ENERGY INDEPENDENCE AND MICROGRID DEPLOYMENT: EXAMINING THE IMPLICATIONS FOR DEFENCE OPERATIONS AND SUPPLY CHAIN RESILIENCE

KHALIL GHOLAMI, ALI AZIZIVAHED, LI LI AND DYLAN LU

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Abbreviations

AC	Alternating current
AI	Artificial intelligence
ACT	Australian Capital Territory
ADF	Australian Defence Force
AS/NZS	Australian/New Zealand Standard
CHP	Combined heat and power
DC	Direct current
DEWs	Directed energy weapons
DERs	Distributed energy resources
ECVs	Electric combat vehicles
EVs	Electric vehicles
FDI	False data injection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of things
L-ion	Lithium ion
NEM	National Electricity Market
RESs	Renewable energy sources
SCADA	Supervisory control and data acquisition
US	United States
UPS	Uninterruptible power supply

/ ABSTRACT

The increasing reliance on a centralised, privately operated power grid in Australia poses significant security risks, particularly for critical defence operations. This research explores the potential for the Australian Defence Force (ADF) to enhance energy resilience through the adoption of decentralised energy systems, specifically military-grade microgrids. The study evaluates a range of alternative energy sources and examines their integration into microgrid configurations, with an emphasis on operational reliability, security and adaptability in remote or high-risk environments. Key areas of analysis include system vulnerabilities, cyber and physical threats, and the strategic implications of global supply chain dependencies. The research identifies microgrids as a viable and resilient solution, capable of ensuring uninterrupted power supply during grid failures. It also underscores the importance of local energy technology development, secure design standards, and the integration of hydrogen and artificial intelligence to support future energy autonomy. By addressing both technological and strategic dimensions, this study provides a framework for the ADF to strengthen its energy infrastructure in support of national defence objectives.

/ INTRODUCTION

1. Introduction

Electricity plays a critical role in supporting modern defence operations, forming the foundation upon which military readiness, communication, logistics, and command systems rely. In an era where military capabilities are increasingly driven by technology, a stable and secure energy supply is essential for ensuring continuous operations under all conditions.[1,2] This is because conventional utility electrical power relies heavily on centralised grids or imported fossil fuels which are susceptible to attack and system-wide failures. A single incident, such as the sabotage of a power station, can cause blackouts that leave critical military infrastructure powerless, severely limiting operational capabilities.[3] At the same time, environmental considerations and global pressure to reduce carbon emissions are driving a shift toward cleaner energy sources. Solar, wind, hydrogen and other renewable technologies offer promising alternatives, but they must be evaluated carefully within the defence context.[4,5]

Independent energy systems play a critical role in enhancing energy security by overcoming the above concerns. By enabling localised generation (microgrids) through technologies such as solar arrays, energy storage systems, and advanced control systems, these systems ensure the continued functionality of critical infrastructure during crises, whether caused by natural disasters, cyber attacks or armed conflicts. Importantly, storage does not need to be static; it can be battery on wheels—for example, electric vehicles (EVs)—adding flexibility and mobility to energy supply. For military applications, independence from national grids allows bases and forward operating locations to maintain mission-critical operations without relying on external energy sources that may be compromised or inaccessible. This independence also provides strategic benefits by reducing logistical vulnerabilities, enabling greater operational flexibility, and supporting sustained deployments in contested or remote environments. Additionally, independent systems can reduce long-term operational costs, increase energy efficiency, and support sustainability goals by integrating renewable resources.[6,7] However, the defence industry depends on a broad and interconnected web of suppliers to deliver essential equipment and components of independent energy systems. Therefore, global instability, natural disasters, and cyber threats can easily disrupt these supply chains. Without a secure electricity infrastructure, even the most advanced defence systems can become ineffective during emergencies.[8,9] Therefore, evaluating supply chain vulnerabilities and exploring alternative solutions require significant investigation to ensure reliable energy independence.[10]

Electricity is critical to all countries for myriad crucial functions within military and defence operations. This research provides the Australian Defence Force (ADF) with vital information to make informed decisions and effective strategies, and to position it to adopt the most suitable technologies to mitigate risks during the transition to global alternative power and energy solutions for defence operations. Ultimately, the research will strengthen the Army's energy resilience and ability to adapt to the changing landscape of energy technologies and security challenges. Briefly, the following items are covered throughout this investigation:

- The research evaluates the current state of electrical utility grids and assesses their vulnerabilities during emergencies such as armed conflicts and natural disasters.
- It investigates both the limitations and the potential of distributed energy resources (DERs) in military contexts, particularly their ability to support mission-critical operations and achieve independent energy systems.
- The logistical feasibility of deploying and sustaining independent energy systems in military applications is explored, considering factors such as mobility, maintenance, scalability, and compatibility with existing infrastructure.
- A comprehensive risk and vulnerability assessment is conducted for independent energy systems, identifying technical, operational and cyber security challenges that may affect their reliability.
- The research examines the context of supply chain resilience, identifying key vulnerabilities to reduce reliance on foreign energy and technology sources.
- Finally, the study explores the integration of artificial intelligence (AI) in independent military energy systems, particularly its role in enabling autonomous decision-making, system optimisation, and real-time response during critical missions.

2. Existing Military Electric Grids and Their Vulnerability in the Case of Emergencies

2.1 Electric Grid Structure in Australia

Australia's grid, shown in Figure 1 and known as the National Electricity Market (NEM), covers the eastern and south-eastern regions. It supplies approximately 200 TWh of electricity each year, roughly 85 per cent of the nation's total electricity generation. With a length of 5,000 km, it holds the record as the world's longest alternating current (AC) system. Given this, renewing the NEM's infrastructure would be a significant financial burden and could also lead to considerable indirect emissions of greenhouse gases.[11] Such a centralised, interconnected electricity network is referred to as the utility grid, which is further elaborated as follows.

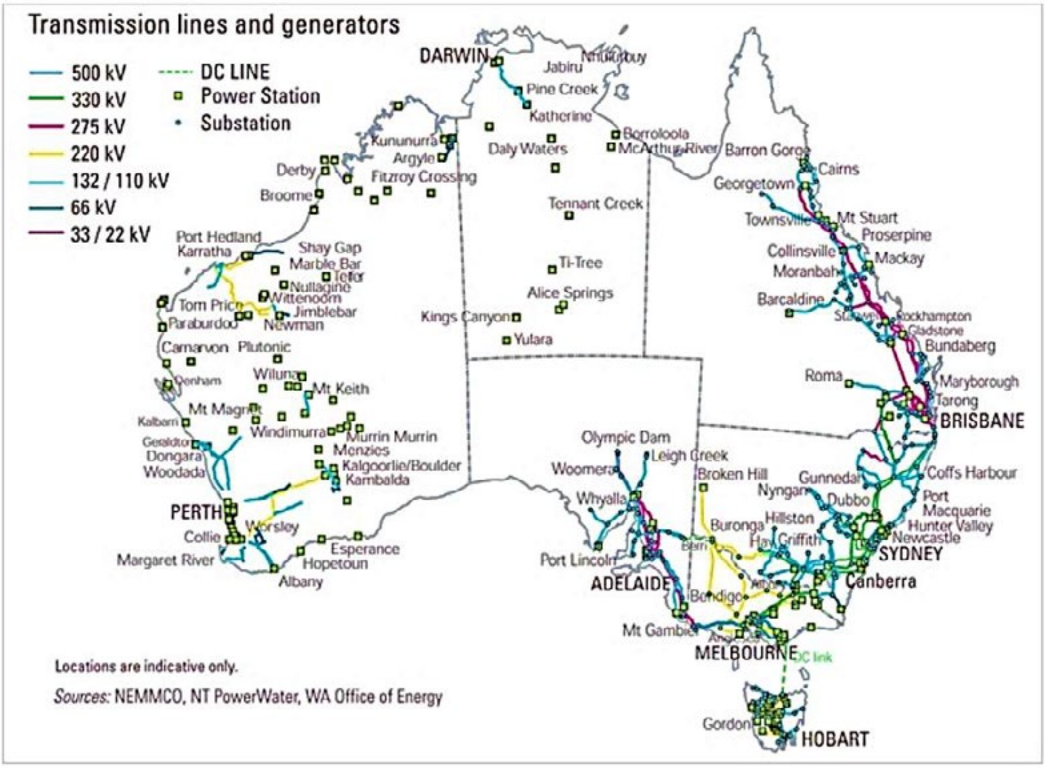


Figure 1. Power transmission networks and power stations in Australia[12]

The utility grids in Australia consist of five main sections, as depicted in Figure 2. These sections are elaborated as follows:[13,14,15]

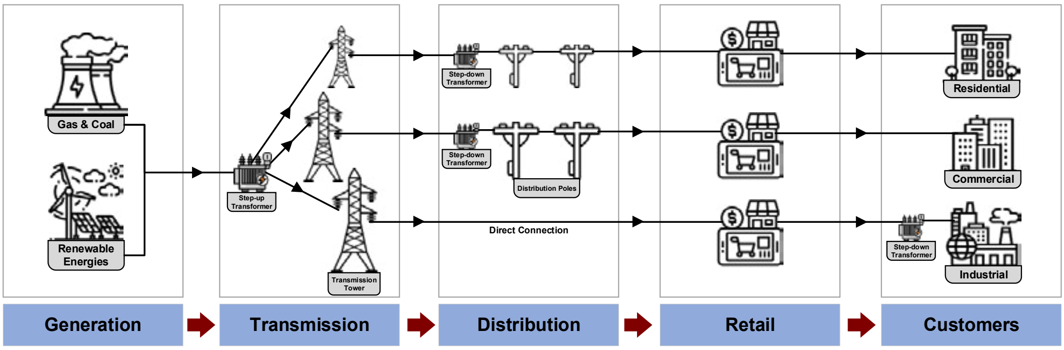


Figure 2. Procedure for power delivery from electric utility grids

- **Generation:** Electricity is generated from thermal sources (coal, natural gas) and renewable energy sources (solar, wind).
- **Transmission:** Power is transmitted via networks, using step-up transformers to increase voltage and minimise costs, especially for operations in diverse areas.
- **Distribution:** Electricity is delivered to infrastructure through distribution networks, using step-down transformers to reduce voltage to levels suitable for customers' equipment.
- **Retailers:** They serve as intermediaries, purchasing electricity from markets and selling to customers while managing billing and customer service.
- **Customers:** They include residential, commercial and large-scale industrial users. Customer operations may opt for a connected set-up or direct transmission for reliable and safe power delivery, depending on their needs.

2.2 Market Operators and Service Providers of Utility Grids in Australia

Due to the expansive nature of Australia's electricity grids, it is impossible for a single organisation or company to manage and operate entire grids individually. Consequently, Australia's electricity and gas grids are operated through public, private, or combined public-private ownership forms, as depicted in Figure 3 and outlined below:[16]

- Victoria and South Australia operate fully privatised electricity networks.
- Tasmania, Western Australia, the Northern Territory and Queensland have fully government-owned electricity networks.
- In New South Wales, one electricity grid is under private ownership, two are partially (50.4 per cent) privately owned, and one is entirely government owned. The Australian Capital Territory (ACT) electricity network operates as a partnership between public and private ownership.
- Gas distribution providers across Australia are all privately owned, except for the ACT's network, which is partially government owned.

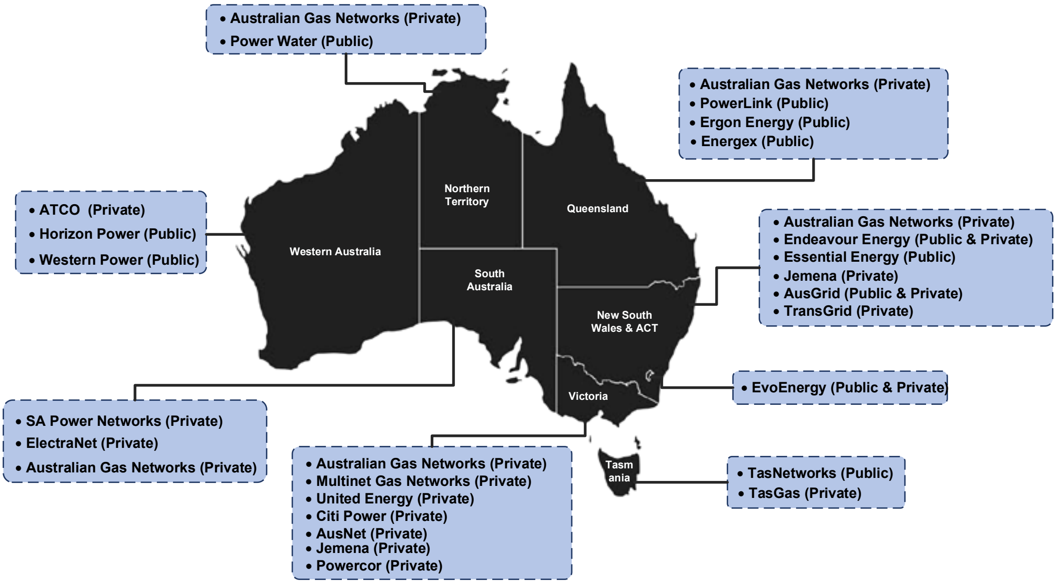


Figure 3. Grid ownership across Australian states

2.3 Electric Grid Structure in the Military

As shown in Figure 4, military electrical services encompass three main categories: tactical electrical power, prime electrical power and utility electrical power. Tactical power, found at the individual level (close to the electric loads over missions), includes batteries and small unit power sources producing under 1 kW, typically operating at voltages of 600 V or lower, and extending up to 200 kW in capacity. In contrast, prime power systems exceed 200 kW, providing medium voltage outputs ranging from 600 V to 69 kV. Utility electrical power, managed and supplied by civilians or contractors, stands as a separate category.[17] Each power source varies in complexity, efficiency and reliability; all are aimed at meeting diverse mission requirements, as discussed below.

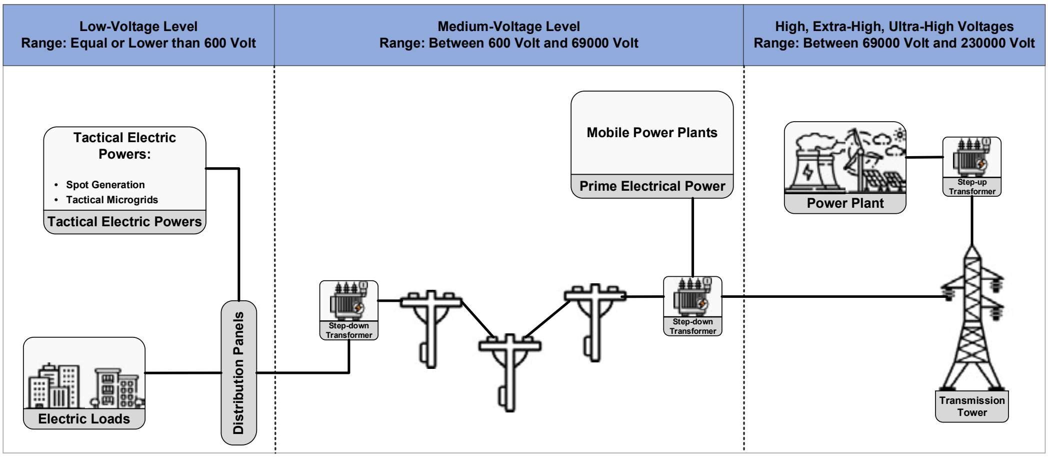


Figure 4. High-level demonstration of military electric systems in the US

A. Tactical Electrical Power

At the start of military operations, units rely on tactical electrical power systems tailored to their specific needs, including batteries, renewable energy sources, and low-voltage generators. These systems enhance mobility despite their limited capacity. Tactical electrical power systems are generally divided into distinct categories.

Spot generation: It is employed to link a group of generators to a set of loads. Spot generation with two generators is advantageous for powering outlying radar units or delivering energy to services and shelters with mission equipment.[18] Figure 5 displays three examples of spot generation and distribution.

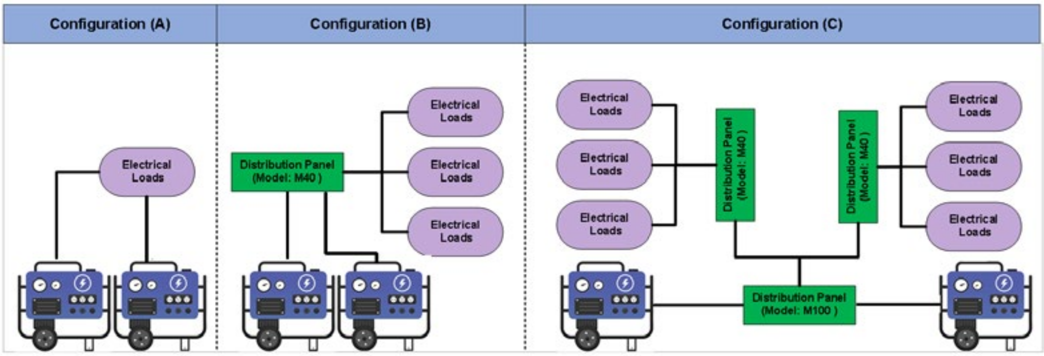


Figure 5. Tactical electrical power: military spot generation configurations

- **Tactical microgrids:** Tactical microgrids rely on on-site power generating and distribution technology, including optimised portable electricity sources. As demonstrated in Figure 6, these microgrids could control functions integrated into the generator set, allowing automatic adjustment of generator activity as demand changes. This design ensures that power production matches demand closely, reducing excess production and labour needs.[19,20] Furthermore, microgrids may expand by adding generators and shifting to prime power or utility grids when mission requirements change.

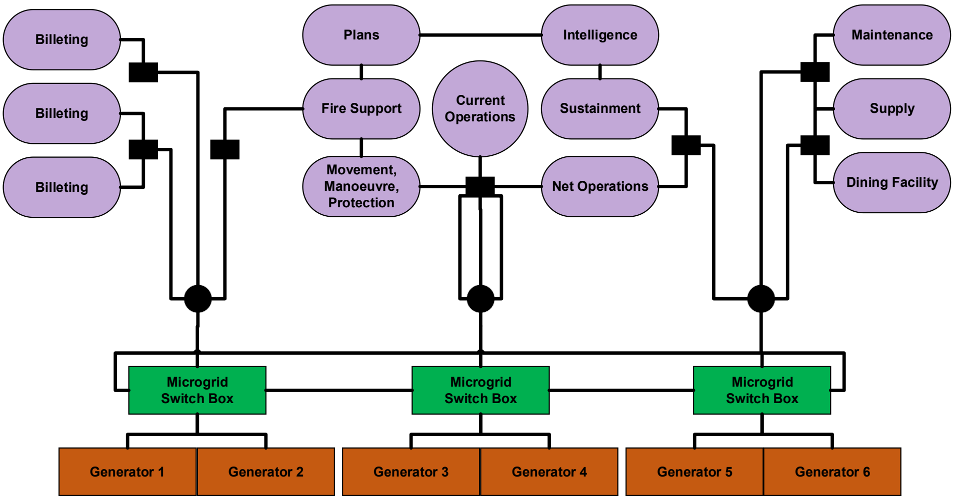


Figure 6. Tactical electrical power: a military microgrid configuration

The benefits of consolidating power generation and distribution (like microgrids) are numerous and include:

- enhanced security for power generation assets
- improved reliability of the power system
- increased cost efficiency
- reduced fuel dependency
- less stress on machinery that is not developed to run constantly
- simplified maintenance processes.

B. Prime Electrical Power

As illustrated in Figure 7, the term ‘prime power sources’ refers to centralised power plants operating at medium voltage levels, capable of consistently supplying reliable power exceeding 200 kW. To reduce the medium voltage to levels appropriate for the device, these sources employ transformers. They can generate and transmit power over long distances via transmission lines, often supporting critical infrastructure. Prime power installations are preferred when tactical generators are impractical or when utility electrical power is unavailable or unreliable.

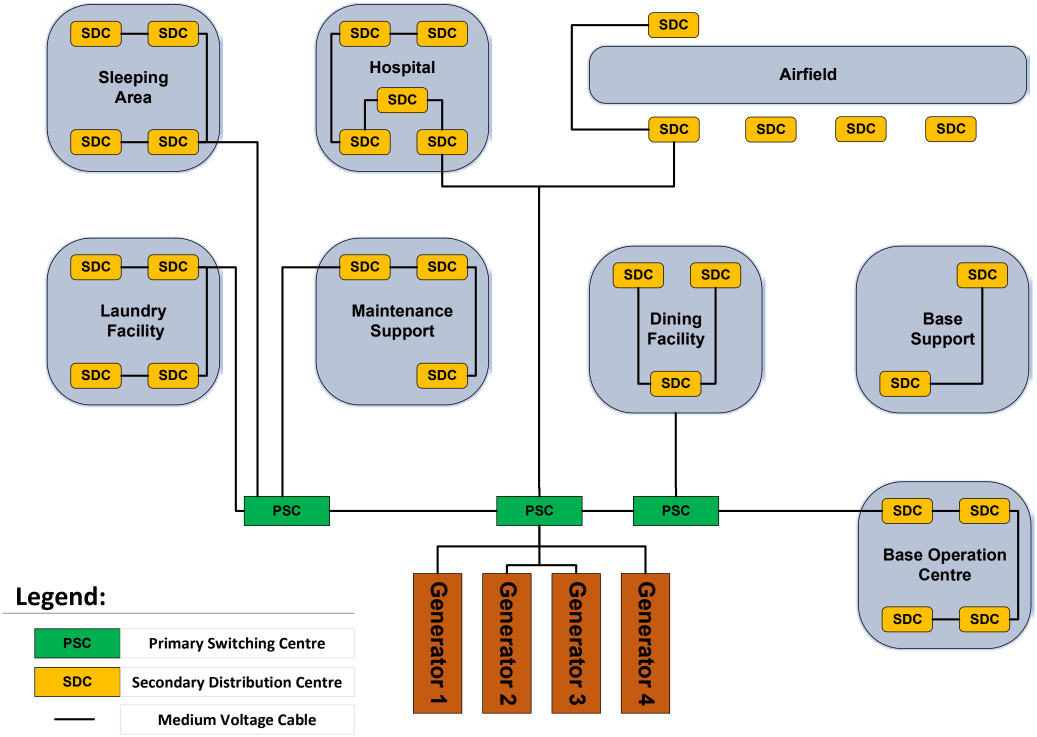


Figure 7. Military prime electrical power configuration

C. Utility Electrical Power

Deciding whether to use utility electrical power depends on how well it works with mission equipment and its reliability to meet operational needs. Utility electrical power is mainly delivered through civilian power grids, which vary widely in sophistication and reliability worldwide. Trained personnel manage connections to commercial distribution networks, ensuring proper coordination and obtaining necessary approvals as required. Alternatively, they may collaborate with local utility organisations to establish connections. Once connected, utility electricity provides continuous service with minimum maintenance. Operating on a utility grid usually needs a contractual or host-nation agreement.

Figure 8 illustrates the adaptability of tactical electrical power, prime electrical power, and utility electrical power to various mission-critical scenarios and operational environments.[21]

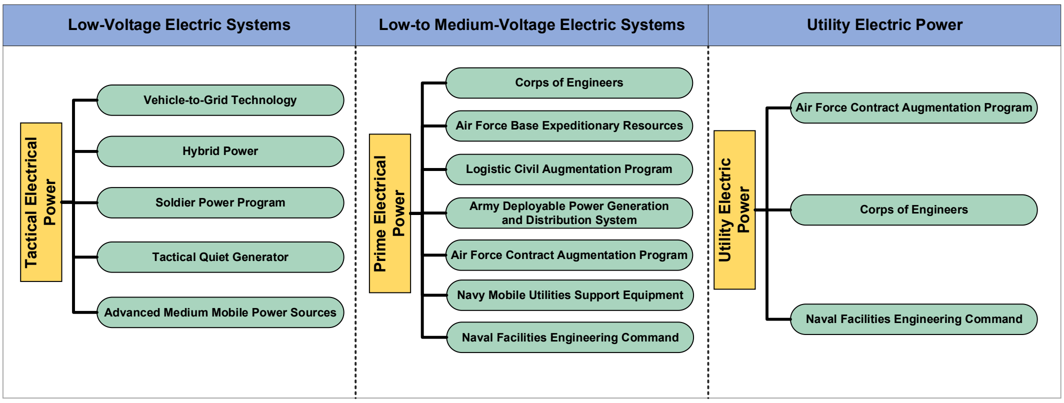


Figure 8. Applications of electrical power architectures in the US

2.4 Vulnerabilities of Electric Utility Grids in Military and Defence Applications

Figure 9 illustrates the average weekly number of cyber attacks per organisation across select industries from 2020 to 2022. As shown, the government/military sector experiences the highest number of cyber attacks, posing a significant risk to critical infrastructure and potentially compromising military and defence services,[22,23,24,25] as discussed in Table 1. Additionally, utility grids remain vulnerable to various physical attacks, which threaten their stability and security,[26,27,28,29,30] as detailed in Table 2. Cyber security is another critical challenge in the energy sector, where the integration of digital technologies increases vulnerability to a wide range of cyber attacks. Table 3 provides an overview of significant cyber security threats and their potential impacts on energy infrastructure.[31,32,33,34,35,36,37,38,39,40,41]

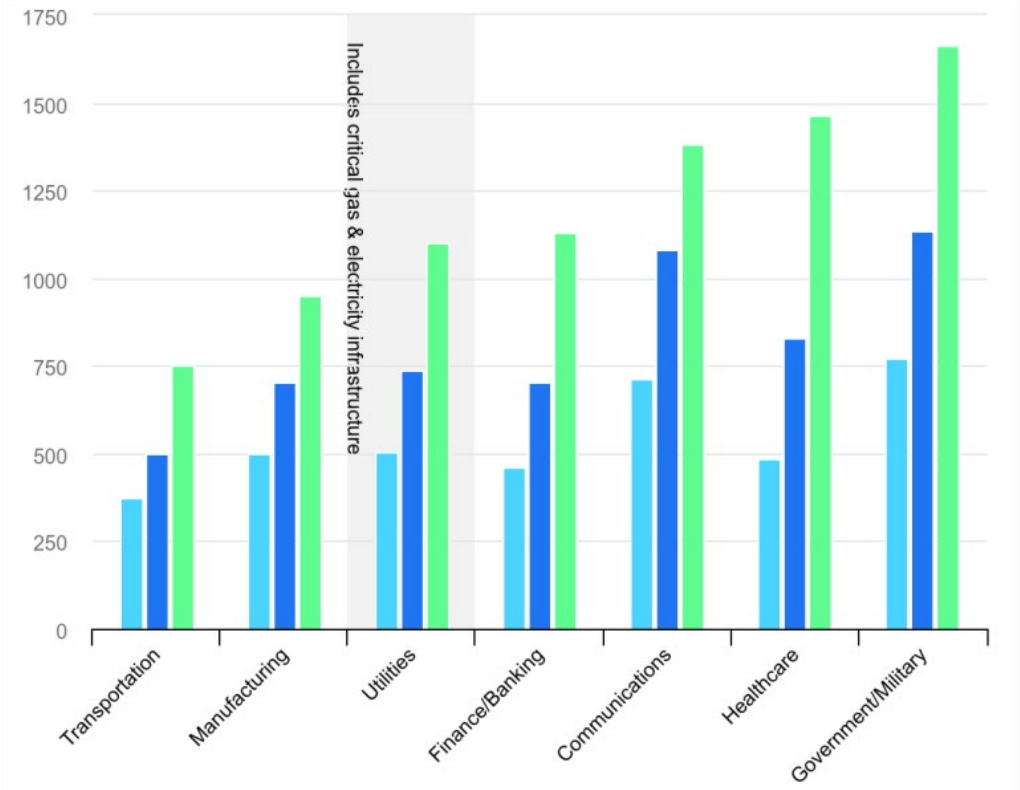


Figure 9. Weekly average numbers of cyber attacks per organisation across industries (2020–2022)[42]

Table 1. General vulnerabilities of electric utility grids

Challenge	Description	Impacts
Natural disasters	Severe weather events, like hurricanes and storms, are primary contributors to widespread power outages in electric utility grids, often resulting in prolonged electrical failures.	Disrupting the power supply not only causes infrastructure damage and resulting financial losses but also poses threats to public safety, hindering emergency response and recovery efforts for military missions.
Aging infrastructure	Aging energy infrastructure presents challenges in maintenance and expenditure, leading to unpredictable power outages.	Increased frequency of equipment failures, widespread power outages affecting urban areas, disruptions to public services, potential safety hazards, and the need for extensive infrastructure upgrades and repairs.
Renewable energy sources (RESs)	Increasing generation from RESs introduces volatility and unpredictability into the grid due to weather-dependent fluctuations. This requires enhanced controllability and flexibility to manage the variability and maintain stability.	Integrating RESs poses grid challenges such as production and load balancing complexities, and load forecasting accuracy. As ensuring reliable power for defence and military equipment is vital, there is a pressing need for enhanced grid control infrastructure to handle RES intermittency.
Dependency on fossil fuels	Electricity generation in utility grids relies heavily on fossil fuel based sources like gas and coal. However, these resources are subject to shortages and may require imports from other countries.	During sanctions or conflicts, importing such sources becomes impossible, particularly disrupting equipment functionality for military and defence missions.

Table 2. Types of physical attacks on utility grids and their impacts

Threat	Description	Impact
Ballistic damage	Gun-related attacks that target critical components like transformers and substations, ranging from pistols to high-calibre rifles.	Causes regional or wide-ranging power outages that interfere with civilian, military, and defence-related operations. Raises maintenance expenses and lowers network reliability.
Intrusion (tampering)	Entering substations or control centres without permission with the intention of manipulating or destroying vital equipment.	Threatens operational integrity and national security, results in equipment damage or malfunctions, and interrupts services.
Vandalism	Intentional acts of destruction or defacement of electrical infrastructure, including vandalism targeting security systems.	Usually causes temporary service outages and requires repair work, which diverts resources and might postpone restoration.
Theft (copper, tools)	The theft of essential assets such as copper or devices from electrical networks, with the aim of either financial gain or sabotage.	Causes power outages, damages infrastructure, raises operating costs, and leads to financial and security risks.
Coordinated attacks	Attacks on numerous grid components, occurring simultaneously or in clusters, with the goal of causing widespread or persistent disruptions.	Causes serious interruptions in greater regions and critical services in military and defence, necessitating extensive response efforts.
Fire targeting	Intentional attempts to target certain weaknesses at substations, transformers, or other grid components to ignite fires.	Can lead to serious equipment damage, prolonged power outages, and safety hazards, impacting the readiness of both civilian and military forces in times of emergency.

Threat	Description	Impact
Explosive device	Use of incendiary or vehicle-borne improvised explosive devices aimed at vital infrastructure, such as substations.	Incurs serious safety risks, extensive damage, and the possibility of widespread outages.
Vehicle ramming attack	Utilising a vehicle as a weapon to attack transformers, substations, or security measures.	Causes serious physical damage to infrastructure and disrupts the operation of critical organisations.
Unmanned aerial system	Unmanned aerial vehicles or drones employed for monitoring, or causing destruction to power lines, substations etc.	Bypasses established security procedures, resulting in potential damage and unauthorised access to key infrastructure data/information.

Table 3. Cyber security threats and risks in energy infrastructure

Threat	Description	Impacts
Power networks and components	Critical components in energy systems include programmable logic controllers, digital relays, remote terminal units, and supervisory control systems such as supervisory control and data acquisition (SCADA). All these components are vulnerable to unauthorised access.	Unauthorised intrusion could threaten network operations, causing major interruptions in energy delivery and increasing supply chain risk. This emphasises the importance of tight supply chain security.
Control system	Energy flow management requires industrial control systems, such as SCADA and protection systems. It is essential to secure these systems and their interfaces to prevent system vulnerabilities from being exploited.	The stability and effectiveness of gas and electricity distribution networks could be compromised by energy management errors resulting from breaches in control systems.

Threat	Description	Impacts
Privacy jeopardisation	Large amounts of sensitive data, including operational and consumer data, are processed by service providers of networks. Strong data protection techniques are needed to stop data tampering, theft, and unauthorised access.	The performance of the network could be severely impacted by breaches that result in the loss of private and financial information, legal problems because of privacy violations, and disruptions in operational data.
Distributed energy resources	There are new cyber security vulnerabilities associated with the increasing usage of DERs, such as battery storage, rooftop solar panels and EVs. An internet of things (IoT) environment connects many of these devices.	The presence of security vulnerabilities in DERs and IoT devices may impede the ability to manage energy in real time, hence increasing the risk of energy supply disruptions, system instability, and a general decline in grid safety and reliability.

3. Distributed Energy Resource Challenges and Capabilities for Military Applications

3.1 Exploring the Types of Distributed Energy Resources

This section considers the different sorts of DERs that exist.[43,44] As Figure 10 illustrates, there are three main types of DERs: dispatchable energy sources, renewable energy, and energy storage systems.

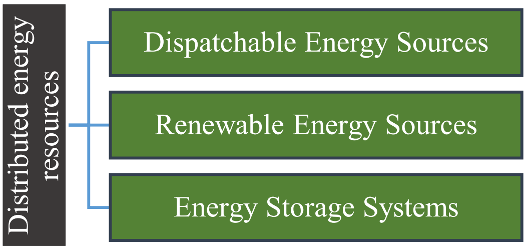


Figure 10. List of different types of distributed energy resources

3.1.1 Dispatchable Energy Sources

Dispatchable sources are equipment/devices that consume fuel to generate electricity. There are different types of dispatchable generators, as follows:

- **Diesel generators:** As shown in Figure 11, they consume diesel fuels to generate electricity and are considered to be the primary backup power technology utilised by the military services.[45] In broad terms, there are three models of diesel generators. The first type is known as building-scale diesel generators, which are sized based on assessments of the facility's peak electrical demand with a focus on supplying individual buildings. The second type is the centralised diesel generators that supply a set of facilities/equipment, along with different operational modes emphasising continuous or standby backup operation. Mobile diesel generators represent the third model, characterised by their portability to various locations, making them particularly useful for temporary military operations.[46]

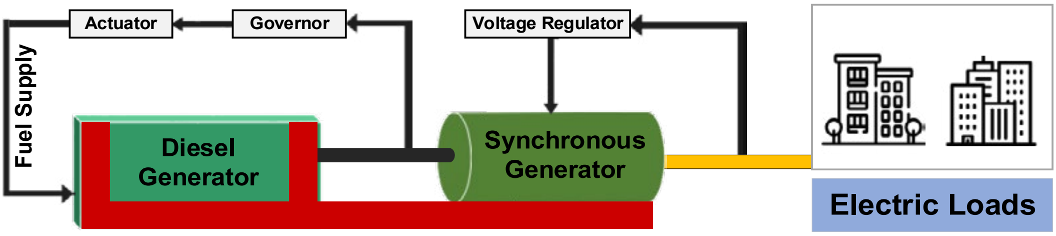


Figure 11. Typical configuration of a diesel generator

- **Combined heat and power (CHP):** In CHP systems, the heat that is typically wasted during electricity generation is effectively utilised for both heating military facilities and supplying electrical power. By implementing CHP systems, military installations can achieve energy independence, ensuring a continuous power supply even if disconnected from utility grids. Furthermore, integrating CHP units into military microgrids allows multiple facilities to operate autonomously, reducing reliance on expensive backup systems usually needed during grid failures.[47,48] Figure 12 illustrates the high-level procedure by which CHP deploys to generate heat and electricity simultaneously.

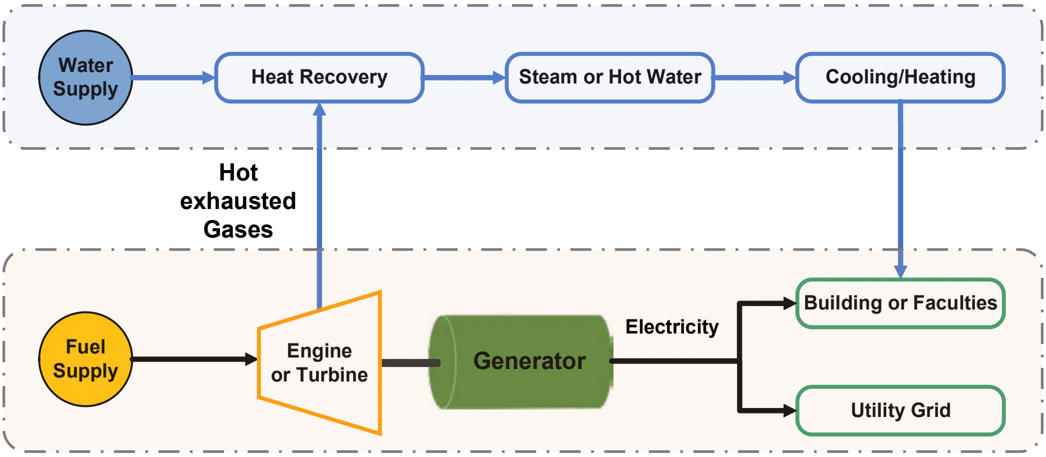


Figure 12. Combined heat and power mechanism

- **Fuel cells:** Fuel cells convert the chemical energy of fuels, such as gas and hydrogen, into electrical energy through an electrochemical process. Fuel cells provide superior efficiency and lower emissions. However, to establish hydrogen infrastructure in military settings, it is necessary to address challenges related to storage, transportation, and the unique properties of hydrogen.[49,50,51,52,53] The high-level procedure for generating electricity through fuel cells is shown in Figure 13.

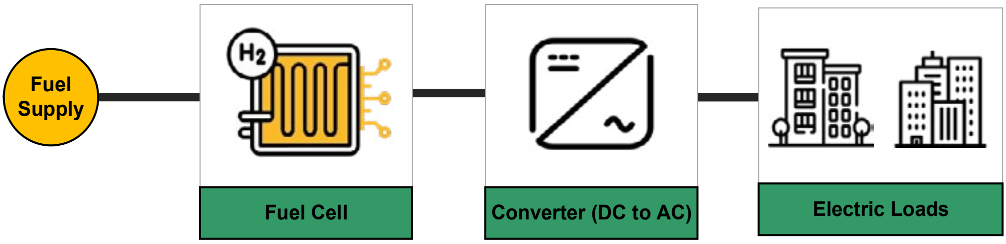


Figure 13. Fuel cell power generation steps

3.1.2 Renewable Energy Sources

Renewable energy plays a crucial role in advancing broader sustainability objectives by minimising the military's carbon footprint and mitigating environmental impacts.[54,55] The most common renewable resources are listed below:

- **Solar energy system:** Photovoltaic (PV) cells, typically made of semiconductor materials like crystalline silicon, directly convert sunlight into direct current (DC) electricity, which is one type of solar energy system. This DC power is either used to supply DC loads or converted into standard alternative current (AC) for connection to AC loads through an inverter. The PV panels are modular and can be arranged into larger arrays to accommodate various load requirements.[56,57] Figure 14 shows the process of generating electricity from solar PV panels and delivering it to customers.

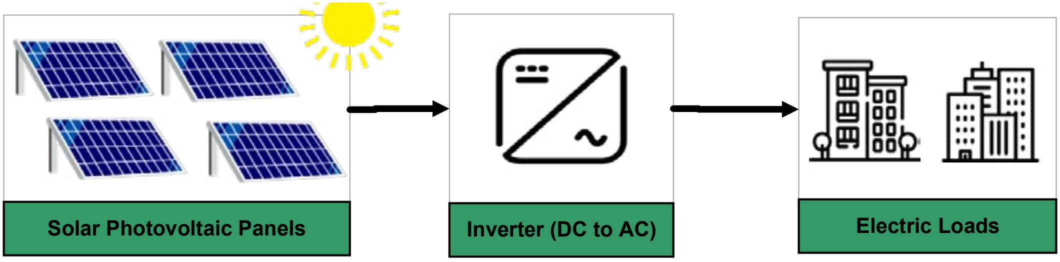


Figure 14. Steps for generating electricity through photovoltaic sources

Various types of PV systems are utilised within military installations. Small-capacity PV panels are often installed on facility rooftops, providing localised power generation that supports critical operations.[58,59] In contrast, large-capacity PV systems, known as grid-scale solar PV, are deployed in open areas across the installation. These systems are integrated with the active electrical grid.[60,61,62,63,64]

- **Wind turbines:** In military applications, wind turbines can range from individual units providing localised power to extensive wind farms with hundreds of turbines. Wind turbines can be deployed in both onshore and offshore environments, with efficiency largely influenced by factors such as air density and wind speed. As wind turbines generate power based on varying wind speeds, converters are employed to adjust the output frequency to the standard grid frequency, typically 50 Hz or 60 Hz.[65 66,67] Figure 15 shows the procedure for delivering electricity to the loads generated by wind turbines.

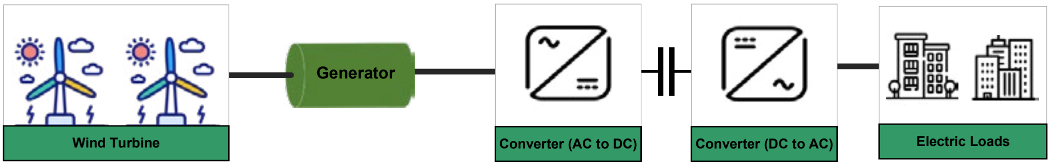


Figure 15. Steps for delivering electricity generated by wind turbines to loads

- **Biomass energy:** It is derived from plant and animal sources and captures solar energy through photosynthesis, making it a renewable and versatile energy resource. In military and defence contexts, biomass can be harnessed in several ways to enhance energy security and sustainability. Direct combustion of biomass can produce heat for military installations, supporting both heating and electricity needs. Thermochemical processes, such as pyrolysis, gasification and torrefaction, convert biomass into solid, gaseous or liquid fuels, which can be used to power equipment and vehicles in the field. Chemical processes, including transesterification, generate biodiesel from oils and fats, offering an alternative fuel source for military operations. Additionally, biological processes such as anaerobic digestion and fermentation produce biogas and bioethanol, which can be utilised for various applications, including energy supply and waste management. These methods collectively provide a sustainable and renewable energy solution, crucial for maintaining operational effectiveness and energy resilience in defence settings.[68,69,70,71,72]

- **Geothermal energy:** This energy taps into the Earth's innate heat, originating from depths where core temperatures surpass approximately 5,273.15 K. This thermal energy gradually permeates through layers, heating underground rocks and water. Utilising hydrothermal convection systems, cooler water infiltrates the Earth's crust, undergoes heating and emerges as steam, which then serves as a potent energy source for electric generators. Geothermal power plants streamline this process by drilling into rock formations to access steam more efficiently.[73,74] There exist three primary designs for geothermal power plants,[75,76] each involving the extraction of hot water and steam from subterranean reservoirs, employing them for energy production, and reintroducing them as warm water to sustain the heat source. The simplest design entails directing steam through a turbine and then condensing it into water. Alternatively, high-pressure hot water can be depressurised to produce steam for driving a turbine. In a binary cycle system, hot water heats a secondary liquid, such as isobutane, which vaporises at a lower temperature, thus fuelling the turbine. Geothermal power plants are particularly advantageous for military and defence operations due to having a smaller ecological footprint, requiring less land and causing fewer ecosystem impacts, though groundwater concerns may arise.[77]

3.1.3 Energy Storage Systems

Energy storage systems are devices designed to store energy to be used for periods when generation is not available. There are several types of energy storage systems commonly used in military services, as follows:

- **Uninterruptible power supply (UPS) systems:** These systems consist of battery storage units that are installed between power generation sources (such as electric utility grids or microgrids) and critical electrical loads within a facility. Under normal conditions, the facility's power demands are met by the grid while the UPS batteries are charged. In the event of a power outage, the UPS provides immediate backup power from its batteries, ensuring that critical systems continue to operate without interruption. UPS systems in military applications are designed to support either the entire facility's power needs or specific critical loads for a brief period, typically ranging from 15 to 40 minutes. UPS systems are not intended to provide long-term power but are vital for bridging the gap during the transition to generator power, ensuring the continuity of essential operations and the functioning of key equipment during emergencies.[78,79,80] Figure 16 demonstrates the structure of UPS systems.

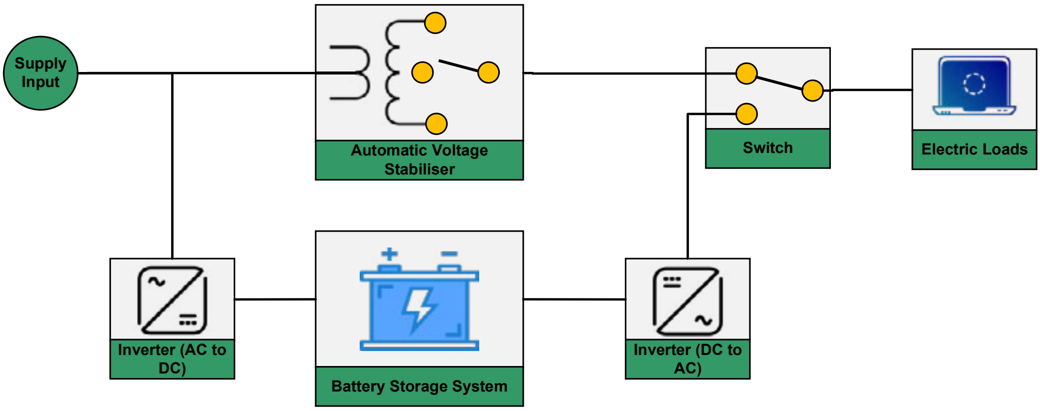


Figure 16. Structure of uninterruptible power supply systems

- **Battery storage systems:** Large-scale battery systems are deployed to supply all critical loads on military and defence missions.[81,82,83] However, the growing interest in using intermittent renewable resources to meet electrical demand and the subsequent need for storage to manage fluctuations throughout the day and night have increased the potential for their adoption.[84] Compared to UPS systems, batteries offer prolonged power delivery to devices and equipment, making them suitable for extended periods of power provision.

- **EVs:** EVs, particularly hybrid- and battery-electric models, play a crucial role in military logistics and operations. Equipped with vehicle-to-grid technology, they serve as mobile energy storage for short-term applications. Hybrid-electric light tactical vehicles offer enhanced mobility and survivability with efficient generators and adaptable batteries. Similarly, hybrid-electric main battle tanks utilise strong electric motors and battery banks for improved acceleration and fuel savings. Lightweight and quick to recharge, battery-electric medium vehicles excel in logistical delivery.[85,86]

3.2 High-Level Advantages and Disadvantages of Distributed Energy Resources

The capabilities and limitations of DERs[87,88,89] such as CHP,[90,91,92,93] hydrogen-based fuel cell systems,[94,95] UPS,[96,97] biomass energy,[98,99] geothermal energy,[100,101,102] battery storage[103,104,105] and EVs[106,107] are summarised in Table 4.

Table 4. Overview of the benefits and limitations of distributed energy resources

DER type	Advantages	Disadvantages
Diesel generators	• Widely used for critical load backup • Capable of providing backup power during grid outages • Available in various sizes to suit different applications • Controllable electricity generation • Liquid fuel, making it easy to refuel, with a less flammable rate	• High complexity because of various components like engines, alternators and fuel systems • Generate carbon dioxide by consuming diesel fuel • High-maintenance practices significantly affect their reliability and performance • Make noise when generating electricity • Dependency on diesel fuel
Combined heat and power (CHP)	• CHP generates both electricity and heat, reducing the need for separate equipment • CHP systems decrease greenhouse gas emissions and air pollutants by consuming less fuel • CHP reduces expenses and offers protection against rising energy prices • CHP systems reduce dependence on the energy grid, ensuring greater energy security • CHP systems are utilised in district heating plants to supply energy and heat to local facilities	• Substantial investment and ongoing maintenance expenses • Complex operation and maintenance requirements • Fixed capacity may limit adaptability, particularly for energy demand growth • Availability and cost of fuel can impact cost-effectiveness, especially if the fuel source is scarce or costly • Complex regulatory requirements may present obstacles, including regulations on energy production and emissions

DER type	Advantages	Disadvantages
Fuel cells	• Hydrogen fuel cells offer a significant 25 per cent reduction in operational energy demand, especially beneficial for fully electric forces • The commercial availability of fuel cell technology allows for easy adaptation to military applications, particularly for unmanned systems • Hydrogen's non-toxic nature and rapid dispersal mitigate environmental risks, enhancing safety in inadvertent releases • Private industry initiatives are addressing safety and supply chain risks, potentially benefiting military operations • Ongoing research focuses on improving storage and transportation methods, promising enhanced efficiency and safety in hydrogen usage	• Despite its environmental safety, hydrogen's high flammability poses ignition risks and safety concerns • Limited energy density of hydrogen necessitates costly storage and distribution methods, increasing overall expenses • Corrosive properties of hydrogen can degrade existing pipelines, requiring expensive mitigation • Dependence on specific energy sources for hydrogen generation and feedstock availability introduces supply chain vulnerabilities • Current hydrogen production heavily relies on fossil fuels, necessitating the development of low-carbon production methods • Electrolysis, while promising, accounts for a small fraction of global production and requires substantial policy support for expansion • Transitioning hydrogen supply chains to renewable sources poses logistical challenges despite ongoing global efforts

DER type	Advantages	Disadvantages
Solar PV systems	• Widely deployed as they are environmentally friendly • Available in various sizes, suitable for different applications • Established reliability in high-scale commercial and utility grids • Noise-free power generation. • Generate DC power that can be deployed to supply DC equipment • Modular design allows for flexible arrangement into larger arrays • Can reduce reliance on costly and logistically challenging fuel deliveries, especially in remote locations	• Vulnerable to weather conditions, causing stochastic output fluctuations • Component failures, particularly inverters which convert DC to AC power • Impossibility in standalone operations • Need inverters to convert DC to AC power • High investment costs • Need to occupy significant land to install PV panels • Limited applicability in specific geographical areas and seasons

DER type	Advantages	Disadvantages
Wind turbines	• Rapid deployment globally, indicating their eco-friendly nature • Potential for both onshore and offshore applications • Mitigate dependency on fuel-based generators • Produce significant electricity if weather conditions are desirable • Facilitate the development of off-grid microgrids in challenging logistical areas	• Variable or intermittent power output dependent on weather conditions, limiting reliability • Offshore deployment adds complexity, particularly in maintenance • Complex systems are prone to more failures • Need electronic-based converters to regulate the frequency • Vulnerable to natural disasters, including typhoons that can cause significant damage to their infrastructure • Require specific foundations for installations, which can increase installation complexity and expenditures

DER type	Advantages	Disadvantages
Biomass energy	• Biomass energy, while reliant on organic matter that diminishes upon use, can be quickly regenerated • Unlike wind and solar energy, biomass provides a consistent energy supply, making it more reliable • Abundant organic materials contribute to the availability and sustainability of biomass energy • Biomass energy utilises waste materials, reducing landfill accumulation and benefiting the environment • As biomass fits into the natural carbon cycle, it is considered carbon neutral, contrasting with fossil fuels, which contribute to carbon dioxide emissions and climate change	• Biomass energy production entails substantial initial costs, including constructing biomass energy plants and expenses associated with harvesting and transporting biomass materials • Biomass energy plants require considerable space, primarily for storage, which restricts their potential locations for construction • Burning biomass fuels emits various greenhouse gases, including nitrogen oxides, carbon monoxide and methane, contributing to environmental pollution • Dependence on biomass energy raises concerns about deforestation • Currently, biomass energy lacks efficiency compared to other energy sources

DER type	Advantages	Disadvantages
Geothermal energy	• Geothermal energy, derived from natural Earth processes, offers long-term sustainability • Geothermal power plants provide continuous electricity, unlike solar and wind sources, ensuring reliability • Nations with geothermal resources can lessen reliance on imported fuels, promoting energy independence • Geothermal infrastructure requires minimal land use, suitable for diverse urban and rural settings • Modern geothermal plants emit minimal greenhouse gases, with significantly lower emissions compared to natural gas	• Geothermal energy relies on specific regions with accessible energy reservoirs, limiting its widespread use • It is the second most expensive renewable energy source to install due to deep well drilling, with payback periods ranging from five to 20 years • Geothermal operations carry risks to ecosystems and groundwater, and may induce gas emissions • Seismic activity risks, particularly from activities like water injection into the Earth's crust, underscore the importance of proper site management to prevent adverse consequences
UPS systems	• Portable to different sites, requiring no specific set-up, as they can link to utility electrical power • No special safety measures are needed for operating and maintaining UPS installations • Ensure uninterrupted power supply, guaranteeing continuous functionality of essential equipment • Protect sensitive equipment from power disruptions, averting potential damage or data loss	• Due to the inclusion of batteries, they are susceptible to weather conditions • The up-front costs during procurement and installation are significant • Routine upkeep and sporadic battery replacements are obligatory • The generated electromagnetic interference may interfere with the operation of nearby electronic and radio systems

DER type	Advantages	Disadvantages
Battery storage systems	• Provide backup power support, enhancing grid resilience • Integration with renewable energy sources like solar and wind contributes to sustainable power provision • Modular design with multiple battery modules allows for scalability and flexibility in system configuration • Wind and solar energy intermittency underscores the necessity for energy storage remedies • By hybridising with renewable resources, they reduce reliance on coal-powered sources and increase energy independence • Battery integration results in reduced electricity bills during peak demand periods	• Lithium-ion batteries are commonly used in battery systems, offering high energy density and efficient energy storage. However, lithium-ion battery incidents like fires and explosions, although rare, pose safety concerns • Lithium-ion batteries encounter performance decline, recycling complexities and material sourcing dilemmas, alongside safety and environmental concerns. Conversely, solid-state batteries present safety advantages and design adaptability but confront obstacles like elevated expenses and market reception issues • Lead-acid batteries necessitate cautious handling due to their corrosive sulfuric acid content • Proper disposal of batteries is crucial to mitigate negative environmental impacts associated with their limited lifespan • The initial cost of battery storage can be substantial

DER type	Advantages	Disadvantages
EVs	• Mobile energy storage by deploying vehicle-to-grid concept • Reduction of greenhouse gases and pollutants by minimising emissions contributing to climate change and air pollution • Simplified mechanics with fewer moving parts, resulting in potentially lower maintenance and repair costs • Reduced reliance on imported oil and other resources, thereby enhancing national security • Noise reduction through quieter operation, decreasing urban noise pollution	• No capability for long-term power delivery • Charging infrastructure limitations with insufficient availability of charging stations and slow charging speeds • High costs of chargers and lack of standardisation hinder adoption • Battery vehicles face challenges regarding longevity and charging accessibility • Necessity to reduce the size and weight of power delivery systems to lower overall costs

3.3 Harnessing Capabilities of Distributed Energy Resource Integration in Defence and Military Operations

DERs can be beneficial for military and defence applications. These include diesel generators,[108] CHP,[109,110] solar energy,[111] wind turbines,[112,113] biomass energy,[114] fuel cells,[115] [116,117,118] geothermal energy,[119,120,121] battery storage[122] and EVs.[123,124] A summary of these technologies and their defence-related capabilities is provided in Table 5.

Table 5. Harnessing capabilities of distributed energy resource integration in defence and military services

DER type	Capabilities
Diesel generators	• Diesel fuel’s high energy density allows diesel generators to deliver substantial power in a compact size, suitable for space-constrained applications • Diesel generators can store fuel long term without significant degradation, making them reliable for remote and extended outage situations • Diesel generators are fuel-efficient, consuming less fuel per power output compared to natural gas generators, resulting in lower operational costs • Diesel engines are robust and durable, ensuring reliability in demanding conditions, ideal for mission-critical applications
Combined heat and power (CHP)	• Engineered and maintained for continuous operation to ensure sustained performance • Natural gas infrastructure is typically resilient against extreme weather conditions, ensuring continuous operation • It can be configured for switching from grid connection to islanded mode operation without interruption • Capable of generating electricity and thermal energy (heating, cooling, hot/chilled water) simultaneously, maximising efficiency • Produces lower emissions compared to conventional power generation methods • Fuel-flexible, utilising renewable fuels, low-carbon waste fuels, and hydrogen when available, with future readiness for higher levels of biogas, renewable natural gas, and hydrogen • Renewable/hydrogen-fuelled CHP systems can decarbonise thermal end-uses in facilities that are difficult to electrify, such as those in remote areas • Provides reliable, long-duration on-site power for critical facilities, ensuring resilience and operational reliability

DER type	Capabilities
Fuel cells	• Hydrogen fuel cells operate silently, offering a tactical edge during field operations • They deliver efficient energy, enabling extended mission duration • Demonstrated to perform consistently well in demanding military environments • Engineered for easy portability, reducing logistical hurdles • Simple to use and set up with a plug-and-play design • Automatically recharge existing batteries and switch to standby mode when fully charged, ensuring consistent energy availability and longer battery lifespan • Guarantee uninterrupted power through seamless switching between battery and fuel cell, with continuous monitoring and automatic charging • Provide reliable power in all weather conditions throughout the year • Reduce battery weight by up to 80 per cent, allowing soldiers to carry more essential supplies or extend mission time • More cost-effective than batteries as they require only methanol, cutting down on costs for primary batteries, recharging, and related logistics • Operate with no detectable signatures, noise, or emissions, making them ideal for maintaining stealth and camouflage • Potential to power a wide range of devices, from cellular phones to entire homes and large buildings, which helps decrease dependence on imported oil and mitigates pollution and global warming • Promotion of fuel cells as a sustainable energy solution that could create new business opportunities and contribute to environmental sustainability • Extended operational lifespan (>10,000 hours) with minimal performance decline (<0.5 per cent per 1,000 hours) • Robust performance in harsh environments and under mechanical stress

DER type	Capabilities
Fuel cells	• Proven reliability in extreme conditions, including testing on Mars • Modular design facilitates easy scalability and customisation for various applications • Enhanced security and reliability through on-site power generation, decreasing dependence on electrical transmission infrastructure • Highly compact and lightweight design, making them ideal for mobile and portable applications • Hydrogen represents the future of air domain energy, offering high energy density and zero-emission potential. It holds promise for powering next-generation aircraft and support systems, enabling longer missions with reduced environmental impact • Hydrogen offers transformative potential for naval energy needs. With its high energy density and clean-burning characteristics, it could enable extended range and endurance for ships and submarines while significantly reducing carbon and acoustic footprints
Solar PV systems	• Off-grid solar energy powers remote satellite ground stations and high-altitude communications relay infrastructure • Solar aircraft enable extended reconnaissance missions with unlimited flight endurance • Silent watchtowers and sensors integrate solar panels for continuous surveillance while remaining undetectable • Solar systems provide fuel-free propulsion for unmanned vessels, enhancing sustainability • Wearable solar fabrics and thin-film chargers keep individual operators powered during extended missions • Solar-enabled innovations offer warfighters expanded reach and flexibility across various environments

DER type	Capabilities
Wind turbines	• Reduce dependence on fossil fuels, resulting in lower greenhouse gas emissions and pollutants • Offer a renewable and cost-effective energy source, promoting sustainable development • Wind is available in many locations worldwide, with extensive data to optimise turbine placement • Useful in remote areas without access to the main power grid, saving on infrastructure costs • Provide a reliable energy source over the medium to long term, despite short-term variability • Convert 40 to 50 per cent of wind energy into electricity, close to maximum theoretical efficiency • Require minimal land, allowing concurrent use for activities like farming or grazing • Have a lower environmental impact compared to many other energy sources, with reduced emissions and resource use • Installation and operational costs are relatively low, with construction times ranging from a few months to two years • Advances in technology and government incentives have further decreased costs and improved accessibility • Minimal maintenance needed, with turbines typically lasting over 20 years with only occasional adjustments • Can be disassembled and recycled, with land restored to its original condition, supporting a circular economy • Small-scale systems can provide energy for homes or buildings, often combined with other renewables • Built to withstand tough conditions, making them suitable for disaster-stricken areas and conflict zones • Can be packed into a standard military shipping container for easy transport and rapid assembly • Reduce reliance on diesel generators, cutting fuel costs, lowering emissions, and minimising risks to personnel • Integrate with microgrids alongside solar panels and energy storage, providing a reliable power source in various conditions • Designed for straightforward operation and quick deployment in emergency situations

DER type	Capabilities
Biomass energy	• Elimination of sulphur dioxide emissions, maintaining balanced carbon dioxide levels, reduced release of airborne toxins, and improved waste management • Lower expenses for waste disposal and fossil fuels, increased energy security at home and abroad for military bases, and promotion of technology for export • Flexible and transportable technologies, use of standard components, and effective deployment of small-scale innovative energy conversion methods • Support for developing countries in addressing energy and waste management challenges, with added potential for obtaining financing from global financial institutions
Geothermal energy	• Utilising geothermal power offers military bases an environmentally sustainable method to conserve energy and water, cut down on operational costs and reduce reliance on imported fossil fuels • Geothermal energy ensures that military bases have a reliable and continuous power supply, capable of operating independently from the grid when needed • Adopting geothermal solutions modernises military energy systems and enhances national competitiveness in future energy markets • Geothermal power supports environmental sustainability and improves living conditions for both on- and off-base communities • Clean geothermal energy decreases reliance on conventional fossil fuels, aligning with fuel demand reduction goals and decreasing supply chain dependency

DER type	Capabilities
Battery storage systems	• Batteries are increasingly vital in military technology, enhancing capabilities in unmanned systems and submarines • Lithium-ion batteries support economic and environmental goals by facilitating the shift to renewable energy sources and reducing carbon emissions • Battery technology improves the efficiency of military systems such as diesel-electric submarines and drones, offering quieter operations and longer operational duration • Portable battery systems reduce reliance on diesel generators, cutting down on fuel costs and minimising logistical challenges in conflict zones • The development of advanced batteries, like solid-state batteries, promises significant improvements in energy density and safety, benefiting both military and civilian uses • Enhancing and diversifying battery supply chains, especially for essential materials, strengthens energy security and reduces susceptibility to geopolitical disruptions • Battery designs can be tailored to specific applications by adjusting capacity and discharge rate • Incorporating smart battery technology improves safety and efficiency by managing charge and discharge rates and monitoring battery health • Batteries provide reliable, efficient and quiet power for current energy needs in air operations, supporting ground equipment, unmanned aerial vehicles and base facilities with clean and readily deployable energy • Batteries also play a key role in naval operations, delivering silent, efficient energy for onboard systems, unmanned surface and underwater vehicles, and shore-based infrastructure. Their low acoustic signature is especially valuable in maritime environments

DER type	Capabilities
EVs	• Electric motors enable swift acceleration, facilitating climbing steep slopes and escaping threats. They also enhance stealth by minimising heat and noise emissions • Hybrid EVs can produce over 500 kW of power, comparable to nine standard generators, making them capable of powering field hospitals or aiding in disaster relief operations • Adopting EVs helps reduce greenhouse gas emissions, addressing a major way the military impacts global climate change • EVs produce less heat and noise than conventional vehicles, making them more difficult for adversaries to detect, enhancing operational stealth and safety • EVs can decrease fuel consumption, particularly when stationary—a common scenario in military operations—leading to potential cost savings and simplified logistics • Transitioning to EVs aligns with broader goals of modernising the military, advancing technological capabilities, and improving energy efficiency and sustainability

3.4 Identifying the Risks of Distributed Energy Resource Integration for Defence and Military Operations

The risks of different DERs, such as diesel generators, CHP,[125,126] renewable sources (wind turbines and solar energy),[127,128,129,130,131] biomass energy,[132,133] geothermal energy,[134,135] fuel cells,[136,137] battery storage[138,139] and EVs[140] are summarised in Table 6.

Table 6. Risks of distributed energy resource integration in defence and military services

DER type	Risks
Diesel generators	• Diesel generators emit higher levels of pollutants, including nitrogen oxides and particulate matter, leading to stricter emissions regulations due to negative environmental and health impacts • Diesel generators are noisier than natural gas generators, posing concerns in noise-sensitive areas • Diesel fuel can be more expensive and subject to price fluctuations, with large-scale storage posing safety and environmental risks • Diesel generators require more frequent maintenance, increasing overall ownership costs
Combined heat and power (CHP)	• Higher volatility of natural gas prices affects CHP projects, making it less appealing compared to grid power • Significant initial investment can be difficult to finance • Potential for system disruptions makes CHP systems less attractive than traditional boilers and grid electricity • Larger CHP units face challenges and costs related to multiple permits and varying local regulations, such as environmental emissions and noise • Dependency on fossil fuels may make CHP impractical in regions with state conflicts or unstable conditions

DER type	Risks
Fuel cells	• Hydrogen/air mixtures, driven by hydrogen's combustible nature, present a highly explosive combination • Hydrogen's combination of low ignition energy (0.017 mJ) and broad flammability range (4 to 75 per cent volume in air) renders it highly susceptible to explosion • Enclosed spaces with potential ignition sources, such as electrical equipment, become potential hotspots for explosions if hydrogen leaks occur • The presence of high barriers like ceilings and impermeable surfaces amplifies explosion risks in the presence of an ignition source • Hydrogen leaks not only pose explosion risks but also have the potential to displace oxygen in confined spaces, leading to asphyxiation • The fuel cell stack's ability to generate high voltages (200–400 V) and currents (500 A) poses significant electrical hazards • Automatic shutdown machinery becomes imperative in gas-hazardous situations to ensure a swift and effective response to potential dangers • Due to hydrogen's molecule size, it can escape from sealed pipework or containers, necessitating careful management of compressed hydrogen discharge to mitigate explosion hazards • Storage of cryogenic liquid hydrogen mandates materials capable of withstanding extremely low temperatures • Spills of cryogenic liquid hydrogen have the potential to harm ship hulls and generate cold vapour clouds, increasing the risks of both asphyxiation and explosion • Although formic acid serves as a viable hydrogen carrier, it possesses corrosive properties and can induce severe burns

DER type	Risks
Fuel cells	• Solid-state storage systems for hydrogen carriers require protection from air and moisture to prevent potentially dangerous reactions • Existing regulations concerning hydrogen safety in maritime transport need to be harmonised with specific safety criteria • Further investigation is essential to assess the safety implications of hydrogen fuel cell equipped vessels and to legislate pertinent safety guidelines and standards • While they are modular, the fuel cell systems still need robust protection against potential physical and cyber threats • Ensuring a consistent supply of fuel and materials is crucial, although flexibility helps mitigate this issue • Managing risks associated with dangerous substances and electrical hazards requires stringent safety measures
Solar PV systems	• Solar thermal plants can emit high thermal signatures, potentially interfering with infrared sensors used in military operations • The type of solar energy technology used can affect special use airspace, military training routes, and areas utilised for ground manoeuvrability training • Large solar farms using panels may decrease available ground training space for military exercises • Solar projects with towers reaching heights over 610 m above ground level can impact various types of airspace, requiring assessment by aviation authorities • Solar energy facilities employing wireless control systems may interfere with or be interfered with by defence systems • Solar facilities can cause glint and glare, posing safety risks and potential eye exposure concerns for personnel on defence ranges • Solar thermal plants may consume substantial amounts of water, impacting both installation and regional water supplies, especially in arid regions • Solar plants necessitate habitat destruction through vegetation levelling and eradication, potentially leading to increased restrictions on military operations under environmental regulations

DER type	Risks
Wind turbines	• Wind farms create avoidance areas, forcing pilots to navigate above lower altitudes and disrupting low-altitude training and missions • Large wind farms can block helicopter routes and other non-standard flight paths • Electrical transmission lines can disrupt low-level flight paths and create areas that must be avoided • Wind turbines cause radar issues, including false signals, clutter, and Doppler effects, which complicate tracking and detection • Turbines can disrupt radar processing functions, including airborne radar and range-tracking instrumentation • Spinning turbine blades can create false weather patterns, complicating weather detection • Wind turbines can affect both military and civilian drones, including those used for inspecting situations • The lights on wind turbines can interfere with night vision training for pilots • Wind turbines may affect weapons and communications systems through electromagnetic interference • Wind turbines can interfere with military equipment used for tracking and communication during training • Wind projects can lead to bird and bat mortality, habitat fragmentation, and disruption of migration patterns, potentially increasing restrictions on military operations • Wind turbines near airfields can disrupt navigation systems, affecting take-off and landing procedures • Wind turbines could impact sea lanes, submarine transit lanes, and coastal test and training ranges, potentially disrupting sonar operations • Wind farms used for military training may necessitate finding new manoeuvre space and require additional environmental documentation

DER type	Risks
Biomass energy	• Biodiesel may solidify at higher temperatures than petroleum diesel, which could lead to operational problems in colder environments • Biodiesel has the potential to damage elastomers, rubbers and certain metals, possibly resulting in maintenance issues and system failures • Challenges exist in acquiring and storing biodiesel, and there is a lack of international standards for marine-grade biodiesel • There are doubts about the actual environmental impact and economic feasibility of biofuels compared to traditional petroleum-based fuels • Differences in biofuel properties can impact engine performance, requiring adjustments or additives to overcome these issues • The commercialisation of algae-based biofuels involves high costs, even though they offer benefits and require minimal agricultural inputs • Biofuels offer a potential reduction in reliance on fossil fuels, but adopting them may necessitate substantial adjustments to infrastructure and integration with current systems, which could heighten military dependence • Ensuring the sustainability and certification of biofuels can be intricate and inconsistent across various geographical areas • Producing biofuels from crops can result in environmental issues like deforestation and other ecological impacts

DER type	Risks
Geothermal energy	• Geothermal projects face significant challenges in securing adequate funding and investment compared to other energy technologies • Geothermal power production is currently confined to areas with accessible hydrothermal systems, limiting its broader application • There is a notable deficiency in dedicated research and development funding for geothermal innovations, which impedes technological progress • Geothermal energy is at a developmental phase akin to early oil production, necessitating increased policy support to foster innovation and technology deployment • While geothermal energy delivers a steady power supply, integrating it with intermittent renewable sources can be challenging for achieving a well-balanced energy mix
Battery storage systems	• Risks of fires or explosions from damaged, overcharged or overheated batteries necessitate the use of proven battery technologies and simple cooling systems. • There is potential for environmental damage from chemicals and metals; use of lead-acid and lithium batteries should be avoided • Vulnerability to cyber attacks that could disrupt operations or share sensitive data means that these systems need strict cyber security measures • Complex systems require skilled technicians to manage and maintain batteries • Disruptions from geopolitical tensions or trade issues could challenge the supply chain for batteries

DER type	Risks
EVs	• Present EV technology cannot adequately fulfil the demanding needs of military applications, due to insufficient battery energy density and difficulties with fast recharging in battlefield conditions • To recharge EVs quickly in the field, enormous amounts of power would be required, which is not available in combat zones • Mobile nuclear power solutions for charging EVs are not expected to be developed in the foreseeable future, and EV technology is unlikely to advance sufficiently by 2035 to address these issues • Military vehicles must endure harsh conditions and combat scenarios, making it difficult to adapt commercial EV technology without extensive modifications • Using multiple fuel types, such as diesel and biofuels, introduces logistical challenges and potential issues with fuel storage and functionality, making it difficult for the Army to maintain a preference for a single fuel type

3.5 Suggested Prioritisation Strategy for Deploying Distributed Energy Resources

After describing the different DERs, Table 7 presents a prioritised list based on strategic importance, deployment feasibility, and operational impact.

Table 7. Strategic recommendations on the priority of distributed energy resource deployments

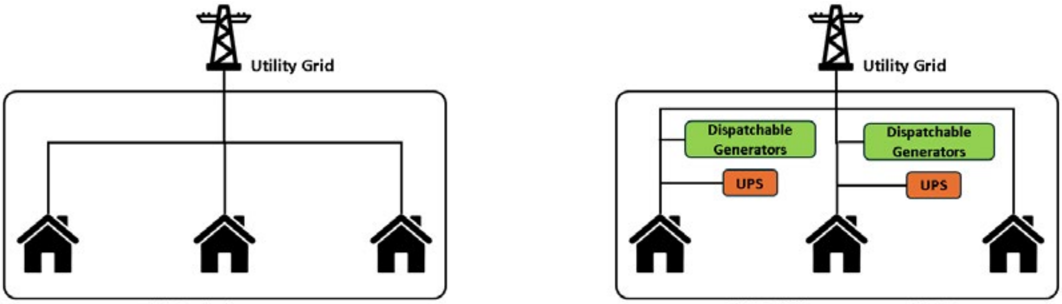
DER type	Case focus	Priority	Rationale/considerations
Battery storage + diesel generators	• Tactical/mobile power • Uninterruptible power supply (UPS) • Remote operations	• High (short term)	• Rapid deployment • High reliability; effective in austere environments • Diesel supply chain is well established • Batteries reduce fuel consumption and noise

DER type	Case focus	Priority	Rationale/considerations
Solar PV + wind	• Semi-permanent bases • Hybrid microgrids • Remote surveillance sites	• High (medium term)	• Abundant in most operational areas • Reduces diesel dependency • Complements mobile generators and storage
Hydrogen + fuel cells	• Silent/mobile operations • Future forward operating bases	• Medium (long term)	• Promising for stealth, weight reduction, and logistics-lite operations • Currently limited by hydrogen production and storage constraints
Biomass	• Remote base support (with local biomass) • Waste-to-energy concepts	• Low	• Not viable for tactical mobility • Requires consistent feedstock • Complex logistics and maintenance profile
Geothermal	• Fixed installations (e.g., training bases or headquarters in geologically viable areas)	• Low	• Very limited applicability • High set-up cost and low mobility • Suitable only for a few static locations

4. Comparative Analysis of Distributed Energy Resource Integration Technologies from the Army's Perspectives

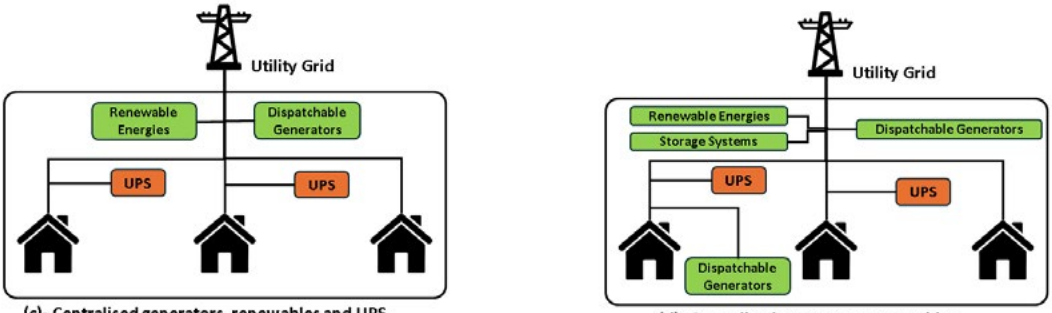
4.1 Delving into Architectures for Integrating Distributed Energy Resources in Military Installations

Energy system architectures consist of strategic combinations of DERs to meet the installation's power requirements. As seen in Figure 17, they range from configurations that rely solely on the utility grid, to those utilising multiple generation sources to achieve self-sufficient local power.[141]



(a)- No backup system

(b)- Building generators & UPS



(c)- Centralised generators, renewables and UPS

(d)- Centralised generators, renewables, storages, building generators and UPS

Figure 17. Demonstrations of distributed energy resource integration into military installations

4.2 Comparing the Features of Distributed Energy Resources

As summarised in Table 8, the applications of DERs can be compared by considering the following variables.[142]

- **Backup power:** This term stands for a backup power source that is utilised if the main power source fails to supply the equipment/devices.[143,144,145,146,147,148,149]

- **Cost-efficient technology:** Technology that is cost-efficient is defined as having lower investment costs.[150,151,152,153,154,155]

- **Standalone operation:** This denotes DERs' capacity to run autonomously without the aid of other resources.[156,157,158,159,160]

- **Producing power or heat:** This indicates if the device can generate electricity, heat, or both.[161,162,163,164,165]

- **Power quality issues:** These problems include harmonics, voltage swings, frequency changes, and interruptions that can impair the functionality of electrical devices and equipment.[166,167,168,169,170,171]

- **Fuel dependency:** This indicates whether the DER requires fuel for electricity generation or if it harnesses natural sources to produce electricity.[172,173,174,175]

- **Noise generation:** Some devices are sensitive to noise, so it is crucial to determine if the DER generates noise during electricity generation.[176,177,178,179,180,181,182,183]

- **Mobility:** This means that the resource is portable and can be easily transported to different locations, which is particularly beneficial for military and defence missions.[184,185,186,187,188,189,190,191,192,193]

- **Thermal detectability:** This indicates if DER could be detected by thermal imagers/ cameras, which are extensively used for military purposes.

Table 8. Application of different distributed energy resources

DER type	Backup power	Cost-efficient technology	Stand-alone operation	Delivering heat or power	Power quality issues	Fuel dependency	Noise generation level	Mobility	Thermal detectability
Diesel generators	Yes	Yes	Yes	Power	Yes	Yes	High	Yes	Yes
Combined heat and power	Yes	Yes	Yes	Heat and power	Yes	Yes	High	Yes	Yes
Fuel cells	Yes	No (*)	Yes	Heat and power	No	Yes	Silent	Yes	Yes
Solar PV systems	No	No (*)	No	Heat and power	Yes	No	Silent	Yes	No (night), Yes (day)
Wind turbines	No	No (*)	No	Power	Yes	No	High	Yes	No
Biomass energy	Yes	No	Not applicable	Heat and power	Not applicable	Yes	Yes	Yes	Yes
Geothermal energy	Yes	No	Yes	Heat and power	Not applicable	No	Low	No	No
UPS systems	Yes	No	Yes	Power	No	No	Very low	Yes	No
Battery storage systems	Yes	No	Yes	Power	No	No	Very low	Yes	No
EVs	Yes	No (*)	Yes	Power	Yes	No	Very low	Yes	Not applicable

* While fuel cells, PVs and wind turbines may not be the most economical power solutions, their environmental adaptation footprint significantly increases worldwide.

4.3 Evaluating the Performance and Safety of Distributed Energy Resources

In Table 9, the performance of different DERs is evaluated based on several criteria:

Efficiency: This criterion assesses the energy conversion efficiency of each resource.[194,195,196,197,198,199,200,201,202,203]

Lifespan: This highlights the expected operational lifespan of each DER.[204,205,206,207,208,209,210,211,212,213]

Fuel type: This illustrates the type of fuel.[214,215]

Safety: This criterion assesses the safety aspects and risks associated with each resource fuel.[216,217,218]

Environmental concern: This shows if the resource emits emissions or not.[219,220,221,222,223,224]

Table 9. Overview of cost and performance characteristics of distributed energy resources

DER type	Approx efficiency (%)	Lifespan (year)	Fuel type	Fuel safety	Emissions (kg/kWh)	
					NO_x	CO_2
Diesel generators	40	20–25	Liquid diesel	Diesel fuel is less flammable and less explosive	0.007711	0.7711
Combined heat and power	60–90	10–15	Natural gas is the most widely used	Natural gas is flammable and explosive	0.002678	0.43999
Fuel cells	60	10–20	Hydrogen is the most widely used	Hydrogen is more flammable and explosive	Depends on its production method[225,226]	
Solar PV systems	7–24	30–35	-	-	-	-
Wind turbines	40–50	20–25	-	-	-	-

DER type	Approx efficiency (%)	Lifespan (year)	Fuel type	Fuel safety	Emissions (kg/kWh)	
					NO_X	CO_2
Biomass energy	25–60	20–30	Biomass materials like plants and waste	Biogas is explosive	0.000118	-
Geothermal energy	12	24–50	-	-	-	0.08165
UPS systems	92–95	8–15	-	-	-	-
Battery storage systems	80–95	5–15	-	-	-	-
EVs	70–80	8–12	-	-	-	-

4.4 Utilisation and Implementation of Distributed Energy Resources in Military Operations

Diesel generators: In its publication Standard Family of Mobile Electric Power Generating Sources, the US Department of Defense has implemented a standardised set of electrical power sources and distribution gear to supply mobile electrical power.[227]

Fuel cells: Hydrogen-based fuel cells could be deployed in several military applications, such as energy storage, hydrogen-powered drones, unmanned aerial vehicles, and missile propulsion.[228,229,230,231] For example, the partnership between the US Army and General Motors led to the development of the Chevrolet Colorado ZH2, an off-road pickup truck fuelled by a hydrogen fuel cell, providing stealth and potential benefits for military use.[232] The US Army has developed hydrogen-fuelled tanks.[233] The US Army sought the creation of a hydrogen fuel cell system to power soldiers' electronic devices, with the goal of enabling mobile battery charging and enhancing compatibility with current soldier equipment.[234] Despite the mentioned small-scale use of hydrogen systems, they have nevertheless been adopted by several US government and commercial entities; some examples are listed in Table 10.[235]

Table 10. Examples of hydrogen-based fuel cell projects

Sites	Capacity	Application
Camp Parks Reserve Forces Training Area, CA	300 kW	Provides electrical power for three years under a demonstration program to enhance energy security at the facility
Naval Submarine Base, Groton, CT	2 x 300 kW	Supplies base load electricity, with byproduct heat used to preheat boiler water, increasing system efficiency
Pacific Missile Range Facility, Kauai, HI	300 kW	Meets about 35 per cent of the facility’s electricity demand; the high-grade waste heat is utilised for air conditioning
Sysco Distribution Centres, Grand Rapids; Canton, MI	Class 3 fuel cell forklifts	Demonstration of hydrogen-powered forklifts under federal fuel cell programs at commercial distribution centres
Fort Jackson, SC; Los Alamitos Joint Forces Training Base, CA; Marine Corps Logistics Base Barstow, CA	5 kW and 15 kW units	Deployed as backup power sources under federal interagency agreements; monitored for performance and lifecycle cost analysis
Santa Fe and Rio Rancho, NM	20 Plug Power GenCore units	Used for backup power to support communication and computer infrastructure at New Mexico National Guard sites

Sites	Capacity	Application
Multiple sites: - Aberdeen Proving Ground, MD - Fort Bragg, NC - Fort Hood, TX - Ohio National Guard - Picatinny Arsenal, NJ - Twentynine Palms, CA - West Point, NY - Cheyenne Mountain AFB, CO - NASA Ames Research Center, CA	217 kW in total (proton exchange membrane fuel cells)	Installed under a broad agency announcement to demonstrate fuel cell backup power systems for critical military and federal infrastructure

Although large-scale hydrogen generation is not yet economically viable in Australia, several pilot and small-scale projects are underway. Figure 18 shows the locations of current hydrogen projects, including a scenario for hydrogen generation from renewable sources using coastal water, constrained by the existing electrical network. The project in the Gippsland Basin is a world-first initiative to demonstrate the feasibility of producing clean liquid hydrogen from brown coal in the La Trobe Valley and exporting it to Japan.[236]

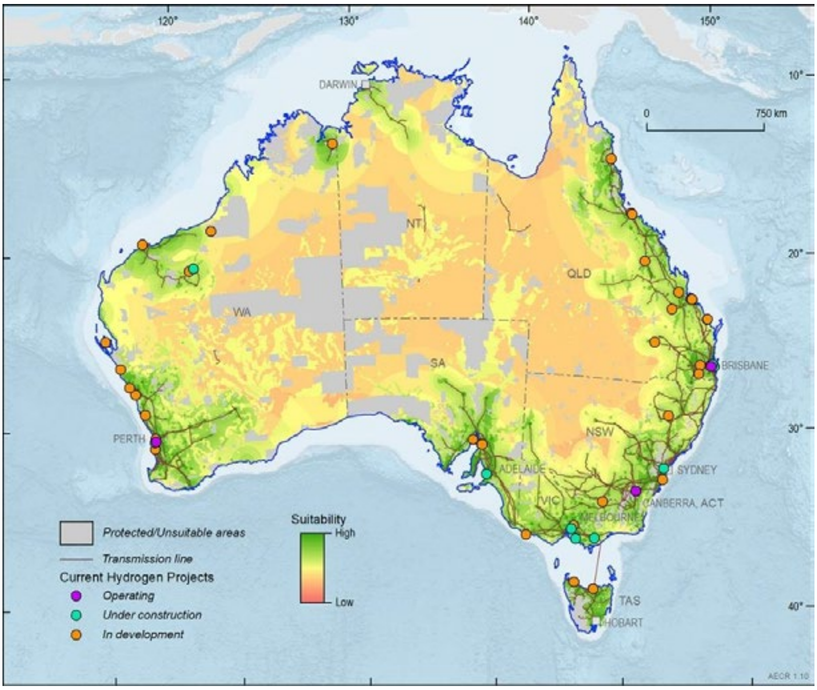


Figure 18. Location and status of hydrogen production in Australia[237]

Combined heat and power: There are 39 military bases in the US which have already implemented CHP systems, providing a total capacity of 247 MW (illustrated in Figure 19).[238] US Department of Defense facilities that currently possess or previously had CHP installations are presented in Table 11 for each state.[239] Assessment of two military support facilities in Maine showed that they significantly reduced their energy and carbon emissions through the implementation of CHP systems.[240]

Figure 19. Combined heat and power installations at military bases across the US[241]

Table 11. Federal combined heat and power sites in the US

Facility	Location	Federal agency	Technology	Capacity
Brooklyn Naval	Kings County, NY	Navy/Marines	Gas turbines	315 MW
Argonne National Laboratory	Idaho Falls, ID	Department of Energy	Not applicable	19.5 MW
Naval Medical Center	San Diego, CA	Navy/Marines	Gas turbine	2.3 MW
VA Medical Center	San Diego, CA	Department of Veterans Affairs	Gas turbine	880 kW
Naval Air Station, Point Mugu	Port Hueneme, CA	Navy	Gas turbine	1.6 MW
Naval Air Station, Point Mugu	Port Hueneme, CA	Navy	Steam turbine	775 kW
Naval Station	San Diego, CA	Navy/Marines	Steam turbine	2.54 MW
Fort Dix	Burlington County, NJ	Army	Spark ignition	30 kW
Naval Submarine Base	New London, CT	Navy/Marines	Combined cycle	20 MW
Naval Surface Warfare Center	Indian Head, MD	Navy/Marines	Steam turbine	10 MW
Naval Shipyard	Norfolk, VA	Navy/Marines	Steam turbine	60 MW
Naval Training Center	Great Lakes, IL	Navy/Marines	Steam turbine	3 MW
Marine Corps Base	Parris Island, CA	Navy/Marines	Steam turbine	3 MW
North Island Naval Air Station	San Diego, CA	Navy/Marines	Combined cycle	36 MW
Naval and Marine Corps Recruit Training Center	San Diego, CA	Navy/Marines	Combined cycle	30 MW

Renewable sources and battery: The US has also been a pioneer in military solar energy integration aimed at reaching the ‘Net Zero’ target. For example, a list of previous solar/wind energy integration in the military services of the US is shown in Table 12.[242]

Table 12. Examples of US defence-based renewable energy projects

Installation	Land use agreement	Generating capacity (MW)	Generating technology
Department of the Army:			
Fort Benning, GA	Easement	30	PV resource
Fort Bliss, TX	Access licence or permit	1	PV resource
Fort Campbell, KY	Not applicable	2	PV resource
Fort Detrick, MD	Lease	15	PV resource
Fort Huachuca, AZ	Easement	18	PV resource
Department of the Navy:			
Naval Air Weapons Station China Lake, CA	Access licence or permit	14	PV resource
Navy and Marine Corps sites, HI	Access licence or permit, site occupancy agreement	17	PV resource
Marine Corps Air Ground Combat Centre Twentynine Palms, CA	Access licence or permit	1	PV resource
Marine Corps Base Camp Lejeune, NC	Lease	17	PV resource
Department of the Air Force:			
Cape Cod Air Force Station, MA	Not applicable	3	Wind
Davis-Monthan Air Force Base, AZ	Lease	16	PV resource
Edwards Air Force Base, CA	Easement	3	PV resource
Luke Air Force Base, AZ	Lease	10	PV resource
Nellis Air Force Base, NV	Lease	19	PV resource

In Australia, the federal government is investing $64 million in energy security to equip 10 Defence sites with solar energy generation and battery storage systems. The program aims to increase energy independence, reduce reliance on diesel fuel, and diversify energy sources. It will deliver a total of 60 MW of solar energy capacity and 25 MWh of storage capacity across the sites, enhancing energy resilience and capability while saving costs for the ADF.[243]

Geothermal energy: It holds promise in Australia, yet its feasibility faces hurdles, for three main reasons:[244,245]

- Locating suitable geothermal reservoirs
- Extracting hot fluid from these reservoirs at a sufficient rate
- Addressing the substantial initial expenses linked with advanced geothermal system technologies and the transmission of electricity from remote areas.

5. Logistic Prospects for Independent Energy Systems with Army Applications

5.1 High-Level Description of Microgrids

As depicted in Figure 20, a microgrid is a localised electrical system that typically incorporates a combination of power generation sources, loads, and storage devices, all managed from a central control point. The microgrid operator serves as this central controller, optimising and coordinating power generation and controllable loads to maintain autonomous operation. This set-up allows microgrids to disconnect from the main electrical grid (utility electrical power) and function independently, a process known as islanding.[246]

Generally, microgrids have five principal parts:

- Distributed energy resources, such as generators and storage units
- Power consumption points, known as loads
- A connection/disconnection interface with the main power grid
- Control systems for managing microgrid operations
- Protection systems to ensure safety.

The key characteristics of microgrids include:

- the ability to autonomously restart the microgrid after a total outage or blackout (islanding mode)
- the capacity to handle large power surges when specific loads are activated, necessitating a significant burst of power
- the ability to maintain voltage and frequency within standard limits.

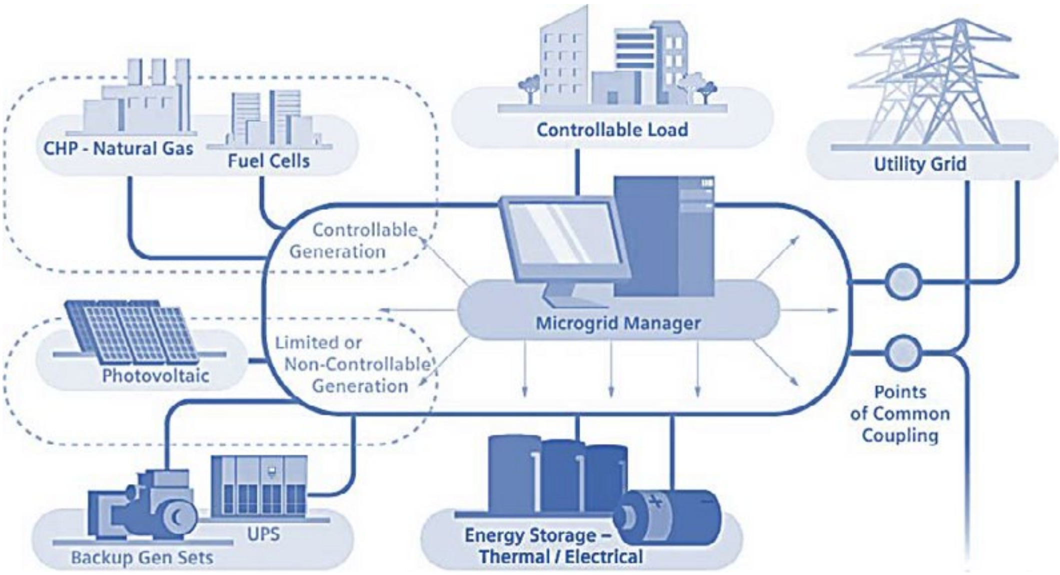
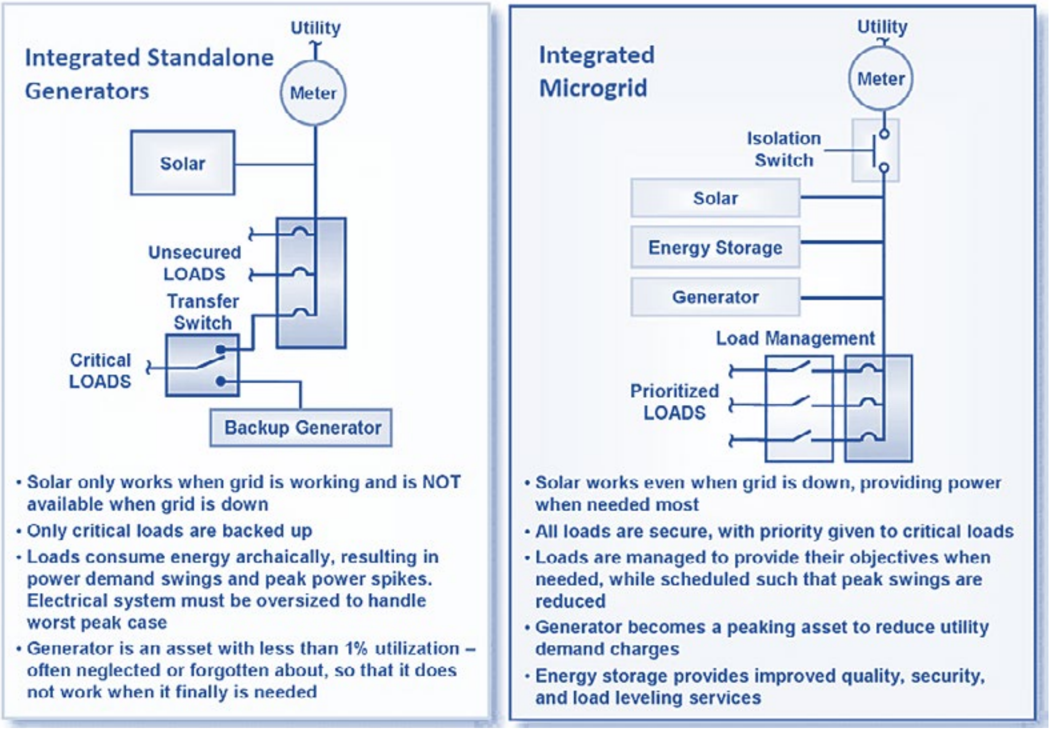


Figure 20. High-level illustration of a microgrid

5.2 Comparison of Standalone Generators and Microgrids

Figure 21 illustrates the operation of standalone generators and microgrids on the infrastructure of utility grids.[247] A detailed comparison between these systems is presented in Table 13.[248,249]



- Solar only works when grid is working and is NOT available when grid is down
- Only critical loads are backed up
- Loads consume energy archaically, resulting in power demand swings and peak power spikes. Electrical system must be oversized to handle worst peak case
- Generator is an asset with less than 1% utilization – often neglected or forgotten about, so that it does not work when it finally is needed

- Solar works even when grid is down, providing power when needed most
- All loads are secure, with priority given to critical loads
- Loads are managed to provide their objectives when needed, while scheduled such that peak swings are reduced
- Generator becomes a peaking asset to reduce utility demand charges
- Energy storage provides improved quality, security, and load leveling services

Figure 21. Network-integrated comparison of standalone generators and microgrids[250]

Table 13. Technical comparison of standalone generators and microgrids

Criteria	Standalone generator	Microgrid
Capacity	Capacity must be oversized, typically at twice the peak demand, which often results in reduced efficiency in practice	By integrating various resources, is optimally sized and benefits from fluctuating peak power demands
Maintenance	High operational and maintenance costs; insufficient testing; numerous generators on large bases often suffer from inadequate maintenance	Easier and more cost-effective to maintain; relies on a few large, standardised and centralised generation units
Dependability	Often unreliable due to poor maintenance and testing; achieving reliability is uncommon and costly	Highly reliable configurations; cost-effective due to a networked structure

Criteria	Standalone generator	Microgrid
Adaptability	Cannot adapt to changing requirements; specifications are fixed at procurement	Can adapt to changing electricity demands, even during outages, without extra costs
Service scope	Provides a binary solution for loads (either critical or non-critical), with limited flexibility	Can serve any connected load with excess generation capacity; supports intermediate loads
Sustainability and security	Traditional fossil fuel based generators are commonly used, resulting in substantial emissions	By integrating various storage systems, can incorporate diverse renewable energy sources, thereby reducing overall emissions
Islanded mode	Capable of black starting and functioning in islanded mode, but only serves loads connected to the transfer switch	Can independently start and operate in islanded mode, delivering power over extended periods
Utility grid integration	Does not operate in parallel with the grid; standby systems can only disconnect loads from the grid	Operates in sync with the grid, allowing for full output utilisation and financial compensation for excess energy

5.3 Configuration of AC and DC Military Microgrids

Microgrids can be classified as either DC or AC systems, and they can differ greatly depending on their energy sources, loads and converters. The characteristics of the ideal military microgrid depend entirely on its specific application and geographical location. However, an advanced military microgrid should encompass the following elements:[251]

- Eliminate the need for fuel resupply
- Include a diverse array of power generation sources
- Feature extensive energy storage capabilities
- Offer or absorb high power levels on demand
- Incorporate resilient distribution systems while maintaining mobility.

Considering an example of a battalion command post is a helpful way to elaborate on how conventional systems can transition to AC and DC microgrids. Figure 22 illustrates a traditional battalion command post schematic that relies solely on a single-direction AC diesel generator, lacking battery storage and renewable energy sources. This configuration is prone to failure, as any issue with the diesel generator can incapacitate the entire system. Conversely, Figure 23 presents an enhanced AC microgrid set-up featuring a PV resource and energy storage systems. This improved configuration maintains the core function of a battalion command post and is prepared for the future integration of directed energy weapons (DEWs) and electric combat vehicles (ECVs), as shown by the dashed lines.

While an enhanced AC microgrid could serve as a blueprint for power systems supporting ECVs and DEWs, modern US Army command posts also require DC power for their dense array of computers and communication equipment. In this regard, current AC-to-DC and DC-to-AC conversions are about 90 per cent efficient, while DC-to-DC conversions reach around 95 per cent efficiency. Other factors are also driving defence and army initiatives towards adopting DC-based power networks. To begin with, the substantial power demands of DEWs and ECVs make a DC-based distribution system more cost-effective. Besides, conversion from AC to DC and vice versa generates harmonics due to the switching characteristics of power electronic devices, which have destructive impacts on defence and military equipment.[252] It is also notable that the US Army typically uses a 24 V DC standard for most equipment, but this low voltage is not suitable for long-distance power transmission within command posts.

Given the complexity of military demands, one solution could involve a 250 V DC distribution and generation system, stepped down to 24 V at the point of use via DC-DC conversion. This higher voltage ensures efficient transmission while maintaining safety and facilitating rapid connections. Future devices, including ECV chargers, could also employ DC-DC converters to achieve the necessary voltages. The schematic for this proposed enhanced DC microgrid is depicted in Figure 24.

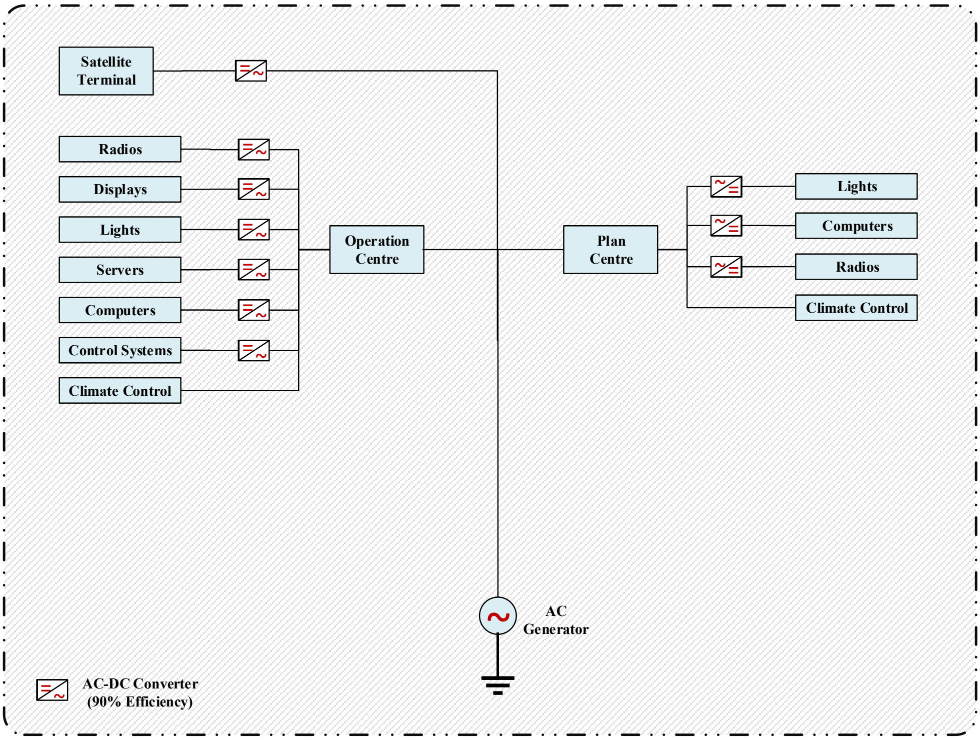


Figure 22. Sample battalion command post electrical schematic[253]

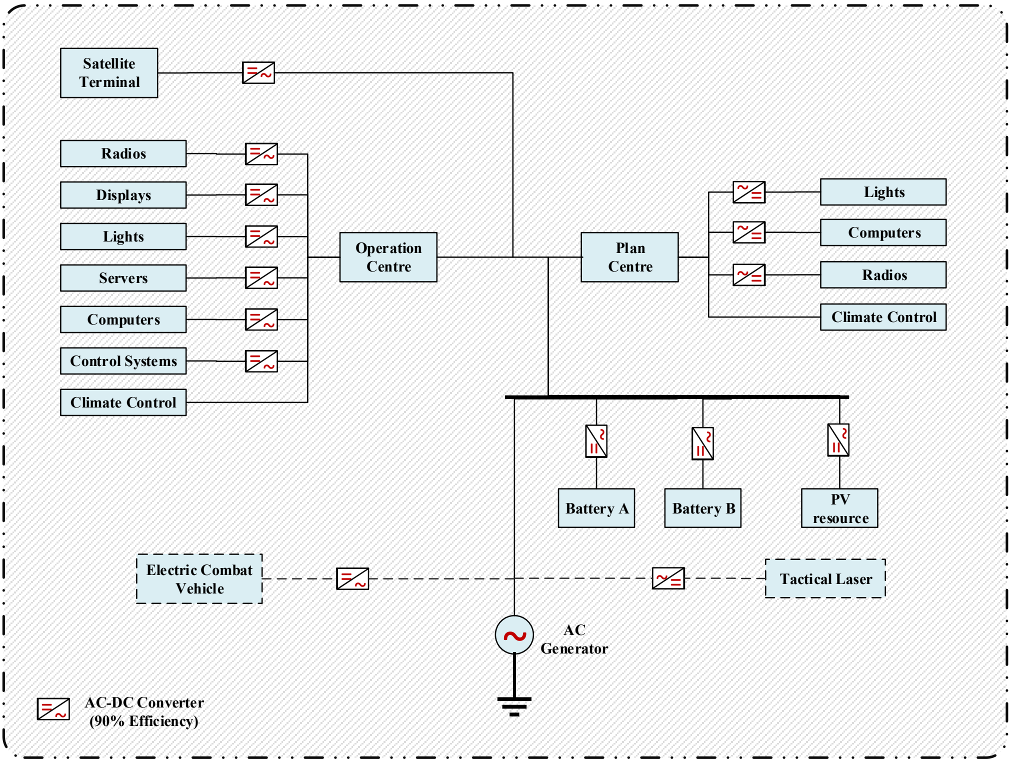


Figure 23. Enhanced AC microgrid electrical schematic[254]

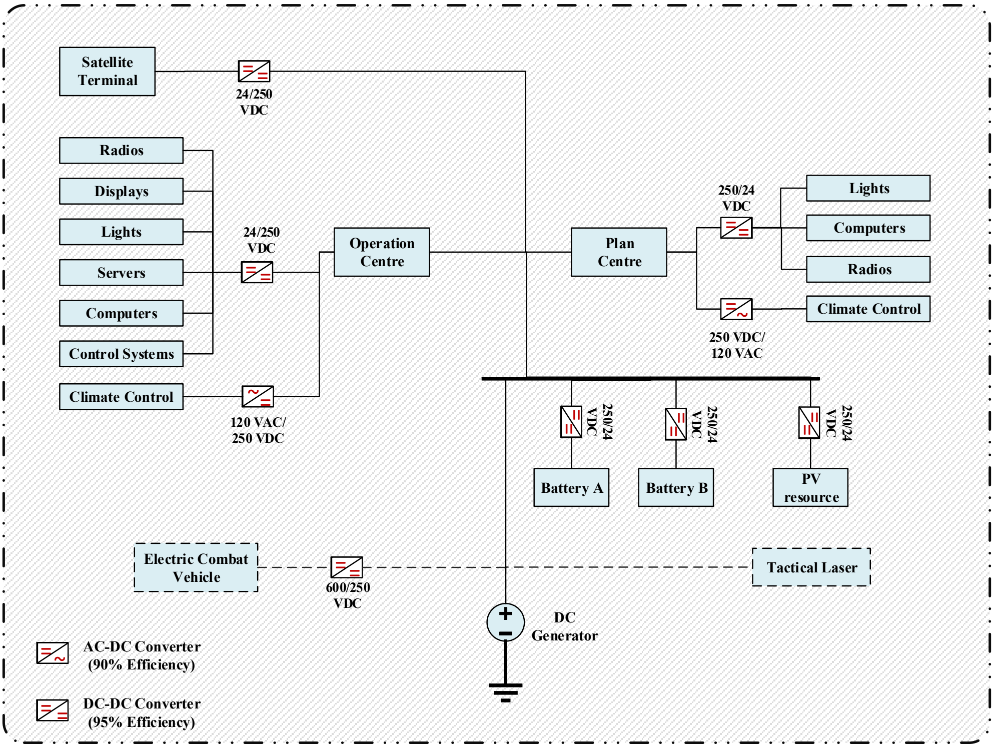


Figure 24. Preliminary enhanced DC microgrid schematic[255]

5.4 Comparison between AC and DC Microgrids

Each AC or DC microgrid presents distinct advantages and limitations depending on the application.[256,257,258,259] These are summarised in Table 14.

Table 14. Features and applications of AC and DC microgrid systems

Type	Benefits	Limitations	Applications
AC microgrids	• AC generators are very efficient. • Easily connected to existing grid infrastructure and can be operated in grid-connected mode or independently • Compatible with AC-based equipment and resources (suitable for systems where AC power is standard) • No need for inverters for AC loads • Cost-effective in terms of power protection • Support a higher availability of AC loads • Lower initial costs with no need for retrofitting • Less prone to short-circuit and ground faults	• Lower efficiency in power conversion • High cost for converters (e.g., DC-AC) • Controlling issues due to frequency and voltage regulation • Reliability may be lower because of their complexity, affecting performance-critical equipment • Less efficient in power transmission compared to DC systems • Power quality issues arise due to power conversion processes • Less efficient when integrating renewable energy sources like PV arrays • May require centralised control, creating a potential single point of failure	• Best suited for applications requiring substantial power and reliability, such as industrial facilities and hospitals • Effective for general use cases like lighting, household appliances and commercial and residential applications • Suitable for non-mission-critical environments and general power distribution purposes

Type	Benefits	Limitations	Applications
DC microgrids	• More efficient power conversion, ideal for high-performance equipment • Lower cost for converter systems • Better transmission efficiency with no reactive power losses • Reliable power supply, even in remote areas • Reduced cabling needs due to high voltage at low current • Simplified control without complex requirements for synchronisation or reactive power management leading to power quality issues • High efficiency in power conversion, especially with PV arrays and energy storage systems. • Improved energy resilience due to smoother power transition • Better suited for integration with renewable energy sources	• Less mature power protection systems, posing risks • Higher up-front costs • Limited market familiarity and less compatibility with AC loads. • Potential for voltage drops in large systems without reactive power • More complex and costly to retrofit from AC to DC conversion • DC generators are less efficient than AC, and rectifiers may be required • High up-front costs for retrofitting and infrastructure • More prone to short-circuit and ground faults, requiring additional safety measures • Decentralised control systems can result in more independent failure points	• Ideal for applications like critical infrastructure in the military (servers, communication devices) and remote or DC power needs • Effective for rural electrification, telecom installations, and data centres • Support integration with energy storage solutions and EVs • Suited for spacecraft power systems • Facilitate renewable energy integration in isolated or off-grid areas

5.5 Design and Operation Criteria for Military Microgrids

This section identifies the key factors in designing military microgrids.[260]

5.5.1 Guidelines for Designing Microgrids within Power System Infrastructure

Defining a microgrid boundary requires a customised approach, considering factors such as the location of critical assets, the proximity and capacity of DERs, and the layout of the local distribution network. Table 15 summarises a straightforward process for selecting a portion of the power system that can be configured as a microgrid.[261]

Table 15. Guidelines for defining microgrids within power systems

Step	Guideline for defining microgrid boundaries
1. Identify essential power assets and their locations	Ensure the microgrid area covers all vital assets, taking into account their physical location and power demand
2. Evaluate local DERs	Design the microgrid with local DERs for critical loads, and expand or add new units if needed during outages
3. Select an isolatable feeder section	The microgrid boundary should include essential assets, DERs, and a feeder that can disconnect from the main grid during outages. Additional switches may be needed for effective islanding

5.5.2 Design Criteria for Microgrids Focused on Robustness, Resilience and Security Needs

The design of a microgrid is shaped by the system's need for robustness, resilience and security.[262]

- **Robustness** refers to the system's ability to continue operating under disruptions or uncertain conditions.
- **Resilience** describes the system's ability to recover quickly from failures or disturbances.
- **Security** is the system's capacity to remain intact following outages or equipment failures.

Table 16 summarises key microgrid design criteria intended to enhance robustness, resilience and security according to the specified technical and operational requirements.

Table 16. Suggested design criteria for enhancing robustness, resilience and security

Requirement	Suggested design criteria
Enhancing system robustness	• Implement alternative power feeds to enable selected loads to receive energy from multiple utilities
Enhancing system resilience	• Deploy intelligent switches and the required communication technologies to facilitate automatic restoration from alternate power sources
Enhancing power system security	• Integrate DERs, including renewable energy and energy storage, to power critical assets during grid outages • Determine the type and capacity of DERs based on the size and needs of mission-critical assets • Install load-shedding mechanisms to disconnect non-essential loads during emergencies when supply is limited • Set up a microgrid master controller and communication technology to manage and coordinate all microgrid components

5.5.3 Selecting the Types and Sizes of Distributed Energy Resources Based on the Needs of Mission-Critical Facilities

The selection of a system will be influenced by the nature of the mission-critical facilities. In this regard, Table 17 provides an overview of suggested design criteria for determining the appropriate types and sizes of DERs in accordance with the requirements of these essential facilities.[263]

Table 17. Guidelines for selecting types and sizes of distributed energy resources based on needs of mission-critical facilities

Type of critical load	Recommendations for DER types and sizes
Mission-critical facilities requiring uninterrupted operation	• Use fossil fuel generators alongside storage systems to ensure continuous operation for mission-critical facilities • Suitable fossil fuel generators include internal combustion engines (diesel, natural gas, or dual fuels), microturbines, and fuel cells • Energy storage options may include battery systems or flywheels, with energy storage maintaining critical loads during the transition to islanded mode. Flywheels are ideal for short-term support (under 30 seconds), while batteries are suited for longer durations (one hour or more) • The size of fossil fuel generators should meet or exceed the power requirements of critical assets, influenced by fuel availability and budget. Operation length depends on fuel supply or storage capacity • Energy storage should be sized to meet critical load demands during transitions, with the energy capacity based on the needed backup duration
Mission-critical facilities with tolerable brief interruptions	• Use fossil fuel generators for loads that can handle brief interruptions • The capacity of DER units should meet or exceed the power needs of critical assets, with generator run time depending on the available fuel supply or storage capacity

5.5.4 Potential Criteria for Prioritising Load Shedding in Microgrids

In many microgrids, the selected capacity of DERs is typically only enough to meet the demands of critical loads. As a result, it may be necessary to reduce or disconnect certain non-essential loads. Table 18 outlines the procedures for prioritising loads within a microgrid.[264]

Table 18. Load prioritisation steps and expected outcomes in a microgrid

Procedures for load prioritisation	Anticipated outcomes
1. Carry out a comprehensive inventory of loads (i.e., identifying building functions and their kW capacities) within the defined microgrid area	• Loads can be categorised according to their respective building functions, such as: • administrative offices • barracks • vehicle wash facilities • cafeterias • medical centres • storage areas • additional facilities
2. Assess and rank the loads based on their building functions	• Prioritise loads from highest to lowest, including their kW requirements (e.g., hospitals first, followed by dining facilities, barracks, administrative offices, car washes, and storage areas) • This prioritisation allows for flexible disconnection or reconnection of loads based on their importance as needed

5.5.5 Describing the Strategies for Microgrid Operations in Grid-Connected and Islanded Modes

Table 19 outlines the suggested operational strategies for microgrids in both grid-connected and islanded states, including the procedures for transitioning between these modes.[265,266,267]

Table 19. Operational strategies in grid-connected and islanded modes

Operation mode	Strategies for microgrid operation
Grid-connected mode	• When the utility grid is operational, load shedding should not be necessary, and all DERs must comply with IEEE Standard 1547 • Optimise the use of generated electricity in systems with renewable energy sources like solar panels • Distributed generators and battery storage can be used to reduce peak demand and avoid high costs during peak periods • Diesel generators used for peak shaving typically have operational hour limits (e.g., 250 hours/year at Fort Bragg, 40 hours/year in California), requiring strategic planning to maximise their benefits • Battery storage systems need careful scheduling for charging and discharging to ensure optimal use • Demand response measures, such as adjusting HVAC temperature settings, can help further reduce peak demand
Transition to islanded mode	• Transitioning to islanded mode can be planned (e.g., initiated by a customer during severe weather) or unplanned (e.g., due to loss of voltage or frequency) • For unplanned transitions, it is essential to detect abnormal grid conditions through: • monitoring voltage and frequency • sensing current (magnitude and direction) • monitoring power flow (magnitude and direction) • other methods like detecting phase shifts or parameter changes • Additional equipment, such as transient damping, may be needed to prevent protective relays from tripping DERs

Operation mode	Strategies for microgrid operation
Islanded mode	• Before operating in islanded mode, each DER must meet IEEE Standard 1547 requirements • Comprehensive system studies, including load-flow and stability analyses, should be conducted to assess potential risks for islanded operations • Locally available DERs must supply both real and reactive power to meet the demands of critical loads • Frequency stability should be maintained, and operations must stay within the voltage parameters specified by AS/NZS 61000.2.2:2003 • Voltage regulation devices may need adjustment to meet microgrid requirements in islanded mode • Internal DERs should have sufficient reserve margins, considering load factors, peak loads, reliability, and availability • To balance load and generation: • each phase should be evaluated for load and generation balance • if load exceeds generation, load shedding or demand response may be needed • DER output adjustments may be necessary to align with demand • Coordination of protective devices should be maintained in both grid-connected and islanded modes • In systems with renewable energy, efforts should be made to fully utilise generated electricity • Fossil fuel based DERs should be operated based on their merit order

Operation mode	Strategies for microgrid operation
Reconnection/ resynchronisation mode	• Before reconnecting to the main grid, the voltage must be within the specified limits (230 V for single-phase or 400 V for three-phase) and the frequency should be stabilised within the range of 49.85 Hz to 50.15 Hz within five minutes • The reconnection device may delay the process for up to five minutes after the voltage and frequency have been restored • DERs must be capable of adjusting island voltage and frequency to synchronise with the utility grid effectively

5.5.6 Key Standards and Necessary Criteria for the Design and Operation of Microgrids

Table 20 outlines the necessary criteria and standards for assessing the design and operational capability of a microgrid, focusing on its ability to function in an islanded mode by detailing required system studies, essential data collection from site assessments, and key standards for effective microgrid development.[268,269,270,271,272,273,274]

Table 20. Standards for design and operation of microgrids

Criteria/standards	Details/description
System studies needed for islanded functionality	• To evaluate if the designed microgrid (including its boundary, DER specifications, and load prioritisation/shedding strategies) can operate in islanded mode, the following system studies are required: • Load-flow analysis • Short-circuit analysis • Protection coordination analysis • Transient stability analysis

Criteria/standards	Details/description
Data collection from site assessments	• **Load inventory**: Information on the size, function and location of all loads • **Internal generation inventory**: Details on the location, size, type, characteristics, fuel sources, and black-start capabilities of internal generators • **Distribution circuit component inventory**: Specifications for distribution line length, characteristics, capacitor banks, voltage regulation devices, protection mechanisms, and transformers • **Operating parameters**: Acceptable values for frequency, voltage, phase imbalance, and harmonic distortions • **Protection devices and their settings**: Parameters for overcurrent, short circuits, and other faults to protect the system from damage
Key standards for microgrid development	• **AS/NZS 61000.2.2:2003** (identical adoption of IEC 61000-2-2:2002): Standard for permissible levels of frequency in low-voltage power supply systems • **AS/NZS 4777.1:2016**: Standard for grid connection of energy systems via inverters, Part 1 • **AS/NZS 4777.2:2020**: Standard for grid connection of energy systems via inverters, Part 2 • **AS/NZS 60255.127:2025**: Standard for measuring relays and protection equipment: functional requirements for over/under voltage protection • **AS/NZS IEC 60904.1:2023**: Standard for photovoltaic devices, Part 1: Measurement of photovoltaic current-voltage characteristics • **AS/NZS IEC 60331.2:2021**: Standard for testing electric cables under fire conditions • **AS/NZS IEC 60947.4.2:2015**: Standard for low-voltage switchgear and controlgear, Part 4.2: Contactors and motor-starters—AC semiconductor motor controllers and starters

Criteria/standards	Details/description
Key standards for microgrid development	• **ANSI/NEMA MG 1-2006**: Standard for motors and generators • **IEEE Std 399™-1997**: Recommended practices for industrial and commercial power systems analysis (known as the IEEE Brown Book™) • **IEEE Std 446™**: Recommended practices for emergency and standby power systems for industrial and commercial uses (the IEEE Orange Book™) • **IEEE Std 519™**: Recommended practices and requirements for harmonic control in electrical power systems • **IEEE Std 1100™**: Recommended practices for powering and grounding electronic equipment (the IEEE Emerald Book™) • **IEEE Std 1547™-2003**: Standard for connecting distributed resources to electric power systems • **IEEE Std 1547.2™**: Application guide for the integration of distributed resources with electric power systems • **IEEE Std 1547.3™-2007**: Guide for monitoring, information exchange, and control of distributed resources connected to electric power systems • **IEEE Std 1547.4™-2011:** Guide for the design, operation, and integration of distributed resource island systems with electric power systems

5.6 Identifying Key Challenges and Priorities for Advancing Military Microgrid Technologies

Current military microgrids encounter issues such as voltage fluctuations, system instability, and reduced reliability due to aging systems and insufficient updates with new technologies. Table 21 and Table 22 offer an overview of capability categories, essential enabling technologies, and insights into specific identified limitations.[275]

Table 21. High-priority investments for enhancing military microgrid technologies (ordered by significance)

Functional part	Sub-functional part	Facilitating technology	Statement/challenge	Plan
Demand management	Plug-level	Information networking (e.g., wire mesh, programmable logic controller)	Essential for creating a dynamic, reconfigurable and self-healing microgrid, which means this technology facilitates point-to-point communication without the need for physical data cables.	Long term
DER management	Legacy generators	Advanced controls (prognostic and diagnostic)	The integration of real-time prognostic and diagnostic systems significantly enhances microgrid control, but leveraging modelling and simulation for cost-benefit analysis is vital to fully determine the actual advantages of prognostic and diagnostic technology.	Long term
	Decreased human involvement	Self-operated control capability	This technology empowers microgrid control systems to automatically respond to equipment malfunctions by employing pre-programmed contingencies and sequencing protocols.	Short term

Functional part	Sub-functional part	Facilitating technology	Statement/challenge	Plan
Communication systems	Peer to peer	Rapid send-receive methods	Modelling and simulation are required to develop strategies for managing the growing volume of data in low-bandwidth settings. Developing effective protocols and techniques to mitigate latency challenges is essential.	Short term
	Ad hoc reconfiguration	Recovery from communication failures	These are technologies that allow microgrids to maintain operations during communication disruptions. They should efficiently handle and prioritise essential data to ensure timely coordination of resources.	Short term
Demand management	Distribution sides	Energy storage systems	Widespread energy storage systems are essential for integrating renewable energy sources into the microgrid effectively.	Long term

Table 22. Moderate priority investments for enhancing military microgrid technologies (ordered by significance)

Functional part	Sub-functional part	Facilitating technology	Challenge/suggestion	Plan
Power distribution	Managing transients	Frequency / renewable integration	The existing modelling and simulation are directed towards renewable energy source integration for static utility grids, while neglecting to assess their impact on reconfigurable networks.	Short term

Functional part	Sub-functional part	Facilitating technology	Challenge/suggestion	Plan
Communications	Peer to peer	Integration and security of mobile devices	A significant number of mobile devices and nodes connecting to a microgrid via a mesh network could overwhelm the system, necessitating a strategy for communication security.	Long term
	Ad hoc reconfiguration	Reliability in lost communication	There is a need for research to enhance the reliability of reconfigurable information networks in dynamic environments.	Long term
	Ad hoc reconfiguration	Mesh networking	The configuration of the microgrid network can significantly influence data transmission, including challenges related to frequency, signal length, and electromagnetic fields. Modelling and simulation will help identify resilient technological solutions.	Long term
Smart controls	Components	Component metadata	Utilising metadata could provide solutions for simplifying intricate challenges in reconfigurable networks.	Short term

Functional part	Sub-functional part	Facilitating technology	Challenge/suggestion	Plan
Power distribution	Storage facilities	Vehicle-to-grid technology	To explore tactical applications, it is essential to invest in modelling and simulation to comprehend the dynamic interactions between various DERs (EVs, batteries etc.).	Long term
	Managing transients	Fault identification and isolation	While many utilities have modelled these for power distribution, tactical grids generally function under low-voltage, high-current conditions, making it challenging to apply high-voltage utility electrical power models effectively.	Short term

5.7 Implemented Military Microgrid Configurations

The examples of microgrid configurations presented below identify which DERs are used in their development and illustrate the layouts of implemented microgrids.

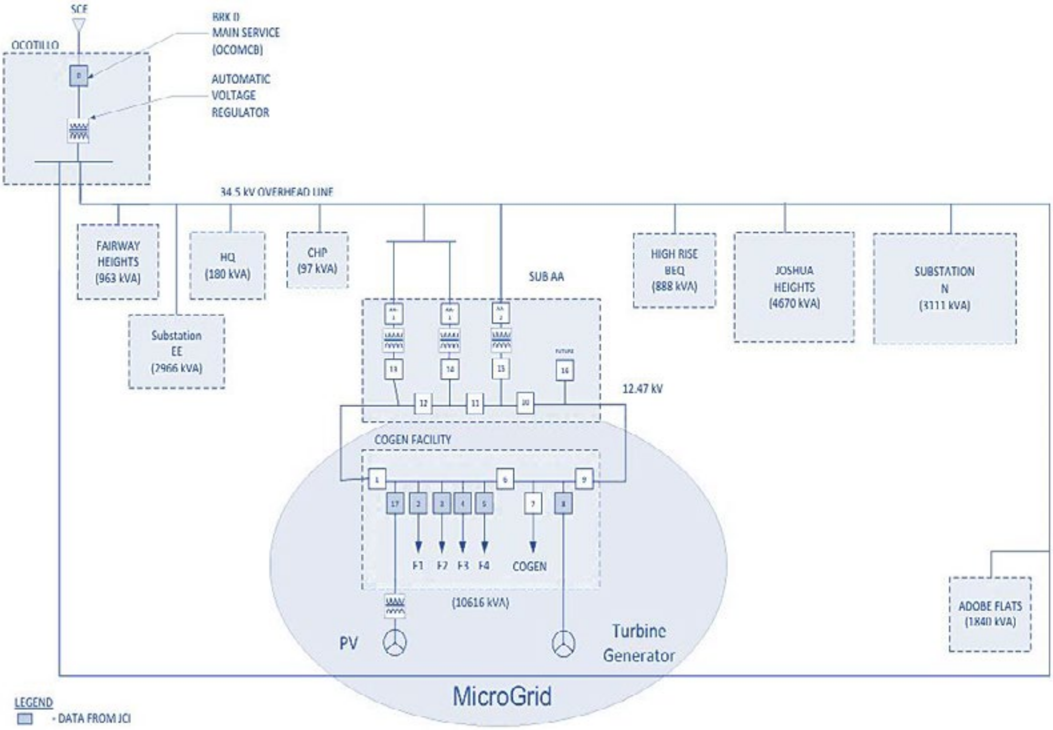


Figure 25. Diagram of Twentynine Palms Marine Corps site in the US[276]

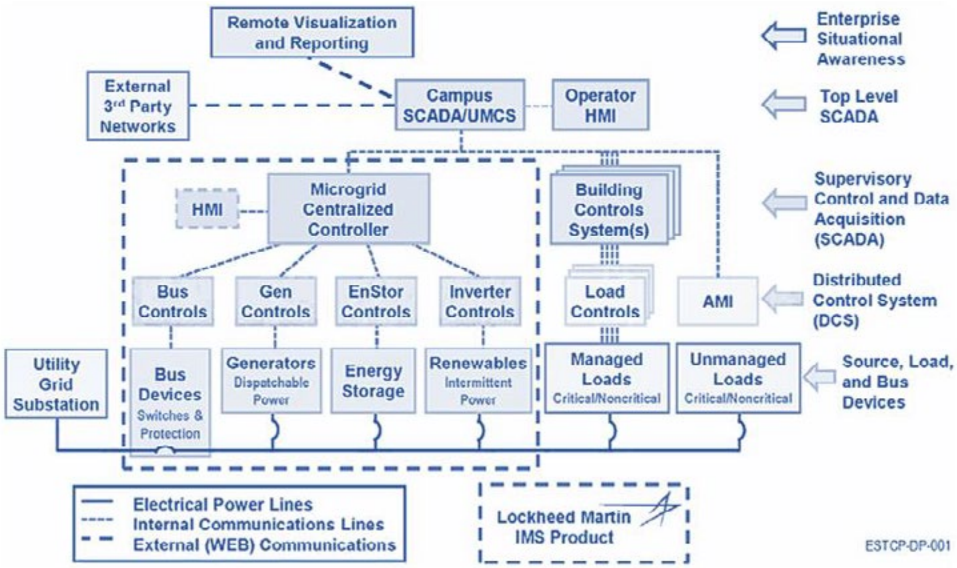


Figure 26. Diagram of Lockheed Martin's microgrid in the US[277]

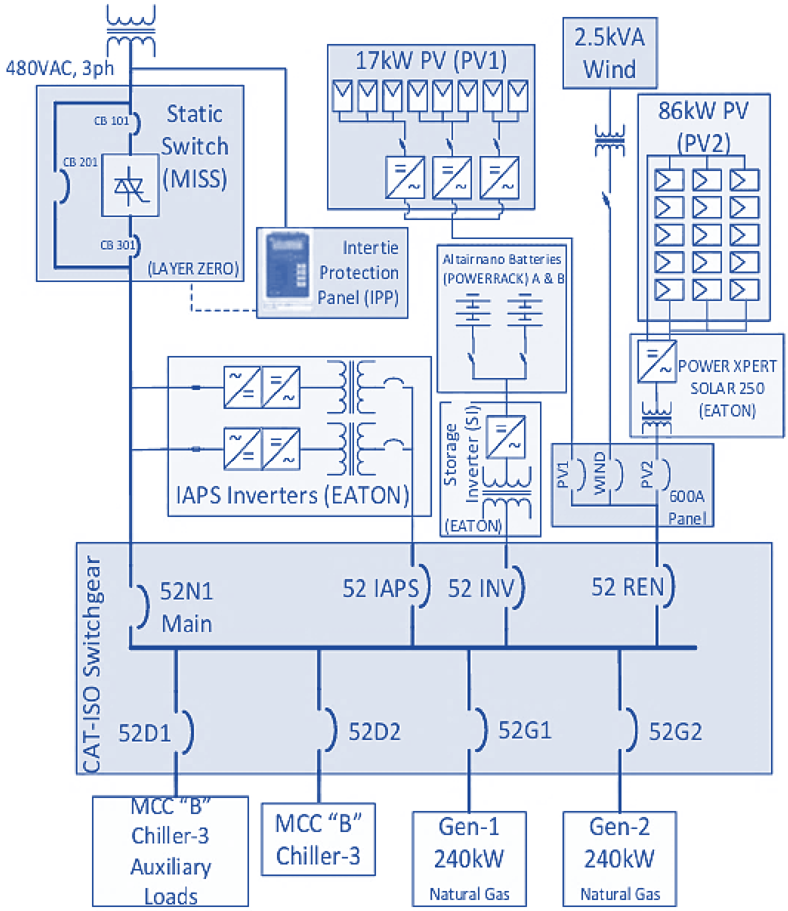


Figure 27. Single-line diagram of Fort Sill microgrid system[278]

5.8 Geographical Distribution of Microgrids

Figure 28 indicates that the US is a leading pioneer in deployment of microgrids, which are located in many of its states.[279] Figure 29 illustrates that many remote regions in Australia, which are located far from the central power grids, rely on off-grid microgrids for their electricity needs.[280] In Brazil, many microgrids are predominantly powered by diesel generators (shown in Figure 30). The available microgrid demonstrations in China are illustrated in Figure 31.[281] Remote areas in Canada are not connected to the North American grid,[282] so these parts are supplied by fossil fuels, as shown in Figure 32. Europe deploys different resources to supply the load demands, as shown in Figure 33.[283] These figures focus on the geographical distribution of microgrids in general, whereas Figure 34 specifically illustrates the geographical distribution of military-based microgrids in the US.[284]

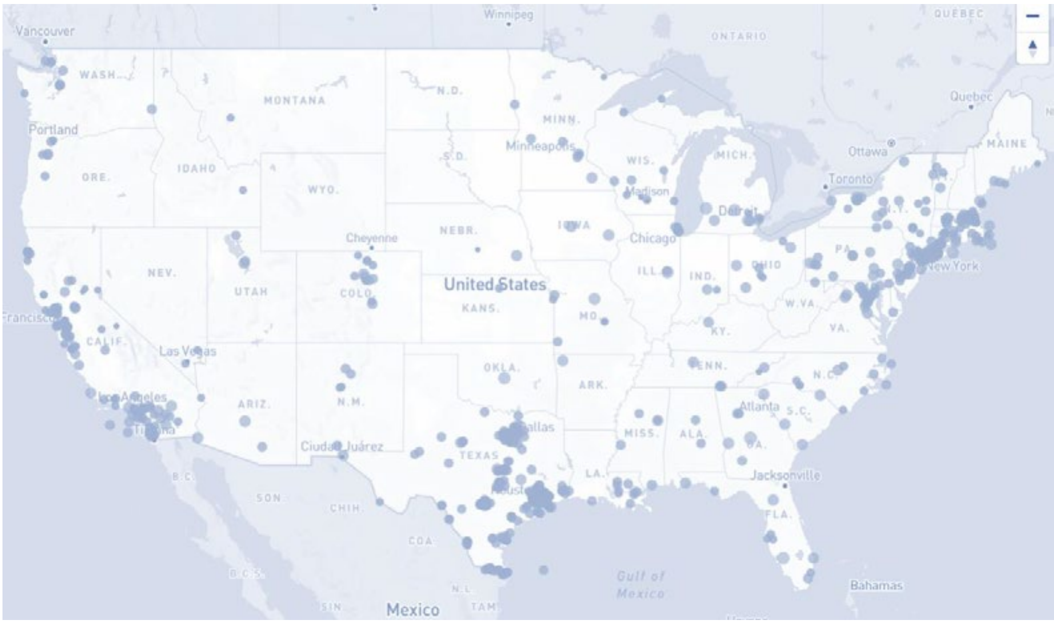


Figure 28. Geographical distribution of microgrid installations across the US[285]

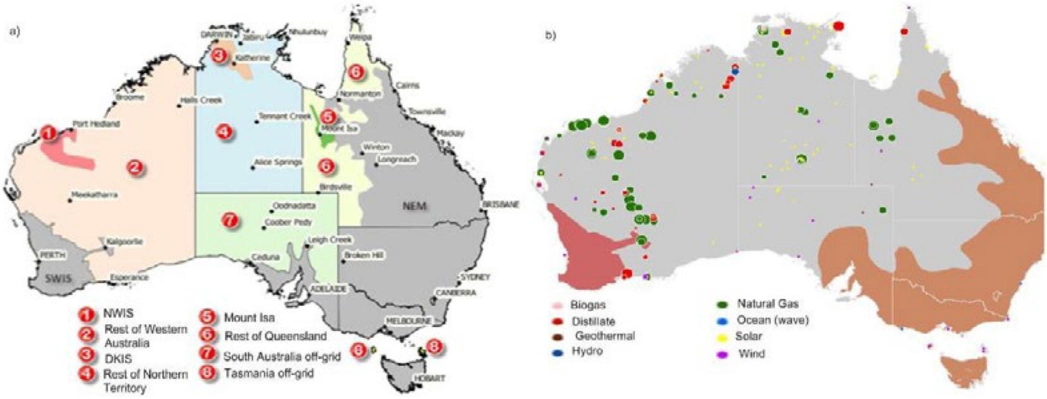


Figure 29. a) Map of off-grid areas in Australia; b) Map of off-grid electricity generation in Australia[286]

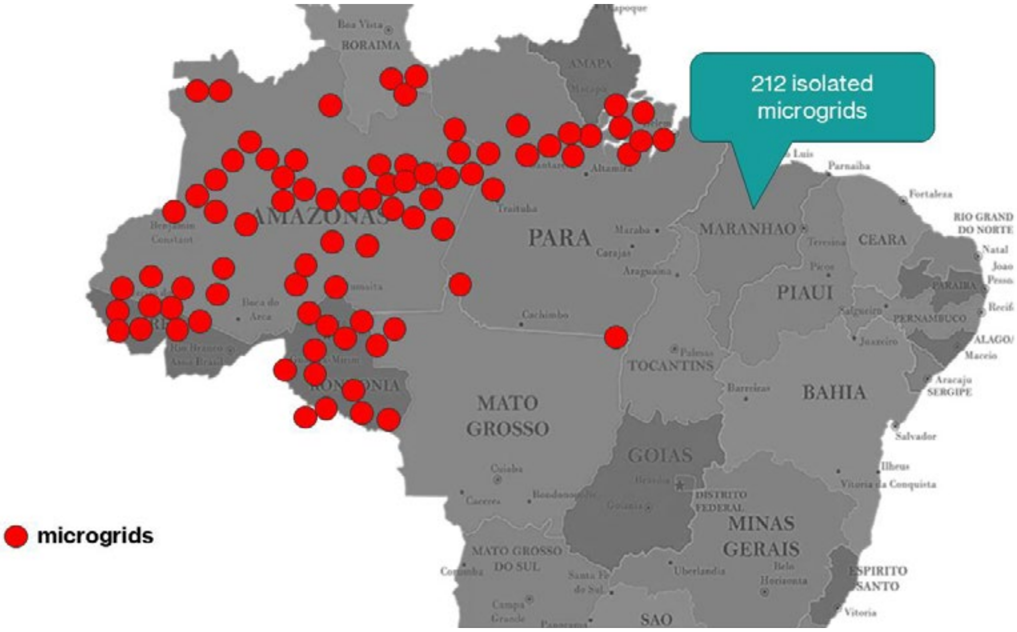
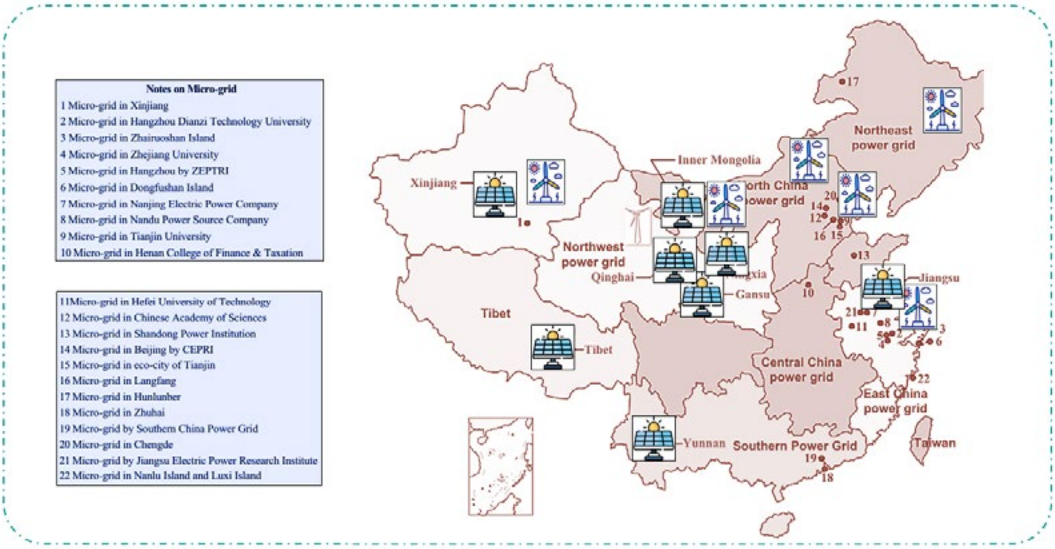


Figure 30. Mapping of microgrids in Brazil[287]


Notes on Micro-grid
1 Micro-grid in Xinjiang
2 Micro-grid in Hangzhou Dianzi Technology University
3 Micro-grid in Zhairuoshan Island
4 Micro-grid in Zhejiang University
5 Micro-grid in Hangzhou by ZEPTRI
6 Micro-grid in Dongfushan Island
7 Micro-grid in Nanjing Electric Power Company
8 Micro-grid in Nandu Power Source Company
9 Micro-grid in Tianjin University
10 Micro-grid in Henan College of Finance & Taxation

11Micro-grid in Hefei University of Technology
12 Micro-grid in Chinese Academy of Sciences
13 Micro-grid in Shandong Power Institution
14 Micro-grid in Beijing by CEPRI
15 Micro-grid in eco-city of Tianjin
16 Micro-grid in Langfang
17 Micro-grid in Hunlunber
18 Micro-grid in Zhuhai
19 Micro-grid by Southern China Power Grid
20 Micro-grid in Chengde
21 Micro-grid by Jiangsu Electric Power Research Institute
22 Micro-grid in Nanlu Island and Luxi Island

Figure 31. Examples of microgrids in China[288]

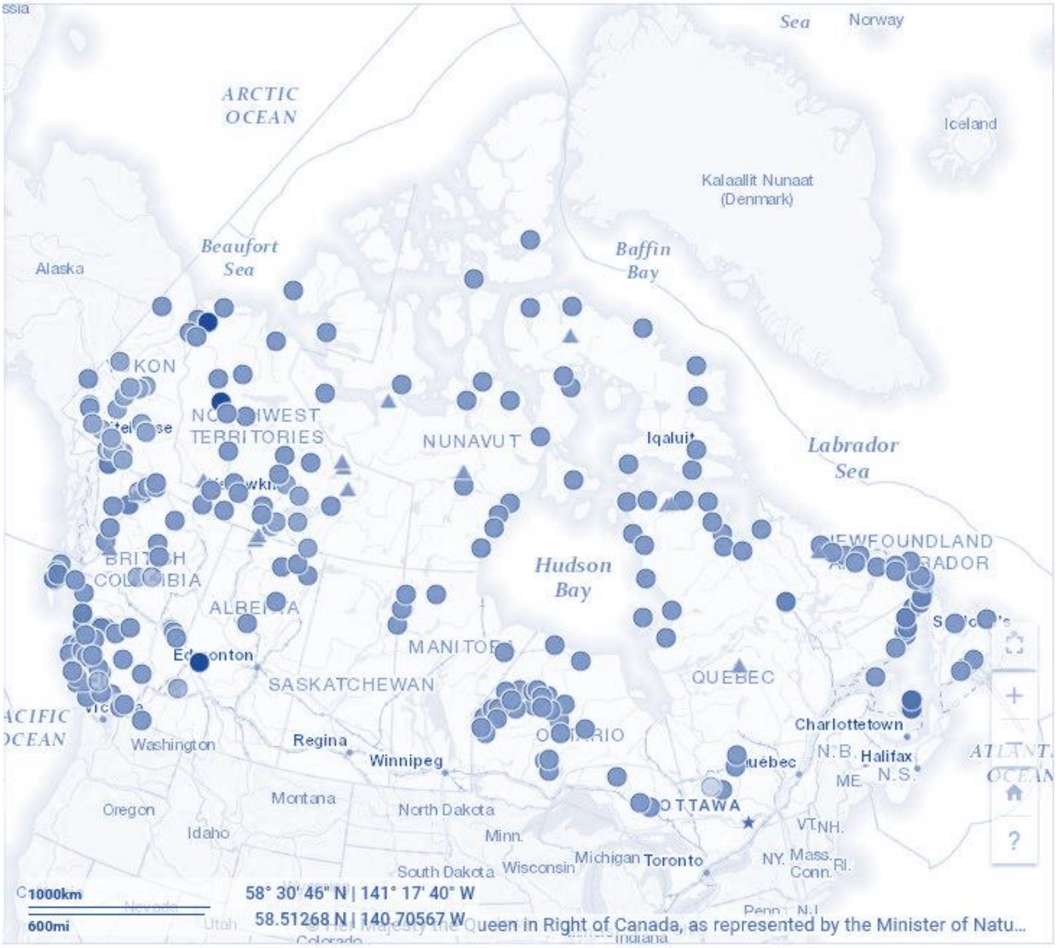


Figure 32. Off-grid areas of Canada supplied by distributed energy resources (often diesel and fossil fuels)[289]

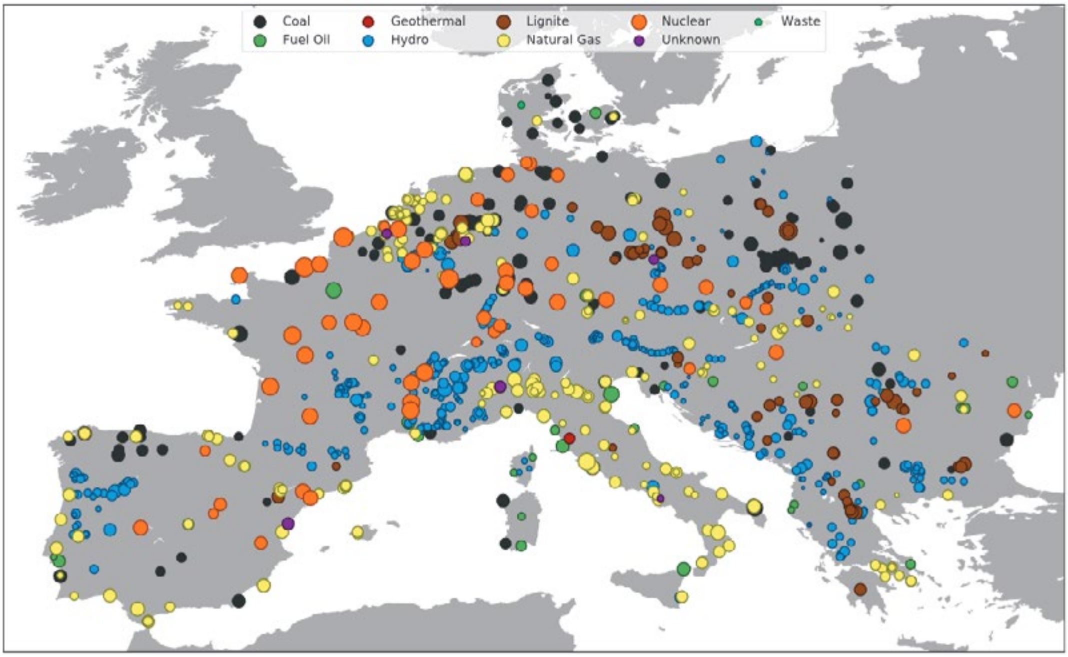


Figure 33. Use of distributed energy resources in Europe[290]

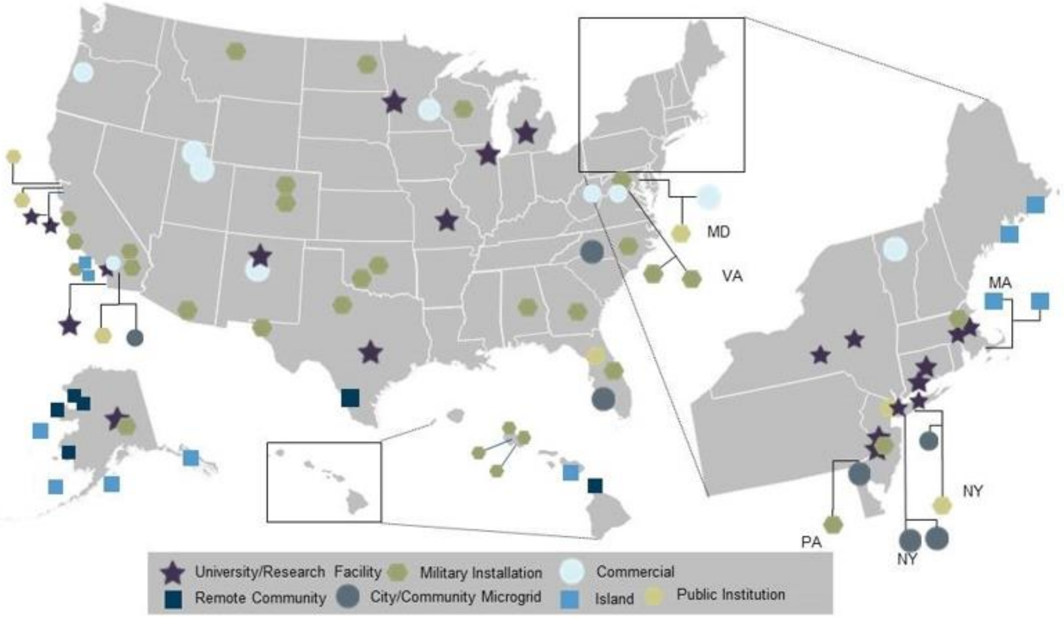


Figure 34. Geographical distribution of military-based microgrids in the US[291]

6. Risk and Vulnerability Assessment of Independent Energy Systems

6.1 Cyber-Physical Description of Smart Microgrids

To interface DERs, microgrids heavily depend on power electronics converters—energy storage, EVs etc. In these systems, physical and electrical components are closely integrated and interconnected through information and communication technologies. Their functionality is intricately linked to the operation of cyber systems, elaborated as follows.[292]

Figure 35 depicts a typical power electronics intensive microgrid that showcases these cyber-physical interactions. In this scenario, the cyber-physical framework of a smart microgrid is organised into four primary layers: the physical power system layer, the sensor and actuator layer, the communication layer, and the management and control layer.

- **Physical layer:** It includes essential power components such as transformers, generators, power electronics converters, circuit breakers, and loads.
- **Sensor and actuator layers:** These feature devices that monitor system states such as voltage, frequency, current and circuit breaker status, alongside control mechanisms that implement decisions made in the management layer, which encompass generator controllers, distributed generation controllers, and circuit breaker relays.
- **Communication layer:** It facilitates the exchange of information among the various layers through devices such as routers, switches and communication mediums, which can be either wired or wireless, depending on system needs.
- **Management layer:** It serves as the central control unit, coordinating the microgrid's operations under different conditions. It processes data from the sensor and actuator layer via the communication layer and generates control signals for optimal performance, which are then sent to the actuators.

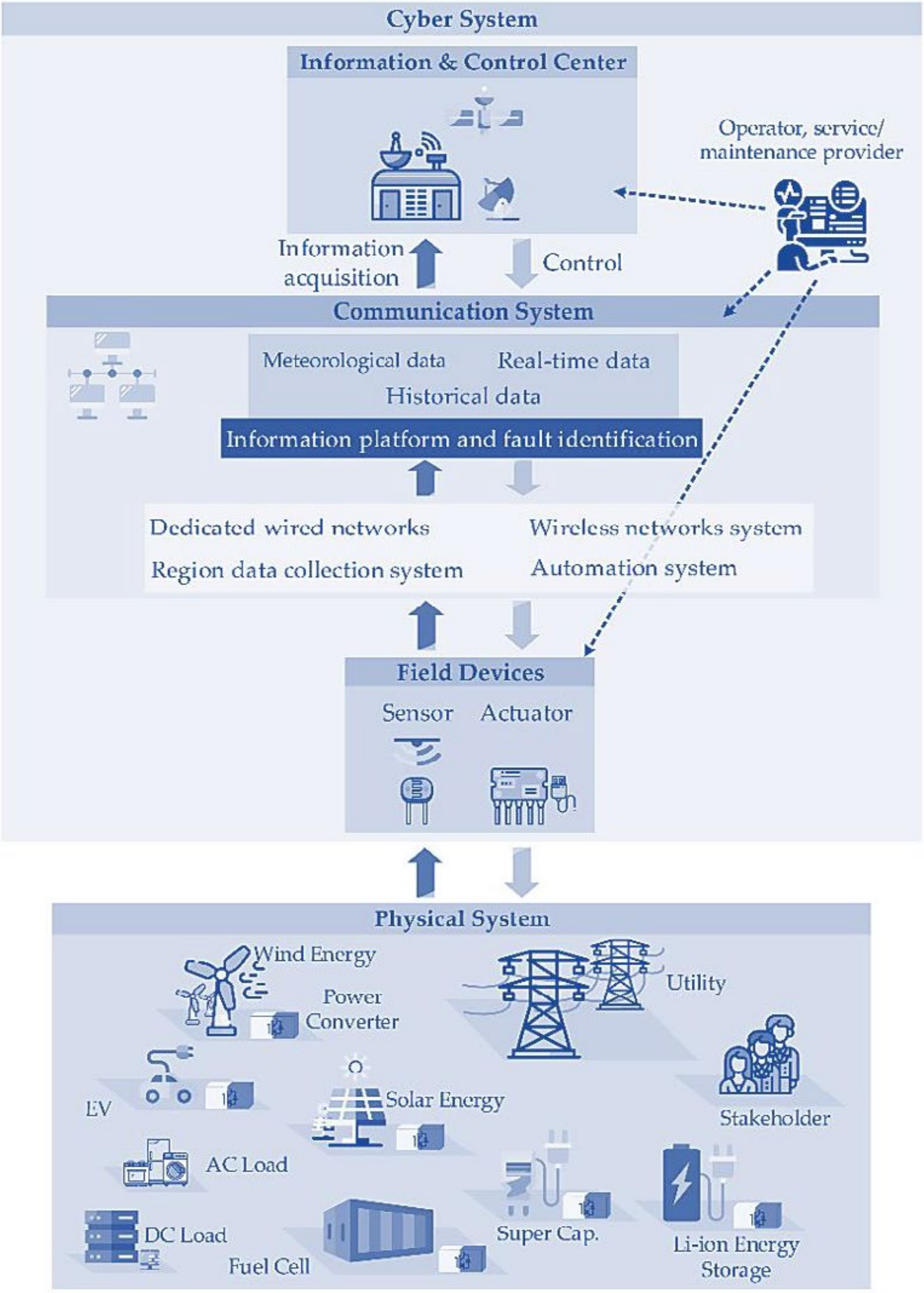


Figure 35. Typical microgrid with cyber-physical features[293]

6.2 Targets of Cyber Attacks on Smart Microgrids

Cyber attacks are deliberate attempts to disrupt, damage or gain unauthorised access to digital systems, and they pose a growing threat to smart microgrids.[294] These attacks can affect all layers of the cyber-physical framework by corrupting control logic in the management layer, intercepting or jamming signals in the communication layer, and sending false data through sensors. This section lists the components of microgrids that are most targeted by cyber attacks.

6.2.1 Targeting State Estimation

State estimation is vital for monitoring smart microgrids, involving the analysis of bus voltage and phase angles from measurements. Cyber attacks aim to disrupt this process by manipulating sensor data, leading to inaccuracies in state variables. Accurate state estimation supports microgrid management, including contingency assessments, load forecasting, and optimal power dispatch. Any false data injection (FDI) attacks that affect state estimation can cause significant disruptions in microgrid operations.[295,296,297]

6.2.2 Targeting Voltage of Microgrids

Voltage regulation in smart microgrids is controlled via power electronics linked to distributed and conventional generators. These systems monitor voltage and reactive power, allowing the control system to adjust reactive power references. Transformer tap changers can also regulate voltage. FDI attacks that manipulate sensor readings or control parameters can disrupt voltage regulation. Additionally, attackers may access the microgrid's control system, altering signals and introducing errors into power reference signals for generators and transformer tap changers.[298,299,300,301]

6.2.3 Targeting Frequency of Microgrids

Attacks on microgrid frequency, referred to as attacks on transient stability,[302,303] involve manipulating control signals, sensor measurements or power source outputs, which can disrupt frequency stability. Microgrid frequency control is particularly sensitive to variations in active power, frequency measurements and reference signals. Typically, frequency regulation is achieved using rotating machines, so attacks on rotor speed or angle measurements can affect stability. Energy storage systems are increasingly used to improve transient stability,[304] and securing their measurement and control signals is essential to maintaining stable operations.

6.2.4 Targeting Protection Systems of Microgrids

One of the primary challenges confronting microgrids is the design of protection systems that operate reliably in both grid-connected and islanded modes. Relay settings must be appropriately adjusted based on the operational mode to ensure responsive protection against current levels. Adaptive protection strategies that comply with the IEC 61850 communication standard are frequently utilised, necessitating a secure, fast and reliable communication network.[305] However, any communication link failures or FDI cyber attacks can severely compromise the performance of these protection systems, potentially leading to catastrophic outcomes for microgrids.[306]

6.3 Strategic Priorities for Advancing Cyber Security Research and Development in Military Microgrids

A comprehensive review of cyber security research and development is crucial to pinpoint critical areas that demand intensified focus. Progress in the prioritised areas outlined in Table 23 is fundamental to advancing cyber security.[307]

Table 23. Research and development priorities in point of cyber security

Research area	Description	Required research
Authentication mechanisms	Developing secure, scalable authentication methods for devices and users within microgrids to ensure proper access control and data integrity	• Infrastructure for secure, distributed identity management across microgrid components • Management of certificates and revocation for microgrid assets • Integrating biometric and physical token authentication for operators and service personnel • Separating authentication from identification to enhance privacy and prevent unauthorised access in decentralised grid environments

Research area	Description	Required research
Securing core internet protocols	Enhancing the security of communication protocols used in microgrid networks to prevent attacks such as spoofing, data corruption or denial of service	• Security solutions for communication protocols within microgrid systems (e.g., SCADA, IoT protocols) • Secure communication for distributed energy resources and control systems • Balancing trade-offs between performance (e.g., latency) and security in energy systems
Software security engineering	Addressing gaps in software development practices specific to microgrid systems, ensuring resilience and reliable operation	• Security-focused programming for control software in microgrids • Secure, adaptable software for diverse microgrid environments (e.g., rural, urban) • Tools for defining and verifying security requirements in microgrid control systems • Verification and validation of control software for secure operation during faults or attacks
Integrated system security	Securing the interconnected systems that make up microgrids, ensuring they are resilient to attacks or failures	• Securely integrating renewable energy sources, storage systems and backup power into microgrid control networks • Proactive vulnerability reduction strategies for microgrid systems • Security for systems operated under adversarial conditions (e.g., grid manipulation or cyber attacks) • Handling insider threats from operators or maintenance personnel • User-centred security interfaces for grid operators

Research area	Description	Required research
Network monitoring and incident detection	Real-time monitoring and detection systems to ensure microgrid resilience against cyber threats	• Dynamic defence mechanisms in microgrids that adjust based on detected threats or attacks • Real-time intrusion detection systems for microgrid communication networks • Ensuring security policies are adhered to in grid operations and monitoring • Improved behavioural models for anomaly detection in energy usage and control systems
Rapid response and system recovery	Developing methods for microgrids to quickly detect disruptions and recover from cyber incidents, ensuring system continuity	• Automated detection of energy outages, cyber attacks or malfunctions in microgrid operations • Architectures for fast recovery of microgrid functions after a cyber attack or failure • Simplified, automated recovery systems to reduce human error during system restoration • Fault-tolerant designs to ensure that critical grid functions continue during incidents
Cyber forensics and crime deterrence	Building tools for tracing cyber attacks and improving forensics within microgrid environments to track threats	• Tracing the origin of cyber attacks on microgrid systems • Identifying cyber attackers based on behavioural patterns in energy management systems • Evidence collection and analysis within distributed microgrid networks • Improving forensics tools for energy theft or malicious tampering with grid data

Research area	Description	Required research
Modelling and testing new cyber technologies	Simulating and testing cyber security measures within microgrid environments to improve resilience and effectiveness	• Creating simulation environments for testing cyber security in microgrids, including interactions with the main grid • Validation of security systems and protocols in large-scale microgrid simulations • Data collection for improving threat models specific to microgrid architectures • Creation of confidential testbeds for validating cyber defences in microgrids
Security standards and best practices	Establishing cyber security standards and best practices tailored for microgrid systems	• Development of security benchmarks and metrics for evaluating microgrid cyber security • Risk analysis and economic impact evaluations of potential cyber attacks on microgrid operations • Tools for assessing compliance with microgrid-specific security standards • Documentation of best practices for securing microgrid configurations and operations
Human and societal cyber security factors	Exploring human and societal factors that affect the cyber security of microgrids	• Raising awareness about cyber security risks and best practices for microgrid operators • Addressing privacy concerns related to the data collected by microgrids and their integration with smart grid systems • Studying human factors in energy management software and interactions within microgrid environments • Analysing how societal perceptions of energy security impact the adoption of secure microgrid technologies • Understanding legal and regulatory concerns surrounding the cyber security of decentralised energy systems

6.4 Examples of Real-World Cyber Attacks on Energy Infrastructure

Table 24 presents some examples of cyber attacks conducted against energy infrastructure around the world.[308,309,310] As can be seen, Australia is among the countries to have experienced significant cyber incidents within the energy sector in recent years.[311,312,313]

Table 24. List of real-world attacks on the energy sector

Location	Incident description	Impact
Washington State, US	Four substations near Tacoma were targeted to cut power for burglary	Significant power disruption
Moore County, NC, US	Intruders breached gates and opened fire on two substations	Outage affecting nearly 50,000 people
Clackamas County, OR, US	Two intruders cut the fencing and shot at the equipment, causing significant damage to the substation	Significant equipment damage
Maryland, US	Authorities foiled a conspiracy to attack multiple substations around Baltimore	Intended to create chaos and unrest
Ohio, US	An extremist plot to attack power infrastructure was blocked	Prevented potential attacks
San Jose, CA, US	A man detonated explosives at two transformers, cutting power for thousands. Additional explosives were found at his home	Power disruption for thousands; potential for more damage
Ukraine (2015)	Remote hackers compromised Ukrainian energy grid operators, seizing control of substations	Power outage affecting 225,000 customers for several hours
Ukraine (2016)	Hackers deployed malicious code targeting a Kiev transmission station	Major blackout in the capital lasting over an hour
United Kingdom	Leaked reports indicated that hackers may have infiltrated Britain's energy grid	Potential exposure of critical infrastructure to cyber attacks
Sweden	Cyber attack on the Swedish transport network caused delays	Significant disruption to train schedules and travel services
Australia	The company of CS Energy was disrupted in 2021 by an attack on the company's IT systems by the Conti ransomware group	Disruptions to the production of electricity, affecting the safety of Australia's vital infrastructure

Location	Incident description	Impact
Australia	A breach at Energy Australia resulted in the exposure of hundreds of its customers' personal information	Weaknesses in the cyber security of the energy industry jeopardised client data

7. Strategic Exploration of Supply Chain Resilience: Challenges and Alternatives

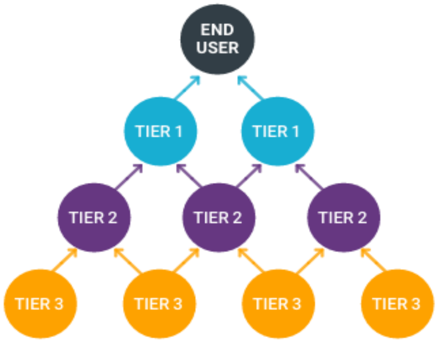
7.1 Supply Chains and Critical Products within the Defence Sector Landscape

In Australia, major global defence corporations, known as 'primes', manage complex supply chains for government, while small and medium-sized enterprises have also developed their own capabilities within the industry.[314] Supply chains are not just a simple flow of goods but are characterised by three key interdependent flows: material flows (movement of goods), capital flows (commercial relationships), and knowledge flows (intellectual property and expertise transfer). These flows create long-term, institutionalised relationships among nations and firms. Modern supply chains should be viewed as complex webs rather than linear sequences, with interconnected nodes and overlapping connections, as shown in Figure 36. Criticality plays a pivotal role in the resilience of global supply chains. Supply chains with critical nodes, such as diamond or hourglass structures, are less adaptable to disruptions, whereas branching models without critical nodes offer more flexibility. These critical nodes are often hidden from downstream users, as seen in Figure 37, which depicts the global battery production supply chain. China dominates key midstream components, even though the upstream and downstream stages involve a diverse range of suppliers.

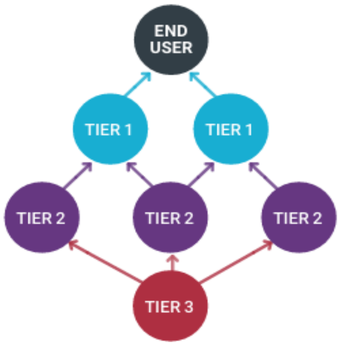
Defence supply chains are particularly complex due to several factors:

- High economic importance for national security
- Increased concentration due to strict design and security requirements
- Reliance on imports by smaller nations
- Intellectual property needs for long-term relationships
- Geopolitical risks that disrupt the flow of critical components
- Longer supply chains with advanced technology requiring multiple tiers.

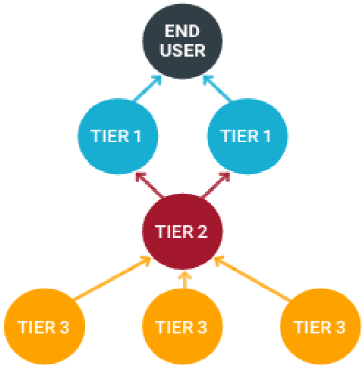
These unique challenges make defence supply chains more prone to risk and require tailored risk management strategies beyond standard commercial practices.



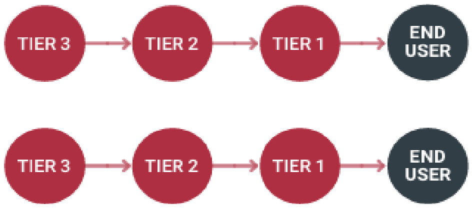
Branching supply chains: This supply chain model, sourcing inputs from multiple suppliers, is competitive and resilient, as it reduces dependency on any single participant, thereby lowering vulnerability at critical points.



Diamond supply chains: In this supply chain model, downstream users rely on various suppliers, each depending on a single upstream source. This concentration creates a critical node at the upstream level, making it a vulnerability for the entire chain.



Hourglass supply chains: In this supply chain model, numerous downstream users and upstream suppliers are involved, yet the system is heavily reliant on a single pivotal player at the midstream stage. This concentration of control at the midstream creates a critical node, making both ends of the value chain dependent on its smooth operation.



Linear supply chains: In this supply chain model, each downstream user oversees its own network of midstream and upstream suppliers, with every link acting as a critical node. This structure is the least resilient, making it rare and typically limited to highly specialised products where such intricate control is necessary.

Figure 36. Different supply chain configurations (critical nodes are shown in red)

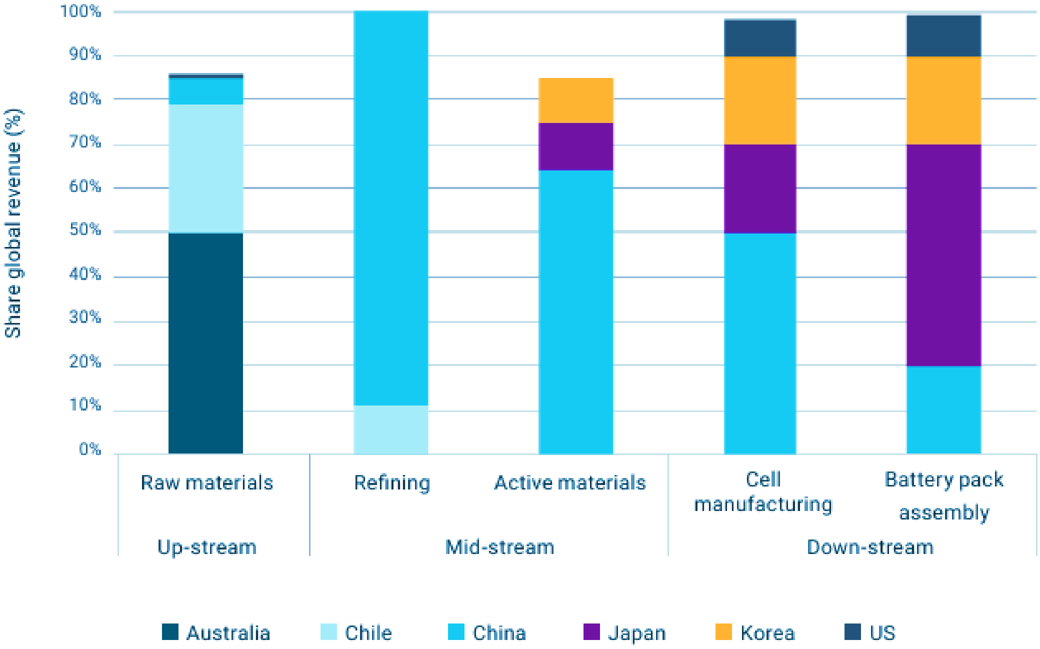


Figure 37. Distribution of country shares in the battery value chain across different production stages

7.2 Identifying and Addressing Supply Chain Vulnerabilities in the Defence Sector

Mapping a supply chain's framework is an essential initial step in pinpointing potential risks, particularly when attempting to identify crucial nodes that could lead to disruptions. The next phase of supply chain vulnerability involves assessing the probability that these risks will result in actual interruptions. Various factors can trigger such disruptions, and these can be divided into two broad categories: traditional and strategic supply chain risks.[315]

Traditional supply chain risks have long been present and affect industries universally. These include:

- **Economic risks:** Abrupt changes in demand or technological innovations that create short-term shortages of vital products. A recent example is the global semiconductor shortage in 2021, which led to production halts in the automotive industry and contributed to a worldwide shortage of cars.

- **Infrastructure and connectivity risks:** Delays in logistics, customs clearance, or transportation that disrupt the flow of goods. Examples include the six-day blockage of the Suez Canal in 2021, ongoing congestion at US ports, and COVID-19-related disruptions at key Chinese ports.
- **Natural disaster risks:** Events such as fires, floods, droughts and pandemics that interfere with normal business activities. The COVID-19 pandemic and natural disasters in Taiwan and Japan, which exacerbated the semiconductor shortage, are prime examples.
- **Societal conflict risks:** These include large-scale protests, civil unrest, and industrial strikes, often affecting resource-based industries. For instance, civil unrest in Kazakhstan disrupted oil and uranium supplies, while labour strikes at Fremantle Ports in Western Australia threatened the building sector.

These risks are recurring and inherent in the global economy, and businesses typically manage them with established practices such as inventory control and supplier diversification. Though significant, these risks are not unique to the defence sector and affect all industries. They tend to be random events that companies must be prepared to address when they arise.

On the other hand, strategic supply chain risks have emerged more recently and are particularly relevant to the defence industry. These risks arise from shifts in the broader geopolitical landscape. They include:

- **Geopolitical intervention risks:** Government actions that deliberately disrupt supply chains for political or strategic reasons, such as trade sanctions or embargoes—for example, China’s sanctions in response to diplomatic tensions with Australia or the US’s security-related restrictions on Chinese tech firms.
- **Geopolitical demand risks:** These risks arise when geopolitical events swiftly alter supply chain demands, such as the exclusion of specific suppliers due to political conflicts or a sudden surge in demand for defence goods during times of geopolitical instability.
- **Security risks to intangible assets:** These risks encompass cyber attacks, intellectual property theft, and breaches of sensitive information, targeting the flow of knowledge within the supply chain rather than physical goods.

Strategic risks differ from traditional risks because they are intentional, politically driven, and often designed to undermine the integrity of the supply chain. While these risks exist in all industries, they are particularly concerning for defence-related sectors, which are primary targets for politically motivated attacks. Additionally, strategic risks are becoming more prevalent due to growing digitalisation and intensifying global tensions.

To manage these risks, companies in global industries typically implement a range of supply chain management strategies, which can generally be divided into two categories:

- **Efficiency-driven models,** which focus on minimising costs and maximising speed to stay competitive. Examples include offshoring and 'just-in-time' (JIT) strategies.
- **Resilience-oriented models,** which prioritise flexibility and risk management, often at the expense of efficiency. This includes strategies like 'just-in-case' (JIC), where companies maintain larger inventories to buffer against disruptions.

These strategies are not mutually exclusive but lie on a spectrum. Companies select their approach based on the likelihood and impact of potential risks. In industries where disruptions are rare and their consequences are minimal, efficiency-oriented strategies like JIT are favoured. However, in sectors facing more frequent or severe risks, resilience-focused strategies are preferred.

When companies seek to strengthen resilience in their supply chains, they can implement various risk mitigation strategies, each with different costs and effectiveness:

- **Strategic inventories:** Keeping additional stock to manage temporary disruptions. This is cost-effective for risks that resolve quickly but may not be suitable for products with limited shelf life or low demand.
- **Supplier diversification:** Broadening the supplier network to reduce dependency on any one source, ideally across different regions to mitigate risks associated with national-level disruptions.
- **Friend-shoring:** Collaborating with trusted partners who are less likely to introduce supply risks, either at a national or a corporate level. This strategy is useful when critical nodes cannot be removed from the supply chain but reliable partners can help secure them.
- **Onshoring/in-housing:** For essential supply chain components, companies may opt to produce goods domestically or within their organisation to minimise reliance on external suppliers. Although resource intensive, this strategy ensures greater control over critical elements.

7.3 Supply Chain Characteristics of the Energy Sector

As shown in Figure 38, energy and technology supply chains encompass the processes required to deliver energy services or technologies to the market. Energy supply chains focus on the steps needed to supply fuels or energy services, including generation, transformation, transportation and distribution, often involving trade. Technology supply chains involve the stages necessary to create and deploy technologies, such as extracting minerals, processing materials, manufacturing components, and managing equipment through its lifecycle, including reuse or recycling. These supply chains are interdependent, as energy production relies on technologies, and technology development requires energy at every stage.[316]

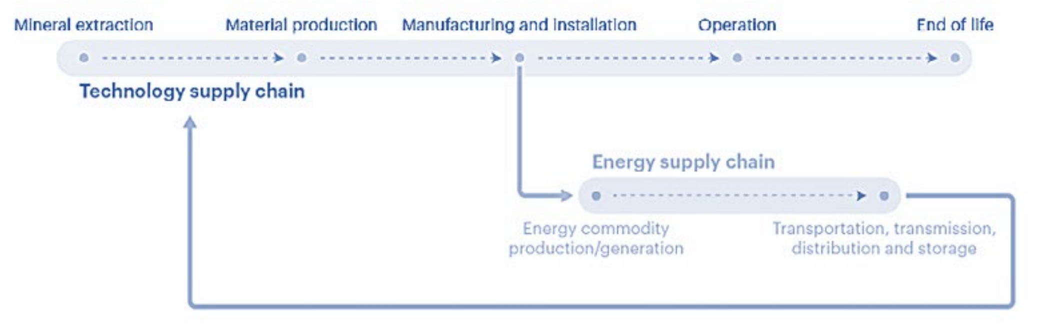


Figure 38. Stages of and connections between technology and energy supply chains[317]

It is important to recognise that each type of equipment within the energy and technology sectors has its own distinct supply chain, which spans across the initial mining of raw materials to the final production of the product. This process is clearly illustrated in Figure 39, Figure 40, Figure 41, Figure 42 and Figure 43, which demonstrate the individual supply chains for various technologies, including low-emission electricity, low-emission hydrogen, battery EVs, heat pumps, and fuel cell trucks. Each of these technologies involves unique processes and stages of development, ranging from the extraction and processing of specific minerals required for manufacturing to the assembly of components and, finally, to the installation and operation of the finished equipment. Additionally, these supply chains are often interconnected, with materials, technologies and services being transferred between different sectors, underscoring the complexity and interdependence of modern energy and technology systems.[318]

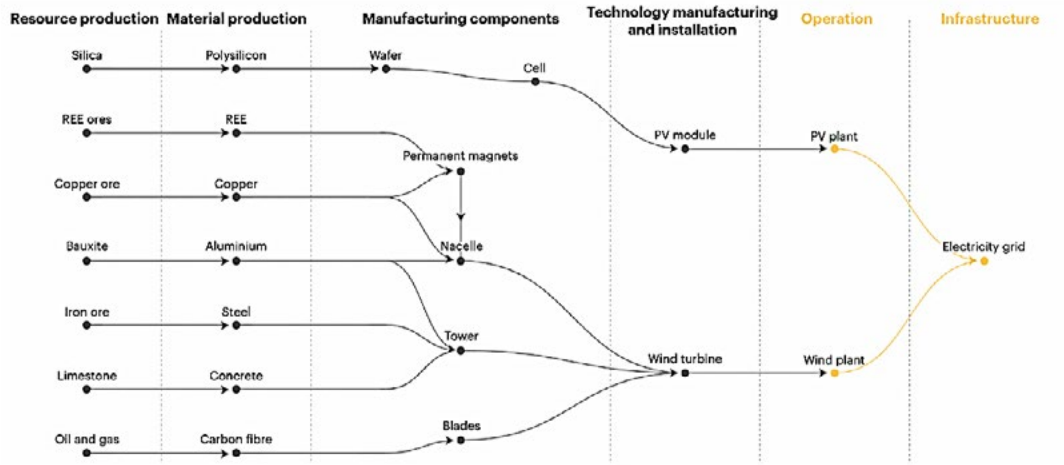


Figure 39. Key components of the supply chain for low-emission electricity[319]

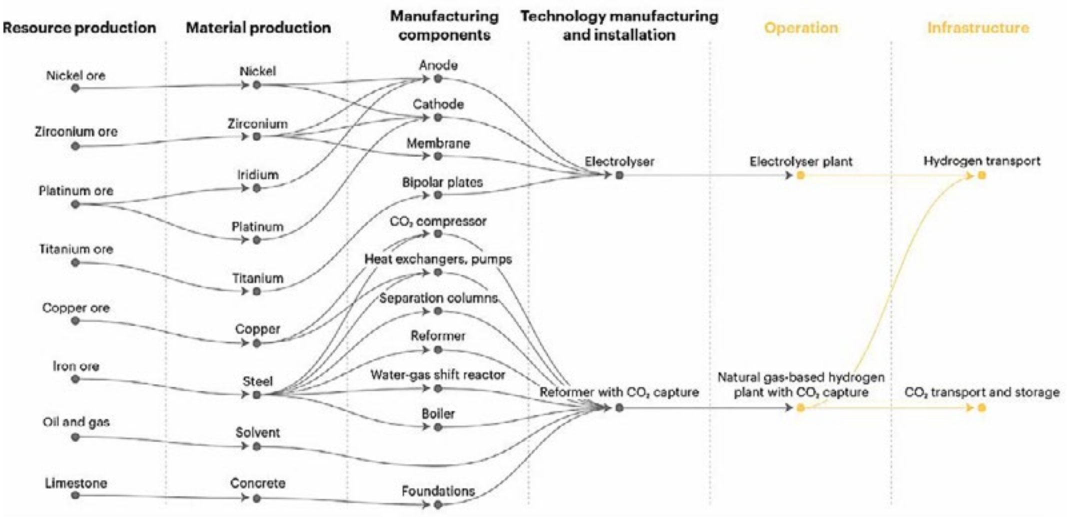


Figure 40. Key components of the supply chain for low-emission hydrogen[320]

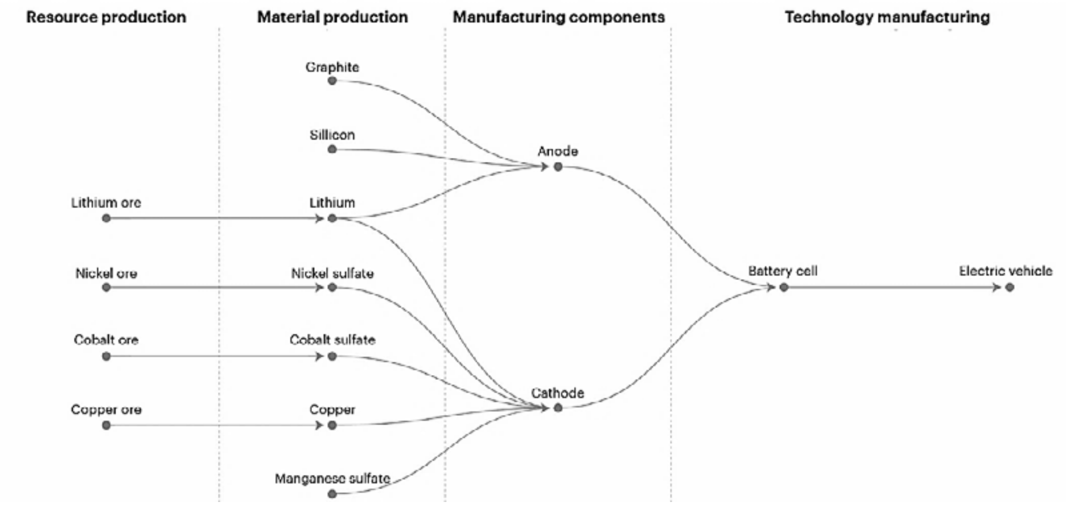


Figure 41. Key components of the supply chain for battery electric vehicles[321]

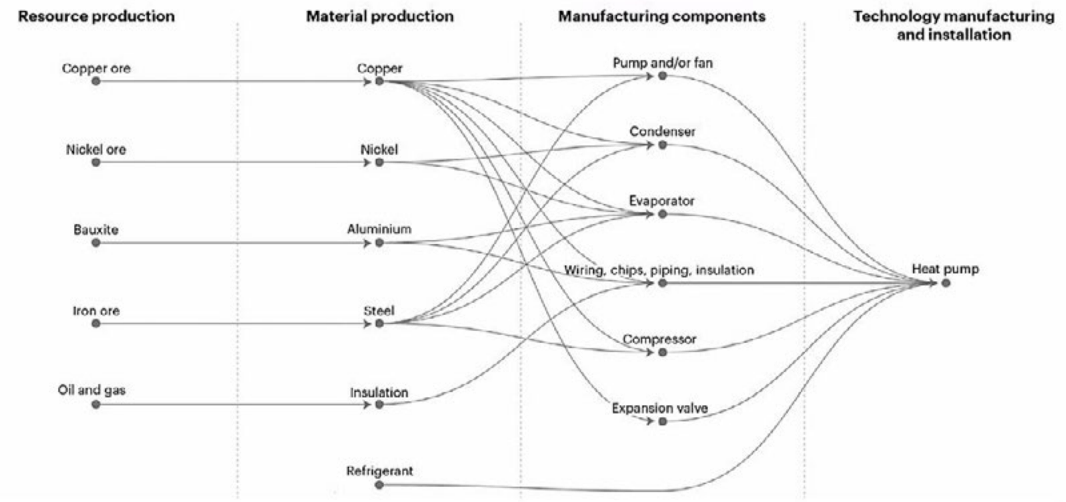


Figure 42. Key components of the supply chain for heat pumps[322]

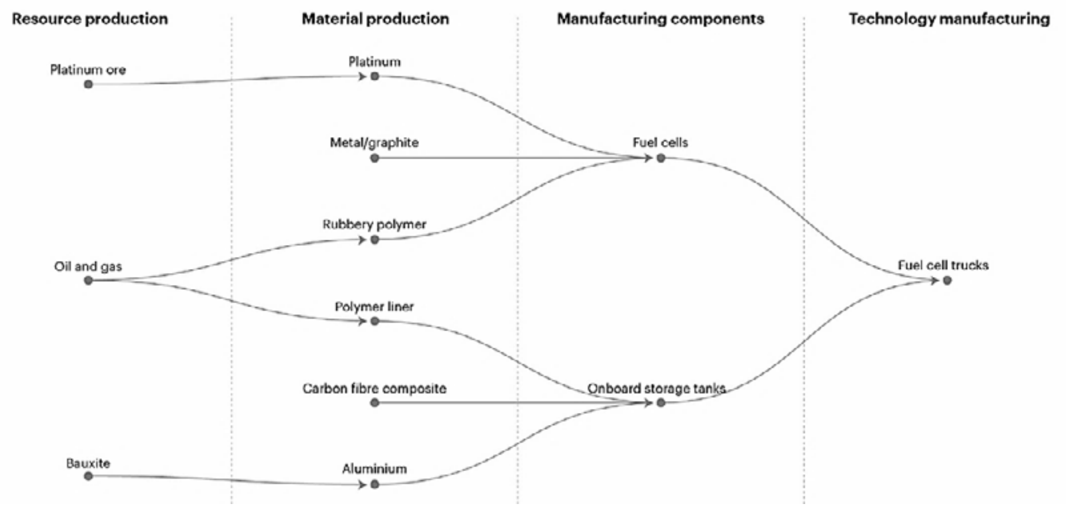


Figure 43. Key components of the supply chain for fuel cell trucks[323]

7.4 Regional Capacity for Mineral Resources and Technology Manufacturing in the Supply Chain

7.4.1 Mining and Material Production

Table 25 provides an overview of regional mining capacities and material reserves. It reveals key global players in resource availability, with some regions holding more significant reserves and mining capabilities than others. From this, it can be seen that the Asia-Pacific region and Central and South America have the largest shares of mining capacities and reserves.

Table 25. Regional capacities for mining and reserves in 2021[324]

Region	Copper		Nickel		Cobalt		Lithium		Rare earth elements	
	Reserve	Mined	Reserve	Mined	Reserve	Mined	Reserve	Mined	Reserve	Mined
World (kt)	880,000	21,000	95,000	2,700	7,600	150	22,000	100	120,000	290
China	3%	8%	3%	4%	1%	1%	7%	12%	35%	57%
Europe	4%	5%	0%	3%	0%	1%	0%	0%	1%	0%
North America	13%	12%	2%	5%	4%	3%	3%	1%	2%	16%
Other Asia-Pacific	13%	11%	49%	66%	30%	13%	36%	56%	26%	24%
Central and South America	32%	41%	17%	10%	7%	3%	42%	29%	17%	0%
Africa	6%	13%	0%	4%	48%	76%	1%	2%	1%	1%
Eurasia	9%	9%	8%	7%	3%	2%	0%	0%	17%	1%
Others	21%	2%	21%	0%	8%	0%	12%	0%	0%	0%

Table 26 outlines the regional production capacities for critical materials. It shows the extent to which different regions can produce essential materials needed for various industries—copper, lithium and so on. From this, China stands out as the leading country in the production of critical materials.

Table 26. Regional capacities for producing critical materials in 2021[325]

Region	Copper	Nickel	Nickel sulphate	Cobalt	Cobalt sulphate	Lithium	Lithium chemicals	Neodymium oxide
World (kt)	22,5000	2,790	228	137	119	95	150	39
China	34%	29%	56%	69%	70%	59%	59%	90%
Europe	11%	0%	11%	16%	16%	0%	0%	0%
North America	7%	4%	0%	4%	4%	1%	1%	0%
Other Asia-Pacific	16%	41%	17%	5%	5%	3%	3%	0%
Central and South America	14%	0%	0%	0%	0%	37%	37%	0%
Africa	8%	0%	0%	4%	4%	0%	0%	0%
Eurasia	7%	4%	0%	1%	1%	0%	0%	0%
Others	2%	21%	16%	0%	0%	0%	0%	10%

Table 27 outlines the production capacity of electrolysers across various countries. China holds the top position as the largest producer, followed by Europe, which has made significant investments in green hydrogen and renewable energy. North America and other Asia-Pacific countries also contribute to production, but on a smaller scale compared to China and Europe. This highlights China's leading role in the electrolyser market, while Europe and North America are working to scale up their production to support the increasing demand for green hydrogen technologies.

Table 27. Regional capacities for manufacturing electrolysers in 2022[326]

Region	Electrolyser
World (GW)	11
China	41%
Europe	26%
North America	19%
Other Asia-Pacific	14%
Others	0%

Table 28 provides an overview of the production capacity for wind turbine components across different countries. China is the dominant player in manufacturing these components, taking the lead in global production. Europe and North America follow with significant but smaller capacities compared to China.

Table 28. Regional capacities for manufacturing wind turbine technology components in 2021[327]

Region	Tower		Nacelle		Blade	
	Onshore	Offshore	Onshore	Offshore	Onshore	Offshore
World (GW)	88	18	100	26	98	25
China	55%	53%	62%	73%	61%	83%
Europe	16%	41%	13%	26%	18%	12%
North America	11%	0%	10%	0%	10%	0%
Other Asia-Pacific	12%	6%	8%	2%	6%	4%
Central and South America	5%	0%	6%	0%	4%	0%
Others	1%	0%	0%	0%	0%	0%

The production capacity of different countries for PV components is shown in Table 29. From this, China stands out as the leader in PV component development, while other countries lack specific production capacities, making them negligible in comparison.

Table 29. Regional capacities and production for solar photovoltaic components in 2021[328]

Region	Wafers		Cells		Modules	
	Production	Capacity	Production	Capacity	Production	Capacity
World	190	370	190	41	190	460
China	96%	96%	78%	85%	73%	75%
Europe	0%	1%	1%	1%	2%	3%
North America	0%	0%	1%	1%	5%	2%
Other Asia-Pacific	3%	3%	18%	13%	19%	18%
Others	1%	0%	2%	0%	1%	2%

As listed in Table 30, the primary challenge in securing battery supplies for the Australian Department of Defence is China's dominance in the global battery supply chain. China leads in the production of key materials and components—anodes, cathodes and so on. Even domestically produced materials often rely on Chinese-produced precursors, creating vulnerabilities in the supply chain. With electrification set to increase significantly by 2030, reliance on China is expected to grow.[329]

Table 30. Regional capacities and production for electric vehicle and battery storage components in 2021[330]

Region	Cathode		Anode		Batteries		Production of electric cars
	Production	Capacity	Production	Capacity	Production	Capacity	
World	440 kt	1,400 kt	250 kt	810 kt	340 GWh	910 GWh	6,800,000
China	77%	68%	91%	86%	66%	75%	54%
Europe	1%	1%	0%	0%	21%	8%	27%
North America	16%	1%	2%	1%	11%	6%	10%
Other Asia-Pacific	5%	26%	7%	13%	2%	10%	7%
Others	1%	4%	0%	0%	0%	1%	2%

Regional capacity and production capabilities are crucial factors in the manufacturing of heat pumps. As shown in Table 31, China has the highest production capacity for these components, followed by North America and Europe in second and third places, respectively.

Table 31. Regional capacities and production for heat pump components in 2021[331]

Region	Heat pumps	
	Production	Capacity
World (GW)	100	120
China	38%	39%
Europe	16%	16%
North America	29%	29%
Other Asia-Pacific	13%	14%
Others	4%	2%

Regional capacity and production capabilities are crucial factors in the manufacturing of fuel cell heavy-duty truck components. As shown in Table 32, China holds the highest production capacity for these components.

Table 32. Regional capacities and production for manufacturing fuel cell truck components in 2021[332]

Region	Fuel cell systems	Fuel cell trucks	
	Production	Production	Capacity
World	19 GW	900	14,000
China	48%	84%	45%
Europe	1%	9%	21%
North America	4%	0%	18%
Other Asia-Pacific	38%	6%	14%
Others	8%	1%	2%

7.4.2 Production Lead Times for Mass-Manufacturing Facilities

Achieving mass production of equipment in the energy sector requires significant lead time due to the complexity of the technologies, production scaling, and the integration of advanced systems. Table 33 illustrates the time required to lead the production of various types of essential equipment in the energy sector.

Table 33. Production lead times for mass-manufacturing facilities[333]

Technology		Years
Solar PV	Polysilicon	1–3.5
	Wafers	0.5–2
	Solar cells	0.5–2
	Solar modules	0.5–2
Wind turbine	Blade	1–2
	Tower	1.5–2.5
	Nacelle	1.5–2
Electrolysers		2–3
EVs	Anode	2–5
	Cathode	2–5
	Battery	0.5–4.5
Heat pumps		1–3
Fuel cell trucks	Fuel cell stacks	1.5–2.5
	Fuel cell trucks	0.5–1.5

7.5 Roadmap for Australian Defence Transition to Mixed Energy Sources

Figure 44 shows an energy transition roadmap outlining the ADF's approach to adopting alternative energy in line with industry and allied military practices while addressing the unique needs of military operations.[334] In the short term, renewable diesel, sustainable aviation fuel and electrification are prioritised, while hydrogen, uranium and further electrification are considered long-term alternatives for specific platforms. Although Defence will ultimately reduce its reliance on fossil fuels, it is expected that these fuels will remain in the energy mix (either in reduced amounts or blended with alternative fuels) beyond 2050. The transition roadmap should be reviewed periodically, every one to two years, to adjust for technological advancements, market changes, and shifts in government policy.

The energy roadmap emphasises the use of drop-in liquid fuels, such as renewable diesel and sustainable aviation fuel, which have similar chemical properties to conventional fossil fuels and do not significantly impact defence platforms or infrastructure. Electrification and hydrogen are also suitable for certain platforms but will not fully replace liquid fuels, due to limitations in range, survivability and infrastructure needs. Besides, some alternative energy types, like alcohols, ammonia and hydrogen, present unique challenges for defence, including lower energy density, reduced range, larger storage requirements, and potential impacts on platform durability and safety.

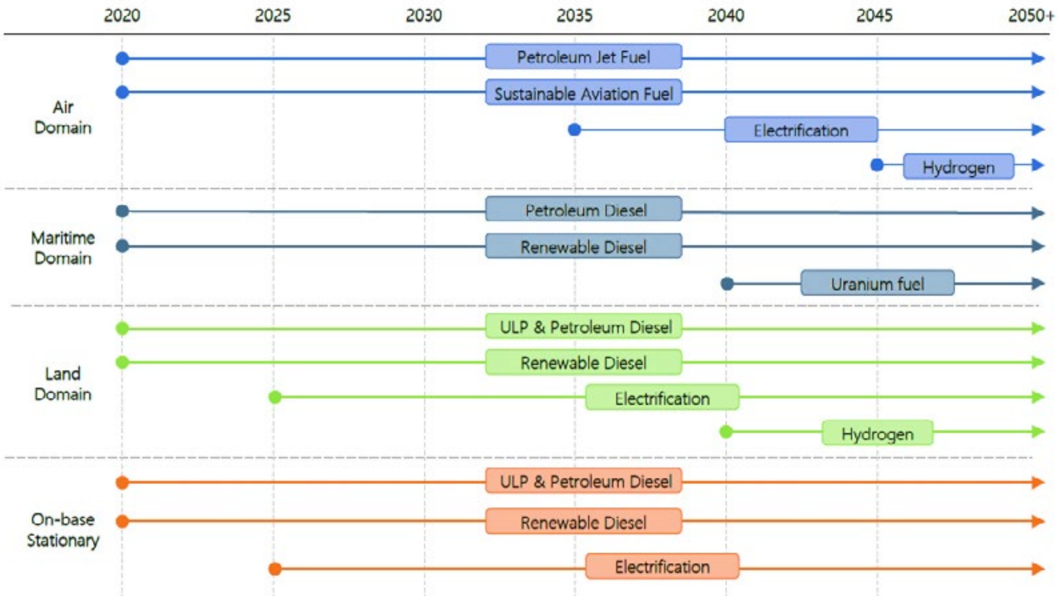
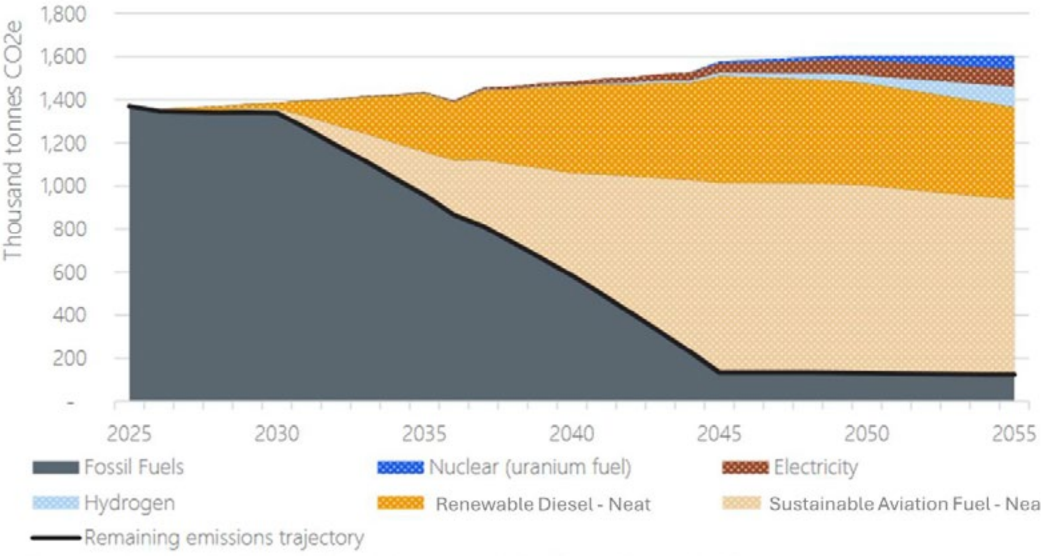


Figure 44. Australian defence roadmap for transition to mixed energy sources[335]

7.6 Future Energy Demand and Emissions Reduction in the Australian Defence Sector

Defence's annual fossil fuel requirements are projected to increase to 487 ML by 2050. However, with a shift towards alternative energy, demand profiles will become more complex due to varying energy densities of different fuels and the use of technologies like batteries. Under a balanced adoption scenario (shown in Figure 45), most fossil fuel demand could be displaced by alternative energy by 2045, or even as early as 2040 with a more ambitious approach. This transition will not only enhance Defence's energy security but also help meet the government's carbon emissions reduction targets. If Defence follows this transition program, emissions could decrease by 86 to 99 per cent by 2050, with a 92 per cent reduction under the balanced scenario. Some emissions may remain due to the use of some alternative technologies, especially batteries. While renewable fuels may incur higher costs in the short to medium term, price reductions are expected from the mid-2040s due to industry scaling and rising crude oil prices. A faster transition will encourage industry investment, leading to more significant cost savings in the long term. However, this excludes operational and infrastructure costs.[336]

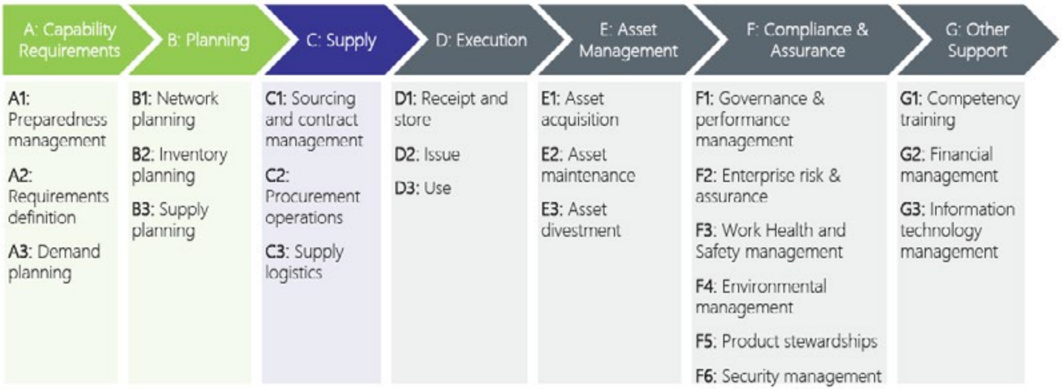


Note: Modelling shows indicative full lifecycle, including emissions from refining and mining uranium

Figure 45. Defence emissions reduction trajectory by fuel types[337]

7.7 Australian Defence Fuel Supply Chain Activities

The energy transition and changes in the ADF's energy needs will significantly affect the defence fuel supply chain. The defence fuel supply chain includes all activities, resources, technologies and organisations involved in the procurement, storage, management and distribution of fuel for the ADF. The commander of joint logistics is responsible for the safe, efficient and integrated operation of the defence fuel supply chain to meet the ADF's needs while ensuring optimal value for money.[338] As the ADF begins to transition towards adopting lower-carbon alternatives, the supply chain shown in Figure 46 needs to be followed precisely.



A: Capability Requirements	B: Planning	C: Supply	D: Execution	E: Asset Management	F: Compliance & Assurance	G: Other Support
A1: Preparedness management **A2**: Requirements definition **A3**: Demand planning	**B1**: Network planning **B2**: Inventory planning **B3**: Supply planning	**C1**: Sourcing and contract management **C2**: Procurement operations **C3**: Supply logistics	**D1**: Receipt and store **D2**: Issue **D3**: Use	**E1**: Asset acquisition **E2**: Asset maintenance **E3**: Asset divestment	**F1**: Governance & performance management **F2**: Enterprise risk & assurance **F3**: Work Health and Safety management **F4**: Environmental management **F5**: Product stewardships **F6**: Security management	**G1**: Competency training **G2**: Financial management **G3**: Information technology management

Figure 46. Fuel supply chain in Australian defence[339]

7.8 Suggested Measures for Enhancing the Supply Chain in Australia

Based on the analysis presented in this paper, Australia is vulnerable in its energy supply chain; therefore, several alternatives are proposed in Table 34 to strengthen the Australian energy sector.

Table 34. Recommendations for enhancing the supply chain in Australia

Vulnerability area	Risk description	Recommended action	Rationale/impact
Fuel import dependency	• Heavy reliance on overseas sources for liquid fuel supply	• Establish strategic fuel reserves; diversify sources and routes	• Enhances national resilience in case of global supply disruptions or access limitations
Extended supply chains for defence operations	• Energy supplies for remote or deployed operations depend on long and fragile logistics chains	• Deploy hybrid energy systems (solar + battery + diesel) at operational sites	• Increases autonomy and reduces reliance on vulnerable resupply networks
Limited domestic processing and manufacturing	• Key parts of the energy supply chain, such as refining or tech manufacturing, are concentrated outside the country	• Invest in local production and modular processing technologies	• Improves national control over critical energy components and reduces external exposure
Centralised energy infrastructure	• Central power systems are exposed to disruptions from physical, natural or digital threats	• Harden infrastructure; deploy microgrids at critical facilities	• Builds resilience and maintains operational continuity under adverse conditions

Vulnerability area	Risk description	Recommended action	Rationale/impact
Uneven adoption of resilient technologies	• Modern distributed energy technologies are not yet widely deployed in all sectors	• Accelerate deployment of distributed energy systems in priority areas	• Enhances adaptability and energy security across diverse environments
Dependence on global supply chains for technology	• Many energy technologies rely on globally concentrated production and supply networks	• Support domestic research and development and advanced manufacturing	• Reduces risk of shortages or delays due to external shocks or trade restrictions
Reliance on externally processed critical minerals	• Key materials used in energy systems are processed or refined outside national borders	• Develop local processing and secure supply agreements	• Ensures long-term access to essential materials for both civilian and defence energy needs

8. Role of AI in Autonomous Decision-Making Development for Independent Military Energy Systems

8.1 Brief Introduction to AI

Operators encounter various difficulties when large amounts of information are rapidly updated, especially in emergency scenarios. One of the most critical tasks is making key decisions, such as restoring service or managing voltage levels. If these decisions were left to a user-based system, it would be nearly impossible to process the vast amount of data and identify the best course of action. In this context, AI presents a valuable opportunity, allowing power system designers, planners and operators to delegate decision-making to machines that can analyse data and make choices more quickly and efficiently.[340] This approach not only speeds up decision-making but also improves accuracy. The efficiency and precision come from AI being pre-trained, meaning it has already learned general patterns from large datasets, allowing it to generate results within a short timeframe. For instance, AI systems are trained using data specific to power grids, and they function as knowledge-driven tools that can automate the management of modern power networks. Figure 47 outlines the four primary categories of AI,[341] which have different applications.

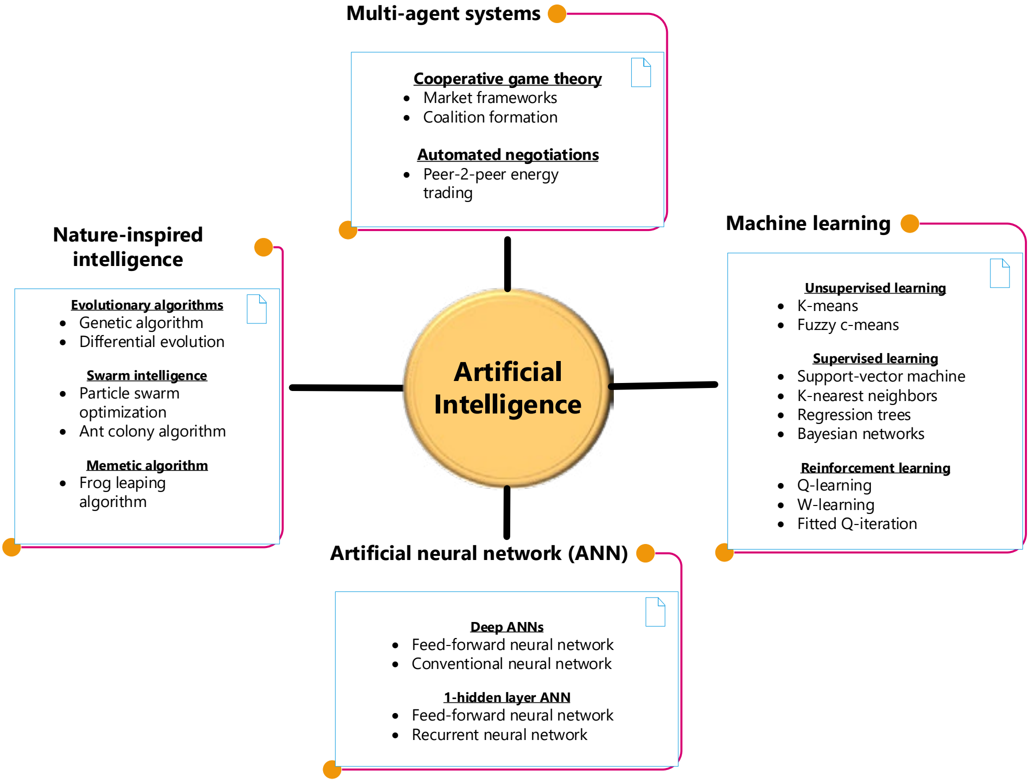


Figure 47. High-level classification of AI

8.3 Features of AI in Military Microgrids

Table 35 provides a summary of the key attributes and roles of military-grade AI, focusing on its architecture, capabilities and operational flexibility.[342]

Table 35. Features of a military-level AI in relation to its design, usability and functionality

Feature	Description
Design	• AI systems are specifically tailored to microgrids, optimising energy management, grid optimisation and resource distribution • Uses algorithms and machine learning to enhance energy distribution, forecasting, renewable integration and predictive maintenance • Adaptable to harsh conditions like extreme weather, grid disruptions and cyber threats

Feature	Description
Operability	• Operates autonomously or with human oversight, adjusting energy distribution, storage and optimisation based on real-time conditions • Integrates with renewable sources, energy storage and smart meters, enabling seamless monitoring of energy usage and generation • Ensures security of sensitive data, including energy usage and grid control information, from unauthorised access
Functionality	• Processes real-time data for monitoring consumption, detecting faults and identifying anomalies • Analyses operational data to help optimise energy usage, balance load, and plan future energy needs • Predicts energy demand, equipment failures and the impact of renewable energy fluctuations • Responds to issues like power outages or malfunctions, ensuring quicker recovery. • Enhances cyber security to protect digital assets and infrastructure • Detects disinformation to ensure accurate data is used for grid operations • Predicts weather patterns to help with operational planning, especially for renewable energy sources

8.3 Role of AI-Driven Strategies for Efficient and Sustainable Microgrid Operation

Table 36 summarises the key roles of AI in microgrid optimisation, including real-time data analysis, demand forecasting, load balancing, predictive maintenance, cyber security and regulatory compliance.[343,344]

Table 36. Role of AI in microgrid optimisation

Feature	Description
Real-time data analysis	AI algorithms process data from IoT sensors to monitor various microgrid parameters (e.g., voltage, power, weather). This data is analysed in real time and stored for future use
Demand response management	AI predicts peak demand periods using both real-time and historical data, allowing the system to adjust resource allocation proactively
Load balancing	Advanced algorithms optimise power distribution from storage systems, responding to supply and demand fluctuations to ensure efficiency and prevent overloading
Predictive maintenance	AI detects minor performance changes to predict when maintenance is needed, automatically alerting staff and scheduling repairs
Cyber security and anomaly detection	AI monitors network activity to detect abnormal patterns or cyber threats, helping prevent breaches and ensuring safety
Regulatory compliance and optimisation	AI helps microgrids comply with energy regulations and environmental standards while optimising system performance and emissions to meet sustainability goals

8.4 Challenges of AI in Microgrid Expansion

Table 37 outlines the key challenges and limitations associated with the implementation of AI in microgrid expansion.[345,346]

Table 37. Challenges of implementing AI in microgrid expansion

Feature	Description
High initial costs	Implementing AI in microgrids requires significant investment, and it may take time to see a return on that investment
Data dependency	AI systems depend on accurate, consistent data; poor or incomplete data can lead to inaccurate predictions and reduced efficiency
Integration challenges	Integrating AI into existing microgrid infrastructure can be difficult, especially for smaller grids with limited data or control systems

Feature	Description
Complexity of managing decentralised resources	Optimising decentralised DERs like renewable sources or EVs is challenging, especially when they are uncorrelated and spread across different locations
Risk of over-reliance on automation	Over-relying on AI could reduce necessary human oversight, making it difficult to address unexpected or nuanced situations
Scalability issues	Scaling AI systems for different microgrid sizes can be complex and costly, particularly for smaller grids
Data security and privacy	Using AI involves processing large amounts of data, raising concerns about data security and privacy, especially when protections are insufficient
Interoperability	AI integration in microgrids faces interoperability issues due to diverse systems, legacy infrastructure, and the need for standard communication protocols

8.5 Technical Challenges in AI-Based Autonomous Microgrids

Table 38 outlines the challenges in developing autonomous systems, including unresolved AI issues, the need to adapt to dynamic environments, and the difficulty of managing emergent behaviours.[347]

Table 38. Technical challenges in design and development of autonomous microgrids

Challenges	Descriptions
Devil in the details	• Use of AI in microgrids faces issues in energy management, dynamic load balancing, and integrating distributed energy resources • Microgrids must perform complex functions such as fault detection, energy needs identification and real-time responses • No system currently integrates all these tasks effectively, especially with the growing complexity of distributed resources

Challenges	Descriptions
Complex and uncertain environments	• Autonomous microgrids must operate in unpredictable environments like varying energy demand or renewable fluctuations • These systems need to adapt to conditions that cannot be pre-tested, such as changes in weather or grid disruptions • Microgrids must manage unexpected issues such as power failures or changes in energy supply
Emergent behaviour	• Autonomous microgrids must adapt to sudden changes, like power imbalances, without human intervention • Unexpected system behaviour can arise from energy surges, demand shifts or external disruptions
Human–machine interactions	• Success depends on the interaction between human operators and the microgrid system • The system must adjust to evolving goals like load balancing or renewable energy adjustments • The interface should include tools (visual, auditory, tactile) to help operators manage the system • A key challenge is converting human objectives into machine instructions and making the system’s decision-making understandable, especially in emergencies
Control	• As microgrids become more complex, controlling and predicting their behaviour, especially with renewable sources, becomes harder • There is a balance between high performance in energy management and ensuring transparency in how the outcomes are achieved

8.6 Recommendation for Addressing the Challenges of AI-Based Microgrids

Based on the analysis conducted in this paper, Table 39 presents several recommendations to address key challenges in the deployment of AI-based microgrids in military contexts, including data protection, transparency, security, integration issues, and ethical considerations.[348]

Table 39. Recommendations for overcoming key challenges in military AI-based microgrid deployment

Concern	Recommendations
Data protection and privacy	• Encrypt energy usage data and communications within microgrids to ensure privacy • Secure data exchanges between microgrid components with protected protocols • Limit access to sensitive microgrid data to authorised personnel only • Use multi-factor authentication to secure access to microgrid systems • Anonymise energy usage data when sharing with external parties • Use secure cloud platforms for microgrid data with strict access controls and encryption • Regularly anonymise and securely delete unnecessary microgrid data to comply with privacy regulations
Clarity and understandability	• Design AI models for microgrid management that are transparent and easy for grid operators to interpret • Implement visualisation tools in microgrid systems to make AI decisions clear to operators
Strength and dependability	• Protect AI models within microgrids from cyber threats with strong security measures • Regularly monitor microgrid systems for vulnerabilities and address them with patches • Restrict access to critical AI models and control systems in microgrids to prevent exploitation

Concern	Recommendations
Technology integration challenges	• Design flexible and scalable AI systems to ensure smooth integration with existing microgrid infrastructure • Ensure AI systems in microgrids are compatible with current energy sources, storage and smart meters • Test AI systems in real-world microgrid environments to resolve integration issues • Collaborate with energy providers and regulators to advance AI integration in microgrids
Insufficient training data	• Use data augmentation techniques, such as simulating weather patterns and energy consumption, to expand microgrid training datasets • Apply transfer learning to adapt pre-trained models for microgrid-specific tasks • Generate synthetic data for simulations to improve AI models for microgrid scenarios
Keeping track of rapid advancements in AI	• Use agile development processes to quickly incorporate new AI advancements into microgrid systems • Invest in in-house AI research for microgrids to stay ahead of evolving technologies • Partner with academic institutions and industry experts to incorporate the latest AI advancements in microgrid management
Ethical and legal considerations	• Develop ethical guidelines for AI use in microgrids, ensuring accountability and sustainability • Ensure microgrid AI systems comply with energy regulations, environmental laws and privacy standards • Promote transparency in microgrid AI decision-making and document the processes

9. Conclusion and Future Work

As Australia works to strengthen the security and resilience of its energy infrastructure, the ADF faces the urgent need to reduce its dependence on centralised power grids and fossil fuels, both of which are vulnerable to disruption and supply shortages. The increasing rates of natural disasters and the escalating risks of cyber and physical threats further underscore the necessity of this transition. This research highlights the strategic importance of localised and independent energy systems, which are essential to ensuring a continuous and reliable power supply for critical defence operations.

The findings indicate that microgrids which combine sustainable sources, battery storage and conventional fuel based generators, such as hydrogen and natural gas, are essential for maintaining operational resilience. These systems provide the capability for military facilities to operate independently when the main grid is compromised, ensuring uninterrupted support for defence activities. However, effective system design must go beyond efficiency. It requires adaptability to varied geographical and operational conditions, and advanced protection systems.

Microgrids also face critical challenges, particularly in the realm of cyber security. As cyber threats grow increasingly sophisticated, the strategic implementation of advanced cyber security measures is vital to protect these systems from potential attacks. Moreover, the integration of emerging technologies, such as AI, holds promising potential for enhancing system autonomy and operational efficiency. However, these technologies also introduce unique complexities, including issues of system integration and maintaining long-term reliability under dynamic and potentially hostile conditions. To ensure resilience, these systems must be equipped with cutting-edge security protocols and adaptive technologies that can effectively mitigate both cyber and physical threats.

Resilience and functionality of microgrids also depend heavily on the stability and reliability of supply chains. Many essential components, such as batteries, solar panels and power electronic technologies, are currently sourced from overseas. This overseas reliance introduces strategic risks, particularly in times of international tension or large-scale supply disruptions. To address this vulnerability, Australia must prioritise domestic manufacturing, promote local innovation, and build a more diverse and secure supply network. These measures will enhance energy security and support the broader goal of strengthening defence capabilities.

For future work, there are several factors that will shape the ADF's successful transition to independent energy systems. These include the development of comprehensive risk management frameworks, increased investment in research and development, and efforts to integrate resilience, innovation and energy independence into long-term strategic planning. It is these measures that will ensure that the ADF is equipped with secure, reliable and adaptable energy solutions to meet evolving operational needs.

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