


Review Article

An overview of critical energy infrastructure of the European Defence sector

Iliana Papamichael^a, Irene Voukkali^a, Kyriakos Vrionides^a, Pantelitsa Loizia^b,
 Marinos Stylianou^a, Paolo Sospiro^{c,d,f}, Marco Ciro Liscio^{c,d}, Vincenzo Naddeo^e,
 Antonis A. Zorpas^{a,*} 

^a Laboratory of Chemical Engineering and Engineering Sustainability, Sustainable Environmental Engineering, Faculty of Pure and Applied Sciences, Open University of Cyprus, Giannou Kranidioti 89, Latsia, Nicosia, 2231, Cyprus

^b Envitech (Environmental Technology) Ltd, Galileou Galilei 11, Deryneia, 5286, Paralimni-Deryneia, Cyprus

^c Dipartimento di Ingegneria dell'Informazione, Università Politecnica delle Marche, Ancona, Marche, 60131, Italy

^d EUAbout, Bruxelles, Bruxelles, 1000, Belgium

^e Sanitary Environmental Engineering Division, Department of Civil Engineering, University of Salerno, via Giovanni Paolo II, 84084 Fisciano, SA, Italy

^f Dipartimento di Scienze Teoriche ed Applicate (DiSTA), Università Ecampus, Via Isibardi 10, Novedrate (CO), 22060, Italy



ARTICLE INFO

Keywords:

Critical infrastructure
 Defence
 Energy
 Energy security
 Military sector

ABSTRACT

The European Defence sector meets countless of challenges at the confluence of climate change and hybrid threats, which pose significant risks to critical energy infrastructure (CEI). This -paper aims to dissect these complex challenges and devise strategies to boost resilience within the European Defence sector through review process based on PRISMA statement using specific inclusion and exclusion criteria. By analyzing the interaction between climate-related risks, hybrid threat tactics, and vulnerabilities in energy security, this review paper seeks to shed light on effective policy frameworks, technological innovations, and capacity-building initiatives. In addition, paper aim to provide actionable insights that can enable policymakers, defence practitioners and stakeholders to navigate the evolving security landscape effectively. Ultimately, the manuscript strives to contribute to a deeper understanding of the intricate dynamics shaping energy security and defence in Europe, offering practical solutions to enhance resilience and mitigate the impact of emerging threats on CEI. It highlights climate change and hybrid threat impacts, offering insights for policymakers, stakeholders related with the defence sector, including Ministry of Defence as well as the entire energy sector. The paper seeks to prompt action for CEI, ensuring operational readiness and security in the European Defence sector as well as the results will be helpful for policy makers and relevant defence stakeholders to boost the sector to mitigate climate challenges

1. Introduction

Nations and organizations including defence sector face an energy trilemma, which combines concern for energy economics and affordability with a desire for environmental protection and assured energy security [1]. Energy reflections have long been important to mission delivery of armed forces universal. These include operations in theater of conflict, for land, air as well as water transport including for installations and forward operating locations. The increasing global

population, along with industrialization for economic advancement, drives a growing demand for energy, underscoring the necessity of diversifying energy sources. Energy's significance can be understood through various aspects, encompassing the provision of basic necessities, fostering economic growth improving health and well-being by reducing exposure to indoor air pollution and addressing climate change by mitigating greenhouse gas emissions (GHGs) [2]. Consequently, energy should be recognized as a fundamental human right, inclusive of access to a safe, healthy environment, adequate housing, and

* Corresponding author.

E-mail addresses: iliana.papamichael@gmail.com (I. Papamichael), voukkei@yahoo.gr, irene.voukkali1@ouc.ac.cy (I. Voukkali), kvryonid@gmail.com (K. Vrionides), info@envitech.org, pantelitsa-loizia@hotmail.com (P. Loizia), marinos.stylianou@ouc.ac.cy (M. Stylianou), paolo.sospiro@unicampus.it (P. Sospiro), marcociro.liscio@gmail.com (M.C. Liscio), vnaddeo@unisa.it (V. Naddeo), antonis.zorpas@ouc.ac.cy, antoniszorpas@yahoo.com (A.A. Zorpas).

<https://doi.org/10.1016/j.nexus.2025.100483>

Received 31 December 2024; Received in revised form 25 May 2025; Accepted 12 July 2025

Available online 18 July 2025

2772-4271/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

information accessibility [3]. Moreover, the energy union strategy (COM/2015/080) published on 25 February 2015, as a key priority of the Juncker Commission (2014–2019), aims at building an energy union that gives EU consumers (households and businesses) secure, sustainable, competitive and affordable energy. Through the proposed strategy the EU intend for energy security, internal free energy market, energy efficiency, adoption of Paris agreement towards decarbonization supporting clean energy and low carbon economy.

The scientific consensus on climate change has urged increased attention and action at various levels, from political spheres to organizational strategies and public awareness. International agreements like the Paris Agreement underscore the global commitment to addressing climate change, further reinforced by recent agreements such as those reached at the Glasgow summit. The Paris Agreement (COP21) from 2015 sets the ambition and this was confirmed at the latest Glasgow summit. The ambitions for renewable energy and the target of a carbon-neutral society are part of the context we must understand [4]. This will impact our societies in many ways and specifically the move away from fossil fuels and the significant electrification of our society, where the power sources mainly will be renewables (wind, solar, biomass) and to a great extent offshore renewable in the form of offshore wind. The EU's revised renewable energy directive reflects this commitment, raising the binding renewable energy target for 2023 to at least 42.5 % [5]. The Paris Agreement by the United Nations [6] emphasizes the pressing necessity for swift decarbonization to address climate change's harmful impacts and the important shifts required in global energy systems. Sustainable Development Goal (SDG) 7 of its sustainable development agenda emphasizes affordable and clean energy as crucial for advancing agriculture, business, communication, education, healthcare, and transportation [7,8]. The long-term unsustainability of fossil fuels is compounded by security concerns and price instability related to geopolitical conflicts due to the fact that EU member states have different defence priorities, budgets and military-industrial complexes and harmonizing energy concepts would require to align these diverse national interests [4].

Policies aim to reduce the discharge of hazardous substances, limit water and soil contamination and promote responsible waste management practices within the defence sector [4]. Relentless waves of

cyber-attacks, challenges from climate change and the COVID-19 pandemic have underscored the urgent need for the EU to enhance its energy security and autonomy [5]. For instance, the Europe energy security can be supported through diversification of energy sources, improved and increase the investments in renewable sources and through the improvement of the energy infrastructure. In addition, advancing hydrogen technology, accelerating offshore wind projects and promoting energy efficiency will further enhance resilience. The EU supports diverse and often cross-border energy infrastructure projects that produce, store and distribute energy efficiently. This support contributes to a more integrated energy system, which is essential to achieve the energy policy and climate objectives [9,10]. In addition to inter-connecting the energy infrastructure and further integrate renewables and clean technologies into the EU energy system, these projects help to reduce the EU's dependence on third-country energy imports [11]. Moreover, considering that the defence sector has too many buildings especially for administrative purpose, those buildings require energy that will cover lighting, colling and heating. Defence sector demands for energy security. Taking this into consideration the decarbonization of the defence building sectors may achieved through PV panes and the use of batteries for energy storage and saving [4].

The energy sector is responsible for >75 % of the EU's GHGs. Simultaneously, the European Green Deal (EGD) serves as a blueprint for tackling climate and environmental issues, aiming to transition the EU into a modern, resource-efficient, and competitive economy, ultimately positioning it as the world's first climate-neutral continent by 2050 (Fig. 1) [12,13]. To achieve this goal, the 'Fit for 55' package targets a reduction in net GHGs by at least 55 % by 2030, compared to 1990 levels [14]. Reinforcing the EGD, REPowerEU emerged as the EU's response to the global energy market disruption following Russia's invasion of Ukraine in February 2022. REPowerEU focuses on swiftly reducing reliance on Russian fossil fuels by diversifying energy supplies, enhancing energy efficiency for consumers, and expanding renewable energy production [15].

The urgent push of the EU towards monitoring and transitioning energy infrastructure into more sustainable pathways constitutes a complex network of systems and facilities that enable the production, transmission, distribution as well as consumption of energy across the



Fig. 1. European green deal action plan (Figure developed by the authors).

continent [16]. The infrastructures encompass numerous components, including but not limited to electricity grids, gas pipelines, renewable energy installations, nuclear power plants, oil refineries and district heating systems [17]. Investments in interconnectors, smart grids and digitalization are facilitating the integration of renewables, improving grid reliability and enabling real-time monitoring and optimization of energy flows [18–20]. Additionally, EU's energy infrastructure is evolving to accommodate decentralized generation, energy storage technologies and the electrification of transport [21–23].

Although, when it comes to the defence sector, the research and development regarding energy storage and security as well as critical energy infrastructure (CEI) seems necessary and vital. The evolving EU security landscape is characterized by heightened competition and multipolarity, accompanied by emerging national threats and a shift towards safeguarding critical infrastructure, including offshore renewable installations and cross-border energy interconnectors [5]. This complex security environment blurs the lines between peace and conflict, giving rise to the "grey zone" condition, where distinguishing between hostile acts and disruptive events becomes increasingly challenging. In this context, both traditional threats from nation-states and non-state actors, including terrorism and organized crime, contribute to the multifaceted risk landscape [5,16]. According to the European Defence Agency (EDA) [24], the energy consumption of the European defence sector ranks among the highest in the EU, similar to the energy usage of a minor EU Member State.

The defence sector's substantial use of fossil fuels and natural resources results in a significant carbon footprint [25]. The defence sector caused several impacts on climate change such as GHGs from military operations, energy intensive infrastructure, soil degradation, deforestation, pollution etc., both directly and indirectly, including carbon emissions from military operations and resource-intensive activities, such as training exercises and transportation [26]. Additionally, land use changes resulting from military installations and operations, as well as deforestation and land degradation in conflict zones, contribute to environmental degradation and biodiversity loss, exacerbating climate change effects. Furthermore, the sector's activities can lead to environmental pollution, releasing hazardous substances into soil, water, and air, which can have long-term consequences for ecosystems and human health. In addition, the defence sector contribute to GHGs, pollution from military aircrafts, vehicles as well as, radioactive, toxic and biological wastes. While the direct contribution of the defence sector to climate change may be relatively small compared to other sectors, its indirect impacts underscore the importance of promoting sustainable practices and reducing environmental footprint to mitigate climate change and foster global sustainability [27].

The aim of this paper is to provide a comprehensive assessment of the challenges facing CEI within the European Defence sector. Through an in-depth analysis, the paper aims to offer insights into the vulnerabilities, risks and complexities associated with the energy infrastructure that supports defence operations in the EU. By highlighting the intersection of climate change impacts, hybrid threats and energy security concerns, the paper seeks to inform policymakers, defence practitioners and stakeholders about the urgent need for enhancing resilience and fortifying CEI against emerging threats. Finally, the paper aims to stimulate discourse and prompt action towards developing effective strategies, policies and innovations to safeguard the energy infrastructure essential for the operational readiness and security of the European Defence sector.

2. Materials and methods

To ensure the acquisition of relevant references, the research employed the PRISMA statement for preferred reporting items for systematic reviews and meta-analysis, designed for systematic reviews and meta-analyses. This protocol comprises 27 distinct pathways, guiding various stages of the review process, including defining eligibility

criteria, identifying information sources, devising search strategies, conducting selection procedures, and analyzing results and data [28, 29]. In adherence to the inclusion criteria, articles meeting the following specifications were considered: (i) written in English, (ii) published between 2010 and 2024, (iii) pertaining to the defence sector and energy infrastructure, and (iv) in accordance with the chosen keywords. Additionally, reports such as statistical reports, legislation, strategies and directives were included regardless of publication date to provide a comprehensive overview of the defence sector and CEI. Exclusion criteria encompassed: (i) technical reports, (ii) irrelevant data, and (iii) materials not meeting the inclusion criteria.

The chosen keywords for the search were: *X* AND *Energy* AND/OR *Energy infrastructure*, *X* AND *Environment*, where X was *Military* OR *Defence* OR *Army*. Each combination was applied individually to gather articles, which were then screened for duplicates using automation tools such as Mendeley. Following duplicate removal, the remaining articles were assessed for eligibility based on the inclusion and exclusion criteria. Articles deemed out of scope were excluded at this stage. Utilizing the SCOPUS database, from a total of 1050 records gathered, 79 records were included in this communication, comprising 62 articles and 11 reports (Fig. 2).

The references cited in Fig. 2 denote search engines utilized to gather additional data, primarily statistical information, from reputable sources such as Statista, Eurostat, OECD, the World Bank, and the European Commission, and were incorporated as necessary.

To create a map based on bibliographic data we used the VOS viewer software version 1.6.20 [30]. 125 keywords were found from the 114 papers for the review process regarding defence sector (including military or army) and energy infrastructure, and were used. As minimum number of occurrences (the occurrences attribute indicates the number of documents in which a keyword occurs at least for 1 time) of a keyword equal with 1. For each of the 203 keywords, the total strength of the co-occurrence links with other keywords were calculated and the number of keywords that were selected was 136 (as were the keywords with the greatest total link strength). Two maps were created. The visualization methods of "keywords network" and "keywords density" depict keyword relationships and their prominence differently. In the "keywords network" visualization, the size of both the label and circle representing each item is dictated by the item's weight. Keywords with higher weights are depicted with larger labels and circles, emphasizing their importance. Meanwhile, in the "keywords density" visualization, keywords are depicted similarly to the network visualization, with labels indicating their presence. Additionally, each point on the visualization carries a color representing the density of items in that area. By default, colors transition from blue to green to yellow. Points surrounded by a greater number of keywords, each carrying higher weights, tend towards a yellow hue, indicating higher density. Conversely, points with fewer nearby keywords, or those with lower weights, lean towards a blue color, denoting lower density.

3. Results and discussion

To provide a comprehensive overview of previous studies in our research area, a visual analysis of the findings was conducted using keyword co-occurrence techniques. Specifically, VOSviewer software was employed to generate a visual synthesis of existing research, enabling the identification of key thematic clusters, conceptual linkages, and patterns of researcher interests. This approach not only highlights the most frequently recurring terms within the literature but also reveals how these keywords are interconnected, offering additional information into the structure and evolution of research on the research area. Fig. 3a presents the keywords network visualization while Fig. 2b the keywords density visualization. It's obvious that defence sector is strongly connected and hyperconnected with many research topics such as but not limited to critical infrastructures, energy efficiency, energy infrastructure, security systems, civil defence and many others. Moreover, the

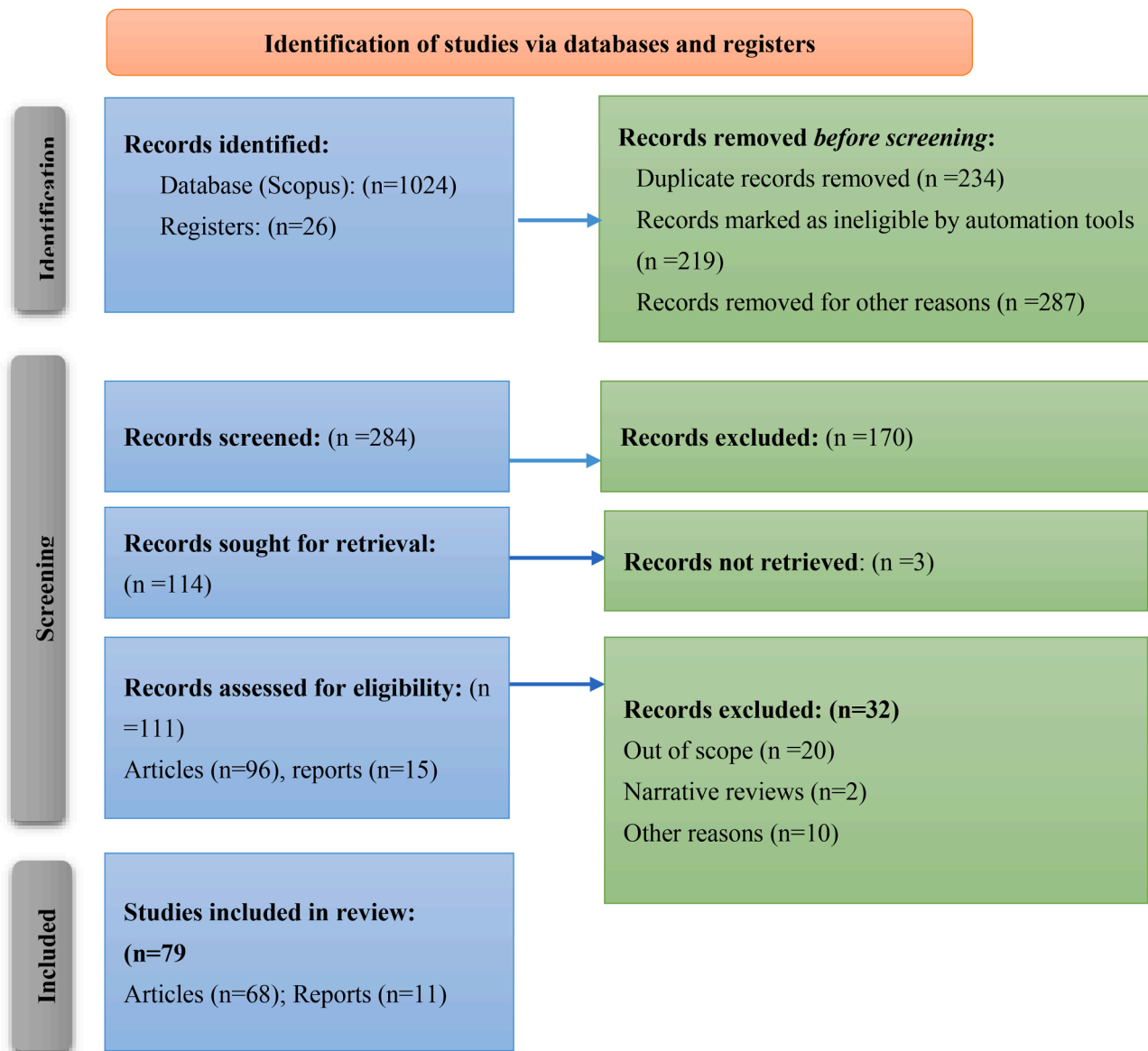


Fig. 2. PRISMA statement for the recruitment of adequate references (Figure developed by the authors).

countries research contribution from the PRISMA statement (from the 2005–2025) was: USA to be the leading country with 35 orientations followed by India with 21, China with 17, South Korea with and UK with 8, Australia with 6, Ukraine and Saudi Arabia with 5, Poland, Norway, France and Canada with 4 while Spain, Italy are presented with 3.

The decentralization of energy infrastructure, particularly with the explosion of offshore wind farms and interconnectors, presents new challenges and demands innovative approaches to planning, doctrine and tactics [31,32]. Offshore renewables, including wind farms and energy islands, are poised to become critical infrastructure, imposing robust protection strategies and coexistence frameworks to mitigate security risks effectively [32]. To reach EU's energy and climate objectives, the EU needs to increase the share of renewable energy used. Renewable energy sources (RES) play an essential role in diversification efforts and fostering sustainable development, with EU nations holding considerable potential to expand their energy mix through greater integration of RES [33]. Moreover, strengthening EU's energy security enhances willingness for political, economic and environmental adversities [34,35]. Initiatives aimed at securing energy supplies, avoidance disruptions and protecting critical infrastructure play a crucial role in

achieving this objective. Additionally, enhancing energy security promotes the adoption of renewable energy and energy-efficient technologies, facilitating access to cleaner and more cost-effective energy for consumers while combating energy poverty [36].

From the references recruited using the PRISMA statement, three (3) of them stood out regarding the Defence sector. First, the report published by the EDA and the European Commission titled: "*Fortifying Defence: Strengthening critical energy infrastructure against Hybrid threats*" highlights the concerning rise in hybrid threats within the EU, which exploit vulnerabilities in CEI [16]. The primary objective of the study was to strengthen defence energy resilience by proposing a comprehensive set of measures at both EU and national levels. These measures aim to assess and mitigate vulnerabilities, streamline policies and procedures and leverage advanced technologies and capabilities to effectively counter hybrid threats in a holistic manner. Additionally, the study provides recommendations for promoting civil-military collaboration, raising awareness, sharing best practices and fostering synergies for joint projects to ensure defence energy resilience. As emphasized by EU Member States in the EU's Strategic Compass for security and defence, these efforts will enhance solidarity and mutual assistance

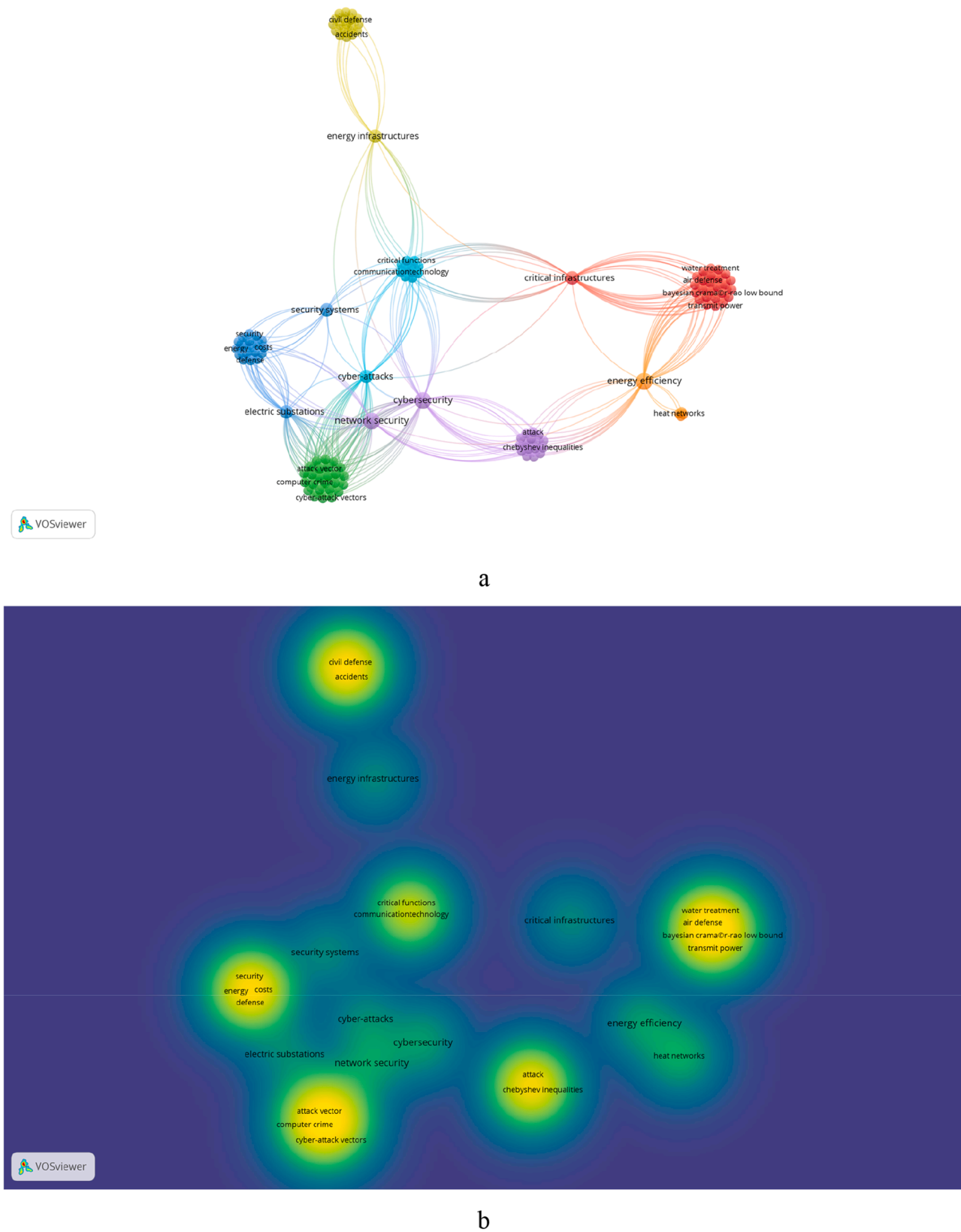


Fig. 3. (a) keywords network visualization (b) keywords density visualization.

among member nations. These threats encompass persistent cyber-attacks targeting crucial entities and escalating challenges stemming from the impacts of climate change and the COVID-19 pandemic. Within the framework of the Consultation Forum for Sustainable Energy in the

Defence and Security Sector (CF SEDSS III), the EDA and the European Commission Joint Research Centre conducted an extensive study on enhancing the resilience of defence-related CEI in response to hybrid threats. This groundbreaking study identified potential stakeholders

capable of undermining EU interests and described various hybrid strategies they may engaged to target critical entities and exploit weaknesses.

The second report by the European Commission Directorate-General Joint Research Centre and the EDA titled: “Impacts of climate change on defence-related critical energy infrastructure” [5] highlights several key findings and gaps, including insufficient integration of climate considerations in defence planning and procurement, lack of a coherent EU strategy for energy and climate in defence and limited coordination between civilian entities operating CEI and Ministries of Defence (MoDs). It also emphasizes the importance of strengthening civilian-military cooperation and addressing security threats posed by foreign-owned civilian CEI. The study also proposes concrete recommendations for EU defence decision-makers. These recommendations included developing an EU Defense Strategy on Climate Change, establishing a multi-stakeholder forum for defence, energy, and climate, defining a strategic framework for CEI in EU defence, and coordinating civilian-military response to climate disasters and energy crises. Additionally, the study recommended integrating climate considerations into military planning, procurement criteria and R&D efforts, as well as modernizing existing infrastructure to address climate risks like offshore energy infrastructure.

The third one entitle “Shaping the future. Energy Transition in the Defence Sector” published from EDA aim on the sustainability imperatives, particularly embodied in the European Green Deal and the strategic considerations of the defence sector, focusing on energy efficiency, building performance and the defence role within this framework. In addition, highlights the deployment of offshore wind, as outlined in the EU’s offshore renewables sector strategy, is examined with a keen eye on its implications for the defence sector. The report also addresses the substantial environmental impact of the defence sector, encompassing areas such as greenhouse gas emissions, waste management, hazardous waste, noise pollution, and habitat destruction [4]

Addressing security implications of offshore renewable development requires a comprehensive approach, encompassing regulatory clarity, stakeholder engagement and capacity-building initiatives. Initiatives such as scenario building, regulatory mapping and trial programs play a crucial role in enhancing understanding and addressing gaps in knowledge [37]. By investing in simulation tools and conducting trials, stakeholders can assess the impact of offshore renewables on defence systems, identify mitigation strategies, and foster consensus among stakeholders. Ultimately, these efforts aim to minimize uncertainty, remove barriers and accelerate the transition towards carbon neutrality while safeguarding national security interests [16].








One of the key priorities for the EU is to make sure all Europeans

have access to supplies of secure, clean and affordable energy. The EU countries utilize a diverse range of energy sources to meet their energy needs. According to EU statistics [38], renewable energy sources such as wind, solar, hydroelectric as well as biomass are increasingly being harnessed to mitigate carbon emissions and strengthen energy security. Wind farms, both onshore and offshore, contribute significantly to electricity generation, alongside solar photovoltaic panels, particularly widespread in countries like Germany, Italy, Belgium, Denmark, France and Spain. Hydroelectric power remains vital, with nations like Sweden, Austria, Finland and Portugal utilizing their abundant resources. Biomass, derived from various organic materials, serves multiple purposes, including electricity generation, heating, and transportation in various EU countries, such as Finland, Estonia, Latvia, Denmark and Luxembourg. Natural gas, imported from diverse global sources via liquefied natural gas terminals, plays a prominent role in electricity generation, heating, and industrial processes in a large number of countries including Belgium, Poland, Spain, Portugal, Italy, Czechia. Nuclear power remains significant in countries like France and Germany, providing low-carbon electricity, albeit amid safety concerns. Oil remains crucial for transportation and heating, with EU countries importing from multiple regions (Table 1).

While enhancing resilience to climate change is imperative for armed forces, their initiatives to limit GHGs are equally vital. Such efforts can enhance energy security and autonomy by diversifying energy sources and reducing reliance on supply chain energy, thus mitigating exposure to vulnerabilities [39]. Therefore aiming at energy efficiency in the defence sector is crucial for numerous reasons including (Fig. 4) [40,41]: (i) cost savings by reducing energy consumption and operational expenses, allowing resources to be allocated more effectively to other priorities [42,43], (ii) enhance the operational effectiveness of the military by extending the range and endurance of vehicles, aircraft and other assets [26]. In this regard, operational effectiveness can be particularly effective for missions in remote or hostile environments where energy resources may be limited or difficult to access [44], (iii) the reduction of the logistical challenges linked to delivering fuel and other energy resources to military bases and operational zones enhances military agility, decreases dependence on fragile supply routes, and boosts operational adaptability [45], (iv) contribute to environmental sustainability by reducing carbon emissions and minimizing the environmental footprint of military activities [46], and (v) increase technological innovation, leading to the development of more advanced and energy-efficient equipment, systems, and processes [47].

In order for CEI to be properly addressed however, additional areas need to be developed. The support the integration of climate resilience and sustainability across all aspects of defence, emphasize operational

Table 1
Main electricity sources per country (source may not be produced in each country directly but may be imported from other countries).

Main Energy Resources	 Solar Power Renewable energy	 Wind Power Renewable energy	 Biomass energy Renewable energy	 Hydro power Renewable energy	 Nuclear Power Non – Renewable energy	 Gas power Non – Renewable energy	 Oil & petroleum/ Fossil Fuels Non – Renewable energy
Main energy resources per EU countries	Italy; Hungary; Malta; Spain; France; Greece; Cyprus	Belgium; Denmark; France; Germany; Ireland; Netherlands; Luxembourg; Poland; Spain; Portugal; Austria; Croatia; Greece; Cyprus Sweden; Estonia; Lithuania;	Finland; Estonia; Latvia; Denmark; Luxembourg	Finland; Sweden; Latvia; Lithuania; France; Portugal; Italy; Slovakia; Austria; Slovenia; Croatia; Romania; Bulgaria; Greece	Finland; Sweden; Belgium; Luxembourg; France; Spain; Czechia; Slovakia; Hungary; Slovenia; Romania; Bulgaria	Latvia; Lithuania; Ireland; Netherlands; Germany; Belgium; Poland; Spain; Portugal; Italy; Czechia; Slovakia; Austria; Hungary; Croatia; Malta; Greece	Estonia; Denmark; Ireland; Netherlands; Germany; Poland; Czechia; Slovenia; Romania; Bulgaria; Malta; Greece; Cyprus

ENERGY EFFICIENCY IN DEFENCE

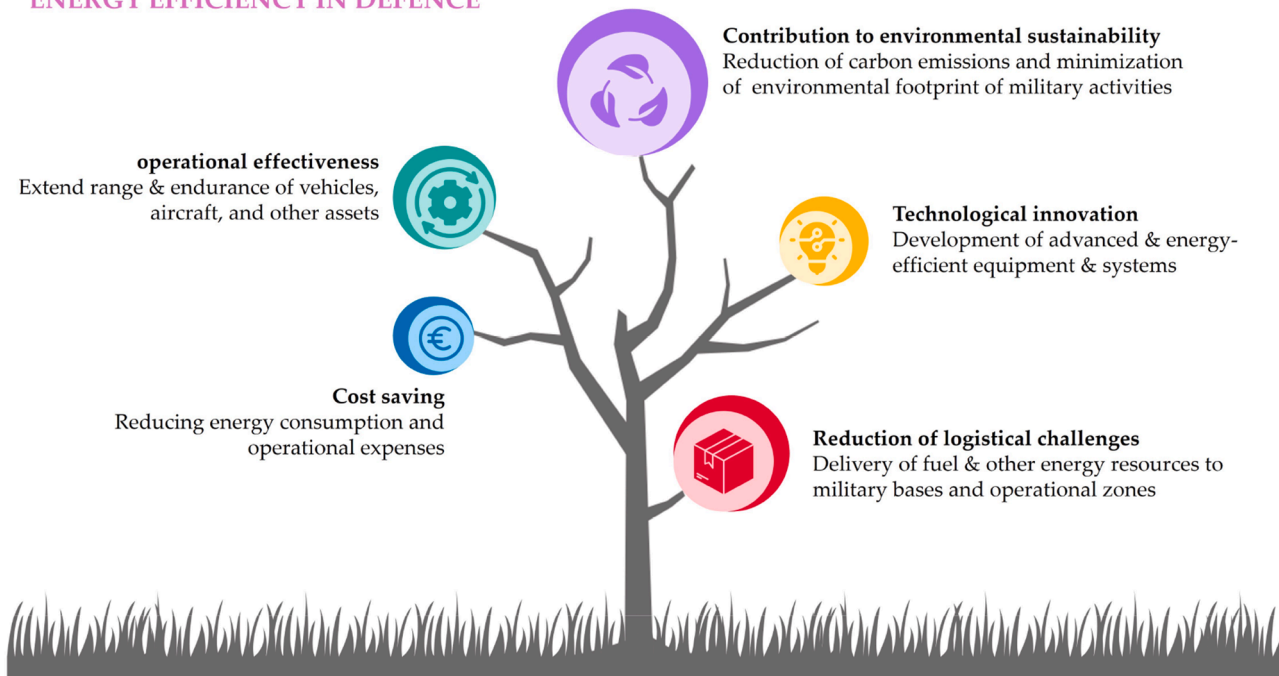


Fig. 4. Benefits of tackling energy efficiency in the defence sector (Figure developed by the authors).

readiness, capability development, governance structures, stakeholder engagement as well as research and innovation [48].

Resilience plays a central role in withstanding actions, particularly in the context of hybrid threats [16]. Understanding the European Union as a whole-of-society system is essential, as hostile actors seek to undermine democracies, challenge decision-making processes, and create cascading effects across society [49]. By targeting CEI like energy networks, these actors seek to exploit vulnerabilities and amplify the impact of their actions. Therefore, a comprehensive understanding of the interconnectedness of several societal elements is crucial for effectively countering hybrid threats [50,51]. The concept of resilience extends

beyond mere protection against physical attacks as includes the ability to adapt and recover from disruptions, whether caused by deliberate attacks, natural disasters, or technological failures. In the context of CEI, enhancing resilience involves not only fortifying physical infrastructure but also developing robust response mechanisms, fostering collaboration between public and private stakeholders and implementing effective risk management strategies [52].

At the same time, a range of tools to target CEI (Fig. 5) and military domains have to be in place, not just for combating hybrid threats but also measure the environmental impacts and energy demands of named infrastructures. These tools include foreign direct investment,

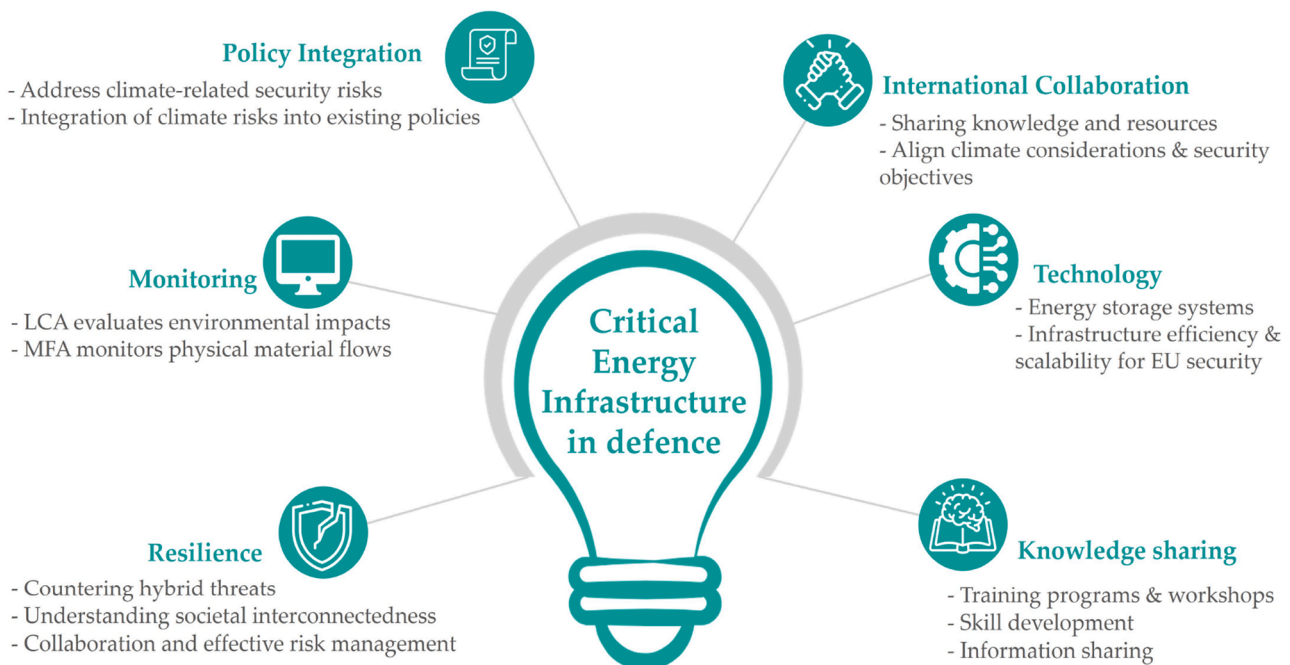


Fig. 5. Recommended mechanisms for tackling CEI in the defence sector (Figure developed by the authors).

infrastructure dependency exploitation, cyber and industrial espionage, airspace/territorial violations, intelligence operations, Life cycle assessment (LCA) and material flow analysis (MFA). To effectively track and assess the environmental impacts stemming from various systems, it is essential to conduct thorough monitoring and quantification of these implications. LCA serves as a fundamental tool in this attempt, offering a standardized approach to evaluate the environmental and energy impacts associated with the entire lifespan of a product, service, or system [53–55]. This includes activities ranging from raw material acquisition through production, utilization, end-of-life management, recycling and final disposal [53].

Over the past three decades, LCA has undergone significant advancement, evolving from a basic energy analysis to a comprehensive environmental assessment that encompasses aspects such as life cycle costing and social considerations [56,57]. Recently, the scope of LCA has expanded further with the introduction of life cycle sustainability analysis, broadening the scope of environmental evaluation [58]. The utilization of LCA enables decision-makers to compare different scenarios within the same system, facilitating the identification of environmentally preferable scenarios [58]. This methodological approach examines the entire life cycle of a process, system, or product, thereby uncovering potential environmental impacts at various stages. Standardized protocols, such as ISO 14,040:2006 and ISO 14,044:2006 [59, 60], provide guidelines for conducting LCA studies, ensuring consistency and reliability in the assessment process.

Similarly, MFA is a systematic approach used to evaluate the movement of materials and their accumulation within a specified system across spatial and temporal dimensions [61,62]. It involves tracing the pathways of materials from their sources to their destinations, known as sinks, within the system. MFA focuses on monitoring and analyzing the physical flows of materials as they enter, traverse, and exit the system, typically centered around economic activities. These analyses are conducted using methodically organized accounts measured in physical units [63]. The application of MFA spans various levels, encompassing economic, administrative and natural entities. It can investigate material flows within the global economy, regional or national economies, specific territories, municipalities, ecosystems, industrial units, or economic activities such as firms or plants. Regardless of the scale, MFA serves to comprehend the dynamics of material flows, their transformations and their implications for both the economy and the environment [64,65]. Using MFA, it becomes possible to pinpoint the sources of environmental pressure, assess the risks associated with material supply disruptions, identify opportunities for enhancing efficiency and productivity and devise strategies to manage and mitigate the adverse environmental impacts of resource utilization [66,67].

In this regard, adequate policy integration and international cooperation regarding the defence sector are essential for addressing the security implications of climate change [68,69]. Policy integration and international cooperation enable the sharing of knowledge, best practices, and resources across borders, enhancing the collective ability to anticipate and mitigate the security risks posed by climate change. This collaborative approach helps to identify vulnerabilities, develop resilience strategies and implement measures to address the impacts of climate change on defence infrastructure and operations [70]. Furthermore, by aligning climate considerations with broader security objectives, policymakers can strengthen the overall effectiveness of security frameworks. This alignment ensures that efforts to address climate-related security risks are integrated into existing security policies, strategies, and operations, maximizing the impact and efficiency of mitigation and adaptation measures [71,72].

Furthermore, technological innovations play a crucial role in mitigating climate risks and enhancing energy resilience in the defence sector. Smart grids, energy storage systems and advanced monitoring solutions, assessing their potential to improve infrastructure efficiency and reliability are vital in both recording and sharing data and success stories in CEI but also examine the scalability and feasibility of these

innovations in the context of EU security objectives [26,73–76]. Simultaneously, the cultivation of capacity and the sharing of knowledge stand as indispensable elements within the defence sector's arsenal against climate-related challenges [77]. Through the establishment of training programs, workshops, and platforms dedicated to knowledge exchange, interdisciplinary collaboration and stakeholder engagement are facilitated. These initiatives not only equip defence personnel with the necessary skills and expertise but also foster a culture of collaboration and information-sharing across different disciplines and sectors [78]. For instance, training programs within the defence sector based on micro credential, to increase the knowledge of cadets, officers, and other military personnel's will increase the knowledge on energy security, energy management [79], energy efficiency, and reduction of defence carbon footprint.

Stakeholders plays crucial role in the defence sector. According to Hadjisavvas et al., [4] to address, approach, or engaged with the stakeholders it is suggested that strategies must be developed. There are various models for stakeholders of categorisation, however, most of the models encompass an appreciation of their needs, expectations, interests and potential impact their engagement may cause. Fig. 6 presents a proposed categorisation of the identified stakeholders according to their level of concern (interest, x-axis) and their level of ability to impact the barriers/risk relevant for the defence (y-axis). Effective stakeholders engagement (e.g. military sector, ministry of defences, SMEs etc.) within the defence sector is critical for aligning strategic objectives, enhancing operational transparency and fostering inter-agency trust. This strategy must be structured, adaptive engagement framework tailored to the unique security, confidentiality and political dynamics of the defence environment. Engagement methods range from high-level strategic forums and classified briefings to collaborative technology development and community outreach, standardised to stakeholder sensitivity and classification requirements. Empirically stakeholders engagement will help defence and security organisations better understand strategic level stakeholder complexity. Moreover, the engagement of stakeholders strengthened relationships with governmental authorities, supported by annual planning assumptions, effectively informing policy makers. A stakeholders engagement strategy must outlines defence priorities, to inspire stakeholder confidence as well as to guarantee safe defence operations across Europe.

5. Conclusions

The paper has underscored the urgent need for resilience-building measures in the defence sector. Insights into effective policy frameworks, technological innovations, and capacity-building initiatives have

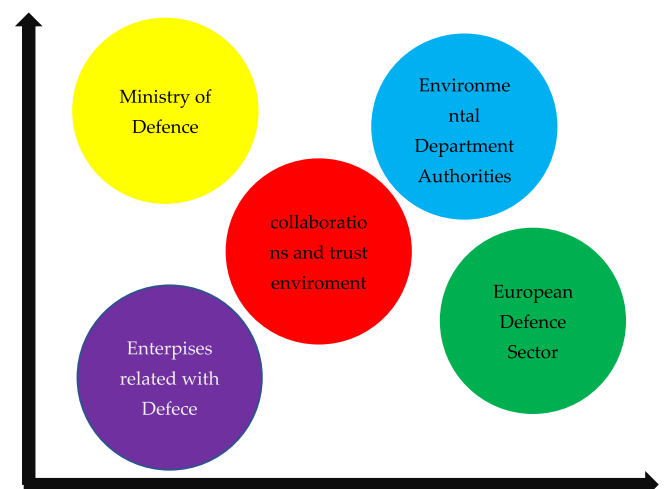


Fig. 6. Stakeholders categorization (figure created by the authors).

been offered to depute policymakers, defence practitioners and stakeholders in navigating the evolving security landscape. Policy integration and international cooperation are vital for effectively tackling the security implications of climate change, aligning climate objectives with broader security frameworks and maximizing the impact of mitigation and adaptation measures. Moreover, technological innovations, such as smart grids and advanced monitoring solutions, play a pivotal role in enhancing energy resilience and mitigating climate risks within the defence sector. These innovations not only strengthen infrastructure efficiency but also provide valuable data and insights crucial for informed decision-making and strategic planning. Furthermore, capacity building and knowledge sharing stand as indispensable pillars in strengthening climate resilience strategies within the defence sector. Moreover, through interdisciplinary collaboration and stakeholder engagement through training programs and knowledge-sharing platforms, defence personnel can acquire the necessary skills and expertise to address emerging challenges effectively.

In addition, the comprehensive assessments of vulnerabilities, risks and complexities associated with energy infrastructure, policymakers, defence practitioners and stakeholders can develop tailored made strategies and policies to safeguard CEI. This holistic approach not only ensures the operational readiness and security of the European Defence sector but also contributes to broader climate objectives and national security interests. Through this research, a deeper understanding of the intricate dynamics shaping energy security and defence in the EU has been achieved, paving the way for pragmatic solutions to enhance resilience and mitigate the impact of emerging threats on CEI. Moving forward, it is imperative to continue fostering collaboration, innovation, and knowledge sharing to safeguard the energy infrastructure essential for the operational readiness and security of the European Defence sector.

Future research in the era may cover the NEXUS framework especially in terms of how it connects with the water-energy-food (WEF) systems. Additionally, defence needs to engage more stakeholders especially from the civil society as well as to strength the relationships with governmental authorities. This has a direct effect on a stakeholder's engagement strategy that each defence sector should developed and monitored.

CRedit authorship contribution statement

Iliana Papamichael: Writing – original draft, Methodology, Formal analysis, Writing – review & editing, Software, Investigation, Data curation. **Irene Voukalli:** Writing – review & editing, Writing – original draft, Resources, Investigation, Data curation, Supervision, Methodology, Formal analysis. **Kyriakos Vrionides:** Investigation, Formal analysis. **Pantelitsa Loizia:** Investigation, Writing – original draft, Data curation. **Marinos Stylianou:** Validation, Data curation, Writing – review & editing, Formal analysis. **Paolo Sospiro:** Validation, Visualization, Formal analysis. **Marco Ciro Liscio:** Writing – review & editing, Formal analysis, Validation. **Vincenzo Naddeo:** Writing – review & editing, Validation, Formal analysis, Visualization, Software. **Antonis A. Zorpas:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Data curation, Writing – original draft, Validation, Software, Project administration, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research received no external funding

Data availability statement

Not applicable

Data availability

No data was used for the research described in the article.

References

- [1] C. Samaras, J.W. Nuttall, M. Bazilian, Energy and the military: convergence of security, economic and environmental decision making, *Energy Strategy Rev* 26 (2019) 100409, <https://doi.org/10.1016/j.esr.2019.100409>.
- [2] G. Kakoulaki, S. Szabo, F. Fahl, F. N. Taylor, A. Gracia-Amillo, R. Kenny, G. Ulpiani, A. Chatzipanagi, K. Gkoumas, A. Jäger-Waldau, European transport infrastructure as a solar photovoltaic energy hub, *Renew. Sustain. Energy Rev.* 196 (2024) 114344, <https://doi.org/10.1016/j.rser.2024.114344>.
- [3] Rathore, N.S.; Panwar, N.L. *Renewable energy sources for sustainable development*; 2007; ISBN 81-89422-72-3.
- [4] Hadjisavvas, C.; Kuzel, M.; Zorpas, A.A.; Voukalli, I.; Papamichael, I. Shaping the future: energy transition in the defence, sector (European Defence Agency, CF SEDSS), (Brussels, Belgium) 2024, Doi: 10.2836/1604831.
- [5] T.D.C. R, K. E, H. C, *Impacts of Climate Change on Defence-Related Critical Energy Infrastructure*, Publications Office of the European Union, Luxembourg (Luxembourg), 2023.
- [6] News European Parliament EU and the Paris agreement: towards climate neutrality, 2019 available online: <https://www.europarl.europa.eu/news/en/headlines/society/20191115STO66603/eu-and-the-paris-agreement-towards-climate-neutrality> (accessed on Apr 3, 2022).
- [7] J.B. Nabukalu, J.A. Asamani, J. Nabyonga-Orem, Monitoring sustainable Development goals 3: assessing the readiness of low- and middle-income countries, *Int. J. Heal. Policy Manag.* 9 (2020) 297–308, <https://doi.org/10.15171/ijhpm.2019.134>.
- [8] IEA, IRENA, UNSD, World Bank, IEA, IRENA, UNSD, World Bank, , W.. Tracking SDG 7: the energy progress report, 2023 available online: https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2023-full_report.pdf (accessed on Nov 18, 2023).
- [9] J. Szabo, M. Fabok, Infrastructures and state-building: comparing the energy politics of the European Commission with the governments of Hungary and Poland, *Energy Policy* 138 (2020) 111253, <https://doi.org/10.1016/j.enpol.2020.111253>.
- [10] M. Tsangas, I. Papamichael, A.A. Zorpas, Sustainable energy planning in a new situation, *Energies* 16 (2023).
- [11] A. Biancardi, A. Colasante, I. D'Adamo, C. Daraio, M. Gastaldi, A.F. Uricchio, Strategies for developing sustainable communities in higher education institutions, *Sci. Rep.* 13 (2023) 20596, <https://doi.org/10.1038/s41598-023-48021-8>.
- [12] *European Commission Resolution of the European Committee of the Regions - the Green Deal in partnership with local and regional authorities*, in: *Proceedings of the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions The European Green Deal*, Brussels, 2019, p. 24.
- [13] A. Biancardi, F. Califano, I. D'Adamo, M. Gastaldi, I. Kostakis, A distributed and sustainable model for future cities: a profitability analysis of integrated photovoltaic systems with storage under different incentive policies, *Energy Policy* 205 (2025) 114691, <https://doi.org/10.1016/j.enpol.2025.114691>.
- [14] European Parliament Fit for 55 package, 2024 available online: [https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733513/EPRS_BRI\(2022\)733513_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733513/EPRS_BRI(2022)733513_EN.pdf) (accessed on Feb 22, 2024).
- [15] European Commission communication from the commission to the European Parliament, the Council, the European Economic and Social committee and the Committee of the regions: rEPowerEU Plan available online: https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF (2022) (accessed on Apr 28, 2024).
- [16] G. Giannopoulos, R. Jungwirth, C. Hadjisavvas, et al., Fortifying defence: strengthening critical energy infrastructure against hybrid threats, 2023 available online: 10.2760/58406 JRC133083 (accessed on Apr 28, 2024).
- [17] J. Abrell, S. Rausch, Cross-country electricity trade, renewable energy and European transmission infrastructure policy, *J. Environ. Econ. Manage.* 79 (2016) 87–113, <https://doi.org/10.1016/j.jeem.2016.04.001>.
- [18] I. Benedetti, G. Guarini, T. Laureti, Digitalization in Europe: a potential driver of energy efficiency for the twin transition policy strategy, *Socioecon. Plann. Sci.* 89 (2023) 101701, <https://doi.org/10.1016/j.seps.2023.101701>.
- [19] G. Escribano, C. González-Enríquez, L. Lázaro-Touza, J. Paredes-Gázquez, An energy union without interconnections? Public acceptance of cross-border interconnectors in four European countries, *Energy* 266 (2023) 126385, <https://doi.org/10.1016/j.energy.2022.126385>.
- [20] A. David, J. Terstriep, P. Sospiro, E. Scibè, *Migrants' Digital Knowledge Flows: How Digital Transformation Shapes Social Behaviour*, Institut Arbeit und Technik (IAT): Gelsenkirchen, 2019.
- [21] D.C. Petrelean, N.D. Fită, G.D. Vasilescu, M. Ilieva-Obretenova, D. Tataru, E. A. Cruceru, C.I. Mateiu, A. Nicola, D.-C. Darabont, A.-M. Cazac, et al., Sustainability management through the assessment of instability and insecurity risk scenarios in Romania's energy critical infrastructures, *Sustainability* 17 (2025) 2932, <https://doi.org/10.3390/su17072932>.

- [22] P. Glavič, Evolution and current challenges of sustainable consumption and production, *Sustain* 13 (2021).
- [23] L. Nibbi, P. Sospiro, M. De Lucia, C.-C. Wu, Improving pumped hydro storage flexibility in China: scenarios for advanced solutions adoption and policy recommendations, *Energies* 15 (2022).
- [24] CESI European Parliament report on green transition in the defence sector: CESI calls for proper consultations of military staff, 2022 available online: <https://www.cesi.org/posts/european-parliament-report-on-green-transition-in-the-defence-sector-cesi-calls-for-proper-consultations-of-military-staff/> (accessed on Apr 28, 2024).
- [25] M. Sparrevik, S. Utstøl, Assessing life cycle greenhouse gas emissions in the Norwegian defence sector for climate change mitigation, *J. Clean. Prod.* 248 (2020) 119196, <https://doi.org/10.1016/j.jclepro.2019.119196>.
- [26] Y. Amakrane, R. Biesbroek, How is the military and defence sector of EU member states adapting to climate risks? *Clim. Risk Manag.* 44 (2024) 100609 <https://doi.org/10.1016/j.crm.2024.100609>.
- [27] I. Papamichael, G. Chatziparaskeva, J.N. Pedreno, I. Voukkali, M.B. Almendro Candel, A.A. Zorpas, Building a new mind set in tomorrow fashion development through circular strategy models in the framework of waste management, *Curr. Opin. Green Sustain. Chem.* (2022) 100638, <https://doi.org/10.1016/j.cogsc.2022.100638>.
- [28] I. Voukkali, A.A. Zorpas, Evaluation of urban metabolism assessment methods through SWOT analysis and analytical hierarchy process, *Sci. Total Environ.* 807 (2021) 150700, <https://doi.org/10.1016/j.scitotenv.2021.150700>.
- [29] A. Abdelmeguid, M. Afy-Shararah, K. Salonitis, Investigating the challenges of applying the principles of the circular economy in the fashion industry: a systematic review, *Sustain. Prod. Consum.* 32 (2022) 505–518, <https://doi.org/10.1016/j.spc.2022.05.009>.
- [30] Jan van Eck, N., Waltman, L. 2023. VOSviewer manual, [www.Vosviewer.Com](http://www.vosviewer.com) https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.20.pdf (accessed 10 February 2025).
- [31] N.T. Xuan Son, P. Thi Gam, Vietnam's policy for promoting offshore wind power and environmental impact assessment, *Environ. Claims J.* 34 (2022) 156–169, <https://doi.org/10.1080/10406026.2021.1932335>.
- [32] G. Lichtenegger, A.A. Rentzelas, N. Trivyza, S. Siegl, Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050, *Waste Manag* 106 (2020) 120–131, <https://doi.org/10.1016/j.wasman.2020.03.018>.
- [33] A. Fedajev, P. Mitić, M. Kojić, M. Radulescu, Driving industrial and economic growth in Central and Eastern Europe: the role of electricity infrastructure and renewable energy, *Util. Policy* 85 (2023) 101683, <https://doi.org/10.1016/j.jup.2023.101683>.
- [34] J.A. Klimek, J. Klimek, E. Barej-Kaczmarek, B. Gębski, S. Kołodziejczak, A. Terelak, Infrastructure fund as an alternative driver in the implementation of green energy policy in European countries, *Energy Reports* 11 (2024) 1766–1773, <https://doi.org/10.1016/j.egy.2024.01.041>.
- [35] D. Anselmi, I. D'Adamo, M. Gastaldi, V.G. Lombardi, A comparison of economic, environmental and social performance of European countries: a sustainable development goal index, *Environ. Dev. Sustain.* 26 (2024) 20653–20677.
- [36] K. Baumli, T. Jamasb, Assessing private investment in African renewable energy infrastructure: a multi-criteria decision analysis approach, *Sustainability* 12 (2020).
- [37] B. Wiersma, P. Devine-Wright, Public engagement with offshore renewable energy: a critical review, *WIREs Clim. Chang* 5 (2014) 493–507, <https://doi.org/10.1002/wcc.282>.
- [38] European Commisio; Directorate-General for Energy, *EU Energy in Figures – Statistical Pocketbook 2023*, Publications Office of the European Union, 2023.
- [39] G. Garfin, D.A. Falk, C.D. O'Connor, K. Jacobs, R.D. Sagarin, A.C. Haverland, A. Haworth, A. Baglee, J. Weiss, J. Overpeck, et al., A new mission: mainstreaming climate adaptation in the US Department of Defense, *Clim. Serv.* 22 (2021) 100230, <https://doi.org/10.1016/j.cliser.2021.100230>.
- [40] M. Mori, U. Zvar Bašković, R. Stropnik, A. Lotrić, T. Katrašnik, R. Šipek, J. Lipar, Ž. Lesar, B. Drobnič, Green energy hubs for the military that can also support the civilian mobility sector with green hydrogen, *Int. J. Hydrogen Energy* 48 (2023) 39138–39153, <https://doi.org/10.1016/j.ijhydene.2023.05.026>.
- [41] C. Sravan, P.P. Mishra, When national defence meets decarbonization: arming India's just transition with military assistance, *Energy Res. Soc. Sci.* 98 (2023) 103030, <https://doi.org/10.1016/j.erss.2023.103030>.
- [42] A. Mohammad, Y. Abbas, Key challenges of cloud computing resource allocation in small and medium enterprises, *Digital 4* (2024) 372–388.
- [43] C. Sassanelli, T. Arriga, S. Zanin, I. D'Adamo, S. Terzi, Industry 4.0 driven result-oriented PSS: an assessment in the energy management, *Int. J. Energy Econ. Policy* 12 (4) (2022) 186–203.
- [44] K. Xu, Y. Guo, G. Lei, J. Zhu, A review of Flywheel Energy Storage System technologies, *Energies* 16 (2023).
- [45] A. Aghmadi, O.A. Mohammed, Energy Storage Systems: technologies and high-power applications, *Batteries* 10 (2024).
- [46] P. Berrill, T.R. Miller, Y. Kondo, E.G. Hertwich, Capital in the American carbon, energy, and material footprint, *J. Ind. Ecol.* 24 (2020) 589–600, <https://doi.org/10.1111/jiec.12953>.
- [47] C. Chauhan, V. Parida, A. Dhir, Linking circular economy and digitalisation technologies: a systematic literature review of past achievements and future promises, *Technol. Forecast. Soc. Change* 177 (2022) 121508, <https://doi.org/10.1016/j.techfore.2022.121508>.
- [48] M. Mata Pérez, E. de la, D. Scholten, K. Smith Stegen, The multi-speed energy transition in Europe: opportunities and challenges for EU energy security, *Energy Strateg. Rev.* 26 (2019) 100415, <https://doi.org/10.1016/j.esr.2019.100415>.
- [49] A. Trantidis, N. Cowen, Is public ignorance a problem? An epistemic defense of really existing democracies, *Polit. Res. Q.* (2024), <https://doi.org/10.1177/10659129241244715>, 10659129241244716.
- [50] C.G. Morales, R.M. Kuns, B. Isaac, M.R. Brown, A.J. Lacey, Waste management strategies for military-generated waste in the United States, *Res. Conserv. Rec.* (2025) 108073, <https://doi.org/10.1016/j.resconrec.2024.108073>.
- [51] C. Zarbà, G. Chinnici, G. La Via, S. Bracco, B. Pecorino, M. D'Amico, Regulatory elements on the circular economy: driving into the agri-food system, *Sustain* 13 (2021).
- [52] I. Ozturk, S. Ullah, S. Sohail, T.M. Sohail, How do digital government, circular economy and environmental regulatory stringence affect renewable energy production, *Energy Policy* (2025) 114634, <https://doi.org/10.1016/j.enpol.2025.114634>.
- [53] F. Economou, I. Papamichael, I. Voukkali, P. Loizia, E. Klontza, D.F. Lekkas, N. Vincenzo, G. Demetriou, J. Navarro-Pedreño, A.A. Zorpas, Life cycle assessment of potato production in insular communities under subtropical climatic conditions, *Case Stud. Chem. Environ. Eng.* 8 (2023) 100419, <https://doi.org/10.1016/j.cscee.2023.100419>.
- [54] M. Stylianou, I. Papamichael, I. Voukkali, M. Tsangas, M. Omirou, I.M. Ioannides, A.A. Zorpas, LCA of Barley production: a case study from Cyprus, *Int. J. Environ. Res. Public Health* 20 (2023).
- [55] M. Tsangas, I. Papamichael, D. Banti, P. Samaras, A.A. Zorpas, LCA of municipal wastewater treatment, *Chemosphere* (2023) 139952, <https://doi.org/10.1016/j.chemosphere.2023.139952>.
- [56] K. Scholz, M. Eriksson, I. Strid, Carbon footprint of supermarket food waste, *Resour. Conserv. Recycl.* 94 (2015) 56–65, <https://doi.org/10.1016/j.resconrec.2014.11.016>.
- [57] B. Corona, L. Shen, D. Reike, J. Rosales Carreón, E. Worrell, Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics, *Resour. Conserv. Recycl.* 151 (2019) 104498, <https://doi.org/10.1016/j.resconrec.2019.104498>.
- [58] M.C. Liscio, P. Sospiro, Life Cycle Assessment on fashion industry: four case studies, in: *Glob. NEST Int. Conf. Environ. Sci. & Technol.*, 2023.
- [59] ISO 14040: environmental management—life cycle assessment—Principles and framework, *Int. Organ. Stand* (2006).
- [60] International Organization for Standardization (ISO), *International Standard ISO 14044 environmental management — Life cycle assessment — Requirements and guidelines management, Work* (2006).
- [61] E. Iacovidou, C.A. Velis, P. Purnell, O. Zwiner, A. Brown, J. Hahladakis, J. Millward-Hopkins, P.T. Williams, Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: a critical review, *J. Clean. Prod.* 166 (2017) 910–938, <https://doi.org/10.1016/j.jclepro.2017.07.100>.
- [62] G. Yang, Q. Zhang, Z. Zhao, C. Zhou, How does the “zero-waste City” strategy contribute to carbon footprint reduction in China? *Waste Manag* 156 (2023) 227–235, <https://doi.org/10.1016/j.wasman.2022.11.032>.
- [63] L. Villalba, Material Flow analysis (MFA) and waste characterization for formal and informal performance indicators in Tandil, Argentina: decision-making implications, *J. Environ. Manage.* 264 (2020) 110453, <https://doi.org/10.1016/j.jenvman.2020.110453>.
- [64] S. Millette, E. Williams, C.E. Hull, Materials flow analysis in support of circular economy development: plastics in Trinidad and Tobago, *Resour. Conserv. Recycl.* 150 (2019) 104436, <https://doi.org/10.1016/j.resconrec.2019.104436>.
- [65] D. Wang, Y.-T. Tang, Y. Sun, J. He, Assessing the transition of municipal solid waste management by combining material flow analysis and life cycle assessment, *Resour. Conserv. Recycl.* 177 (2022) 105966, <https://doi.org/10.1016/j.resconrec.2021.105966>.
- [66] I. Papamichael, I. Voukkali, P. Loizia, G. Pappas, A.A. Zorpas, Existing tools used in the framework of environmental performance, *Sustain. Chem. Pharm.* 32 (2023) 101026, <https://doi.org/10.1016/j.scp.2023.101026>.
- [67] I. Papamichael, I. Voukkali, P. Loizia, M. Stylianou, F. Economou, I. Vardopoulos, E.E. Klontza, D.F. Lekkas, A.A. Zorpas, Measuring circularity: tools for monitoring a smooth transition to circular economy, *Sustain. Chem. Pharm* 36 (2023) 101330, <https://doi.org/10.1016/j.scp.2023.101330>.
- [68] P. Basílico, A. Biancardi, I. D'Adamo, M. Gastaldi, T. Yigitcanlar, Renewable energy communities for sustainable cities: economic insights into subsidies, market dynamics and benefits distribution, *Appl. Energy* 389 (2025) 125752, <https://doi.org/10.1016/j.apenergy.2025.125752>.
- [69] I. Papamichael, I. Voukkali, F. Economou, P. Loizia, G. Demetriou, M. Esposito, V. Naddeo, M.C. Liscio, P. Sospiro, A.A. Zorpas, Mobilisation of textile waste to recover high added value products and energy for the transition to circular economy, *Environ. Res.* 242 (2024) 117716, <https://doi.org/10.1016/j.envres.2023.117716>.
- [70] B. Fu, M.E. Meadows, W. Zhao, Geography in the Anthropocene: transforming our world for sustainable development, *Geogr. Sustain.* 3 (2022) 1–6, <https://doi.org/10.1016/j.geosus.2021.12.004>.
- [71] H. Tokuchi, Climate security and Japan's new national security strategy: a policy analysis, *Third World Q* 1–18 (2023), <https://doi.org/10.1080/01436597.2024.2314681>.
- [72] European Defence Agency Defence Energy Data 2016 & 2017, 2019 available online: <https://eda.europa.eu/docs/default-source/eda-factsheets/2019-06-07-factsheet-energy-defence>.

- [73] C.X. Hui, G. Dan, S. Alamri, D. Toghraie, Greening smart cities: an investigation of the integration of urban natural resources and smart city technologies for promoting environmental sustainability, *Sustain. Cities Soc.* 99 (2023) 104985, <https://doi.org/10.1016/j.scs.2023.104985>.
- [74] N.A. Ryan, Y. Lin, N. Mitchell-Ward, J.L. Mathieu, J.X. Johnson, Use-phase drives lithium-ion battery life cycle environmental impacts when used for frequency regulation, *Environ. Sci. Technol.* 52 (2018) 10163–10174, <https://doi.org/10.1021/acs.est.8b02171>.
- [75] I. Ganesh, Conversion of carbon dioxide into methanol – a potential liquid fuel: fundamental challenges and opportunities (a review), *Renew. Sustain. Energy Rev.* 31 (2014) 221–257, <https://doi.org/10.1016/j.rser.2013.11.045>.
- [76] P. Sospiro, L. Amarnath, V. Di Nardo, G. Talluri, F.H. Gandoman, Smart grid in China, EU, and the US: state of implementation, *Energies* 14 (2021).
- [77] L.D. Montoya, L.M. Mendoza, C. Prouty, M. Trotz, M.E. Verbyla, Environmental engineering for the 21st century: increasing diversity and community participation to achieve Environmental and social justice, *Environ. Eng. Sci.* 38 (2021) 288–297, <https://doi.org/10.1089/ees.2020.0148>.
- [78] C.R. Payne, O. Swed, Disentangling the US military’s climate change paradox: an institutional approach, *Sociol. Compass* 18 (2024) e13127, <https://doi.org/10.1111/soc4.13127>.
- [79] M.E. Craparo, G.J. Sprague, Integrated supply and demand side energy management for expeditionary environmental control, *Appl. Energy* (2019) 352–366, <https://doi.org/10.1016/j.apenergy.2018.09.220>.