biology as well. It features the Chinese Academy of Sciences’ (CAS) innovation 2050 roadmap which created the Key Laboratory for Synthetic Biology in 2008 (DoD, 2015). The CAS, furthermore, established an Institute of Synthetic Biology which is supposed to further technological developments and enhance safety of research efforts (Trump et al., 2021a). A similar example of the PRC’s activities is the opening of the “Wuhan Synthetic Biology Innovation Center” in 2022 which constitutes a multi-stakeholder initiative between CABIO Biotech (Wuhan), the Wuhan Institute of Industrial Innovation and Development, as well as the Hubei Yangtze Science Innovation Service (PR Newswire, 2022). These activities go hand in hand with technological advancements that are, for instance, reflected in the fact that the PRC fielded more teams for the iGEM competition than the United States for the first time in 2017 (CRS, 2022a). Chinese scientists made advances in the usage of CRISPR as well (Eastwood, 2017).

54. Chinese military research labs are part of these activities. They publish, for example, CRISPR-related outputs that focus on producing albumin in piglets (Eastwood, 2017). China can be expected to make use of such insights in both the military and civilian sphere through its concept of “military-civil fusion” (Dieuliis, 2018; NSCEB, 2023), with influential military thinkers emphasising the technology’s role for national defence (Johnson & Kraska, 2020). Whilst it is difficult to obtain precise information about defence-related research, there is a set of identifiable security concerns. The United States Department of Defense’s BPR states that the PRC “released plans to make China the global leader in technologies like genetic engineering, precision medicine, and brain sciences. These Chinese publications have called biology a new domain of war” (DoD, 2023, p. 6). The chiefs of the Five Eyes Alliance called for further measures to tackle Chinese spying efforts in high-end technological sectors, including synthetic biology (Sevastopulo, 2023). Such calls speak to earlier reports about the collection of biomedical and genetic data by Chinese companies (Barnes, 2021; Moore, 2020). The National Genebank in China is the largest world-wide repository of such data and includes genetic data from the United States (CRS, 2022b). In 2023, the United States included parts of the Chinese genetic sequencing company BGI Group on its Entity List which restricts the transfer of technology because the collection of data could be forwarded to the Chinese military (Miller, 2023). These reports are concerning in and of themselves but making efficient use of this data can be a challenge. Regulators, therefore, also need to account for the export of technology that would allow for the interpretation and usage of this data (Vogel & Ouagrham-Gormley, 2022). In any case, the PRC is set to be a central player in the field of synthetic biology.

VII- CONCLUSIONS AND RECOMMENDATIONS

55. It is evident that synthetic biology is set to have a significant impact on both the civilian and military domains. The introduction of entirely synthetic materials or products may lie in the future but the work of maintaining the Alliance's technological edge starts today. The Alliance and NATO member countries are well positioned to ensure that the wide-range application of synthetic biology will be a boon and not a bane. As NATO's BHE Strategy states, the Alliance "will provide the transatlantic forum for BHE in defence and security" (NATO, 2024b). This ambition was further substantiated by NATO leaders at the Washington Summit 2024 which, amongst others, committed to the implementation of the Biotechnology Strategy (NATO, 2024c).

56. In doing so, several principles should guide Allied activities. Firstly, any steps should be forward-looking, in the sense that they recognise the rapid evolution of the technology and engage in foresight exercises. Policy initiatives should not be developed on the basis of 'what is' but based on 'what will be'. Secondly, the dual-use characteristic of synthetic biology requires the harmonisation of civilian and military considerations. Put differently, any measures would need to strike a balance between commercial and defence interests as well as innovation and safety. Thirdly, it is necessary to balance the prioritisation of opportunities and threats associated with synthetic biology. Preparation and mitigation measures are necessary, but they must not obscure the possibilities associated with synthetic biology, even if the applications may appear mundane in comparison to the potential threats. Fourthly, ethical questions must be central to any debate. The possibilities of synthetic biology require a constant (re)assessment of whether activities cross boundaries related to life and nature. Such debates should also be at the core of regulatory discussions and decisions. Fifthly, Allies should continuously make use of the work conducted by NATO on biotechnology and human enhancement technologies, build on the activities within the SPS Programme, and avail themselves of the expertise offered by NATO STO and its network.

57. Against the background of these guiding principles, there is a set of concrete steps that NATO, Allies, and NATO Parliamentarians should pursue. These steps should be undertaken simultaneously as they are interdependent, build on, and mutually reinforce each other. Combined with NATO's BHE Strategy as well as the guiding principles elaborated above, these steps are necessary to ensure that the Alliance embraces the promise and avoids the perils of synthetic biology and maintains its technological edge:

- **Work towards a joined-up approach:** Allies should work towards a common definition and understanding of synthetic biology to ensure the coordination of efforts, for example through NATO and the STO. Clearly demarcating synthetic biology from related technologies is a necessary step for jointly reaping the technology's rewards and mitigating its risks, for instance through regulation. Such efforts should include ethical, moral, and normative questions. They should, at the same time, respect national traditions and positions. Moreover, these conversations should not exclusively focus on governments, but include stakeholders from the private sector, academia, and civil society. The multi-stakeholder consultations for NATO's Principles of Responsible Use for BHE provide a blueprint in this regard. Incorporating a wide range of actors is central to striking a balance between opportunities and threats of synthetic biology, not least because biodefence requires a whole-of-society-approach.
- **Engage in awareness raising efforts:** NATO Parliamentarians are particularly well-placed to advance such multi-stakeholder conversations that would also raise awareness about the technology. Public consultations, town-hall meetings, and outreach campaigns are concrete steps that can generate awareness about the technology, as well as its opportunities and risks. Such measures would not only help to fostering a whole-of-society approach but can provide the basis for enhancing trust in the technology, increase societal acceptability, and provide a justification for public investments in synthetic biology. A constant dialogue between governments, parliamentarians, researchers, and practitioners would enable policymakers to stay abreast of technological advancements and provide the basis for ensuring and enhancing biosafety and biosecurity.

- **Prepare the ground for the future:** NATO, national governments, and parliaments should work towards laying the foundation for taking full advantage of synthetic biology. Necessary steps include, inter alia, funding for fundamental research to overcome prevailing technological obstacles, investments into the underlying infrastructure, including laboratories, biofoundries, and supply chains, support for standardisation efforts of protocols to enhance safety and interoperability, improvements of expertise in national authorities and armed forces, and efforts towards increasing societal resilience against threats. In the security and defence domain, this entails the funding of agencies, such as DARPA, investments into research projects that focus on the needs of the armed forces and provide tailored solutions, and measures that help in making academic and commercial research and development available for the defence sector.
- **Monitor developments and engage with external actors:** NATO and Allies should continuously monitor technological advancements of synthetic biology, including developments that lower the entry threshold. They should, furthermore, engage in efforts to strengthen the international regulatory framework that advances synthetic biology in a safe and secure manner, and leverage opportunities, whilst mitigating risks. They should, preferably, do so through a common and coherent approach across different international organisations, conventions, and regional organisations. NATO's Principles of Responsible Use for BHE in defence and security provide an optimal basis to this end. These efforts should also include the objective of curtailing proliferation through export screening and warning mechanisms, for example through the Australia Group, which helps member countries in identifying exports which need to be controlled so as not to contribute to the spread of chemical and biological weapons. NATO Allies should also monitor activities of external actors such as the Russian Federation and the PRC. At the same time, the Alliance should stand ready for constructive engagements and reciprocal transparency with the PRC with a view to strengthening the rules-based international order in this technological field. It is of utmost importance that NATO and Allies lead by example in this regard.

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